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HANDS-ON RADIO

Experiment 94 — SWR and Transmission Line Loss

SWR (standing wave ratio) is something everybody measures — it's one of the most widely used numbers in ham radio. But not everybody understands what SWR is and what affects it. In this month's experiment, we'll have a quick refresher on SWR basics and then examine the effect of losses in the transmission line on the SWR you measure back at the shack.

SWR Basics

If power traveling through the transmission line encounters a load impedance, Z_L, different from the transmission line's characteristic impedance, Z_0, some of the power is reflected back along the transmission line. This creates a stationary pattern of voltage (and current) along the line. The stationary pattern is called a *standing wave* and the ratio of the peak to minimum voltage or current is called the *standing wave ratio* or *SWR*. (A complete treatment of SWR is available in *The ARRL Antenna Book*.[1])

SWR is a numeric way of describing the relationship between the transmission line's Z_0 to the load impedance, Z_L, such as the impedance of an antenna. The simplest SWR calculation is SWR = Z_L/Z_0 or Z_0/Z_L, whichever is greater than 1. (SWR is never less than 1:1, pronounced "one to one.") If a 50 Ω transmission line is connected to a 75 Ω load, the SWR = 75/50 = 1.5:1. If the load is 25 Ω, the SWR = 50/25 = 2.0:1.

In order to work with the incident or forward power, P_f, traveling toward the load and reflected power, P_r, traveling away from the load, it is useful to define a *reflection coefficient*, denoted by the symbol ρ (rho). Sometimes the symbol Γ (gamma) is used.

$$|\rho| = \frac{\text{SWR} - 1}{\text{SWR} + 1} \quad \text{and} \quad \text{SWR} = \frac{1+\rho}{1-\rho}$$

This equation only calculates the magnitude of the reflection coefficient, which is a complex number when either the line or load impedance contains reactance.

The amount of forward and reflected power can be used to calculate the SWR (and vice versa):

$$\rho = \sqrt{\frac{P_r}{P_f}} \quad \text{and} \quad \text{SWR} = \frac{1+\sqrt{P_r / P_f}}{1-\sqrt{P_r / P_f}}$$

Thus, forward and reflected power, SWR and the reflection coefficient are all conveniently related.

Line Loss

No transmission line is perfect — some of the power input to the line will be dissipated as heat. The heat is the result of either resistive loss (proportional to the square of the current) in the conductors or from losses in the dielectric (proportional to the square of the voltage). This is called *line loss*. The amount of loss in the transmission line as power flows through it to a load with $Z_L = Z_0$ is called the *matched-line loss*, abbreviated ML and measured in dB per unit of length, such as dB/ft.[2]

ML increases with frequency and is usually specified in dB/100 feet at several frequencies, often 1-10-100-1000 MHz. For example, the table of transmission line characteristics on page 24-18 of *The ARRL Antenna Book* shows that RG-58C/U (Belden part number 8262) has an ML of 0.4 dB/100 feet at 1 MHz, 1.4 dB/100 feet at 10 MHz, 4.9 dB/100 feet at 100 MHz, and 21.5 dB/100 feet at 1 GHz. (This would not be a good transmission line for use on the 23 cm band!)

Loss Due to SWR

If the load impedance is not equal to that of the transmission line, causing some of the power to be reflected from the load, not all of it is absorbed by the load. If the load is an antenna, that means not all of the power is radiated. The reflected power travels back to the other end of the line where all or part of it may be reflected again for another trip to the load. Eventually, all power input to a transmission line is either dissipated as heat in the line or absorbed by the load or generating source impedances.

Is this extra loss a problem to worry about? On HF, for SWR of less than 2:1, the additional loss over and above ML due to part of the power being reflected is usually less than 0.5 dB. For lines of reasonable length, this is an insignificant amount in nearly all circumstances. Once the SWR reaches 3:1 or higher, however, the additional loss can be noticeable, or worse. Figure 1 is a graph of additional loss due to SWR for varying values of ML.

To use Figure 1, first determine ML for the length of transmission line being used. (Table 1 lists data for a few common cables and Figure 23 on page 24-20 of *The ARRL Antenna Book* shows ML for 100 feet of many types of common transmission lines over the frequency range from 1 to 1000 MHz.) Then use Figure 1 to determine the additional loss and add it to the ML to obtain the total loss.

For example, what is the total loss of a 200 foot piece of RG-58C/U at 100 MHz if the SWR is 4:1? The manufacturer specifies ML for RG-58C/U as 4.9 dB/100 ft at 100 MHz, so ML for a 200 foot length is

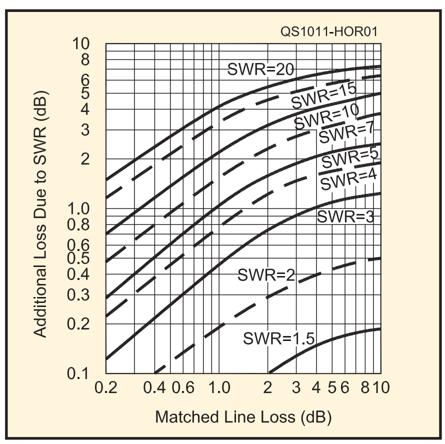

Figure 1 — Additional line loss due to SWR as measured at the load. Total loss is equal to ML plus the additional loss.

[1]R. D. Straw, Editor, *The ARRL Antenna Book*, 21st Edition. Available from your ARRL dealer or the ARRL Bookstore, ARRL order no. 9876. Telephone 860-594-0355, or toll-free in the US 888-277-5289; **www.arrl.org/shop**; **pubsales@arrl.org**.

[2]S. Ophanidis, *Electromagnetic Waves and Antennas*, ECE Department, Rutgers University, **www.ece.rutgers.edu/~orfanidi/ewa/**, Chapter 10.

H. Ward Silver, NØAX ♦ 712 Jefferson St, St Charles, MO 63301 ♦ n0ax@arrl.org

Table 1

Matched Loss (ML) of Common Transmission Lines as a Function of Frequency

Line Type	*ML for 100 feet at Frequency (MHz)*			
	1	*10*	*100*	*1000*
RG-213	0.2	0.6	1.9	8.0
RG-8X	0.2	0.7	2.3	7.4
RG-58C/U	0.4	1.4	4.9	21.5
RG-59	0.3	0.9	2.6	8.5
RG-174	1.9	3.3	8.4	34.0

Cables with the same RG designation from different manufacturers may differ in characteristics. Consult manufacturers' data sheets.

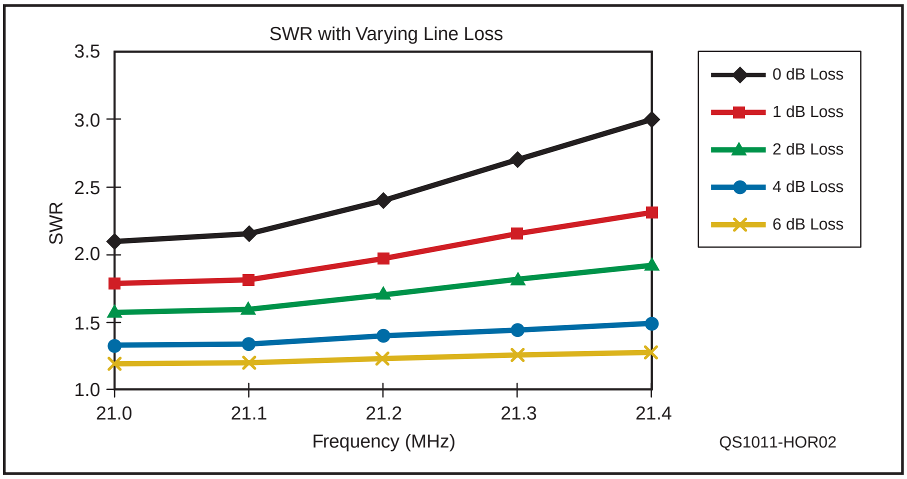

Figure 2 — Increasing line loss (ML) reduces SWR of a 15 meter quad measured at the input to the transmission line. The top curve (0 dB line loss) shows SWR at the antenna that is the same as input SWR for a lossless line.

2 × 4.9 = 9.8 dB. From Figure 1, start at ML ≈ 10 dB on the horizontal axis and follow a vertical line up to where it intersects the SWR = 4 curve. On the graph's left hand vertical axis, that intersection is just less than 2 dB, so additional loss is about 1.9 dB. Total loss is then 9.8 + 1.9 = 11.7 dB. Again, this would not be a very good transmission line choice, since only about ¼ of the input power would make it into whatever load is attached.

Input SWR

Note that the caption for Figure 1 refers to *SWR measured at the load*. When first studying SWR, say for a license exam, the study material often states that "SWR does not change along a transmission line." For this statement to be true, the transmission line must be lossless. Why? Because some of the reflected power is lost due to ML on its return trip from the load back to the source. As we get closer to the source, less of the original forward power has been lost, so its value is increasing! From the second equation, you can see that if P_r decreases and P_f increases, then SWR gets closer to 1:1. In other words, line loss causes the SWR at the input to the line — *input SWR* — to be lower than if it were measured at the load, the point at which the ratio of P_r to P_f is lowest.

Let's take this to an extreme and assume that we have a very, very long and lossy transmission line and apply some power to it, P_f. If we measure SWR at the input to the line, it will always be 1:1 because no power ever returns from the load and $P_r = 0$. It doesn't matter what the load impedance is at all! This is an important lesson: line loss reduces input SWR.

Most transmission lines are not terribly lossy in the frequency ranges they're designed for, but how much do they really affect the typical SWR curve? Figure 2 shows the effects of loss on the input SWR curve for a 15 meter quad antenna for ML values of 0, 1, 2, 4 and 6 dB. As you can see, the lossier the line, the better the antenna looks — in terms of SWR, anyway. With 6 dB of line loss, you might wonder why your received signal is weak, even though SWR never exceeds 1.3:1. (The formula for input SWR was obtained from Reference 2 and an *Excel* spreadsheet is provided on the Hands-On Radio Web site for making these calculations and graphs.[3])

Observing the Effects of Line Loss

You can observe this effect yourself with the help of an antenna analyzer that can operate at and above 100 MHz, such as an MFJ-259 or similar instrument. Acquire a long piece of coaxial cable and short the far end of the cable with a short piece of wire, creating a load SWR equal to infinity. (A short circuit is easier to create than an open circuit due to stray capacitance.) Connect the antenna analyzer to the other end, set to a frequency of a few MHz. The SWR indication should be very high or infinite. Now increase the frequency while watching SWR on the analyzer. As frequency increases, you will see SWR begin to decrease. For most cable types, above 100 MHz SWR will decrease rapidly. Compare different types of cable to see the effects of line loss. The lower the input SWR reading (at the analyzer), the lossier the line at that frequency because load SWR is infinite!

For Further Reading

Read the Transmission Lines chapter of either the *ARRL Handbook* or the *ARRL Antenna Book* for more information about these amazing cables that we take for granted.[4] The mathematically inclined reader may enjoy browsing through Reference 2 or any engineering textbook that covers transmission lines.

[3]All previous Hands-On Radio experiments are available to ARRL members as downloadable PDF files at **www.arrl.org/hands-on-radio**.

[4]*The ARRL Handbook for Radio Communications*, 2011 Edition. Available from your ARRL dealer or the ARRL Bookstore, ARRL order no. 0953 (Hardcover 0960). Telephone 860-594-0355, or toll-free in the US 888-277-5289; **www.arrl.org/shop**; **pubsales@arrl.org**.

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