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HANDS-ON RADIO

Experiment #72 — Return Loss and S-Parameters

If you look up the performance specifications for RF equipment, such as filters, in the literature from a commercial manufacturer, you may be surprised not to find SWR in the data tables. In its place, you'll find a parameter called *return loss*. What's up with that and how does it relate to SWR? That's the topic of this month's column and we'll also touch on *S-parameters*, not commonly used by hams but well-known in industry.

The Basics

Let's start with basic transmission line operation. If the load attached to a transmission line has the same impedance as the line's *characteristic impedance*, Z_0, all of the power flowing as electromagnetic waves toward the load in the line will be transferred to the load. If the load has some other impedance, higher or lower than Z_0, some of the power will be reflected back toward the power source (aka — the generator).

The forward wave (generator-to-load) and the reflected wave (load-to-generator) interfere with each other to create stationary patterns of voltage and current in the line called *standing waves*. The greater the difference in impedances between the line and the load, the larger the amplitude of the interference pattern will be.

If the pattern of voltages in the line is measured, the ratio of peak to minimum voltage is the *voltage standing wave ratio* or VSWR. The pattern's amplitude can also be measured as current to give ISWR, but voltage is more easily measured. VSWR and ISWR have the same value and are usually given the more general term, SWR.

Voltage and current in the transmission line are rarely measured directly outside the laboratory. Amateur SWR meters use directional coupler circuits to create voltages proportional to the power flowing in each direction and use a special meter scale to convert the ratio of the voltages to SWR. (Hands-On Radio Experiment #52 discusses how garden-variety SWR meters work.[1]) Wouldn't it be easier to just display forward and reflected power? Yes, but SWR is the mental model that amateurs use to describe the relationship between Z_L and Z_0, so our equipment displays SWR.

[1]Previous Hands-On Radio columns are available to ARRL members at **www.arrl.org/tis/info/HTML/Hands-On-Radio**.

Outside Amateur Radio the situation is different. What RF engineers usually want to know is how much of the power in a transmission line will be delivered to a device or antenna and how much will be reflected. These engineers think in terms of power, not SWR. Their mental model is different because they are more concerned with system efficiency and other similar calculations. They also tend to use more sophisticated instruments that measure power directly.

Thus the term *return loss*, measured in dB, is used. Return loss and SWR measure the same thing — how much power in the transmission line is sent to the load and how much is reflected by it — but state the result differently.

Return loss (RL) = $10 \log_{10} (P_{REFL}/P_{FWD})$ dB [1]

Because P_{REFL} is never greater than P_{FWD}, RL is always negative. The more negative RL, the less the amount of power reflected from the load compared to forward power. If all the power is transferred to the load because $Z_L = Z_0$, RL = $-\infty$ dB. If none of the power is transferred to the load, such as at an open or short circuit, RL = 0 dB. For practice, calculate RL for the following values of P_{FWD} and P_{REFL}:

(A) P_{FWD} = 100 W, P_{REFL} = 25 W
(B) P_{FWD} = 100 W, P_{REFL} = 1 W
(C) P_{FWD} = 1 kW, P_{REFL} = 50 W
(D) P_{FWD} = 5 W, P_{REFL} = 0.1 W

(Answers are provided at the end of the article.) Table 1 contains a series of values for P_{FWD} and P_{REFL} and the corresponding value of RL. Note that RL only depends on the ratio of power values, not the absolute values of the powers involved. RL is the same wherever P_{REFL} / P_{FWD} has the same value.

RL can also be calculated directly from power ratios, such as dBm (decibels with respect to 1 mW) or dBW (decibels with respect to 1 W). In this case, RL = $P_{REFL} - P_{FWD}$ because the logarithm has already been taken in the conversion to dBm or dBW. (Ratios in dB are computed by subtraction, not division.) For example, if P_{FWD} = 10 dBm and P_{REFL} = 0.5 dBm, RL = 0.5 − 10 = –9.5 dB. Here are some more practice exercises:

Table 1
Return Loss Versus Power

P_{FWD} (W)	P_{REFL} (W)	P_{REFL}/P_{FWD}	RL (dB)
1	0.1	0.1	–10
1	0.2	0.2	–7
1	0.5	0.5	–3
1	1	1	0
10	0.1	0.01	–20
10	0.2	0.02	–17
10	0.5	0.05	–13
10	1	0.1	–10
100	0.1	0.001	–30
100	0.2	0.002	–27
100	0.5	0.005	–23
100	1	0.01	–20
100	2	0.02	–17
100	5	0.05	–13
100	10	0.1	–10
100	20	0.2	–7
100	50	0.5	–3
100	100	1	0

(E) P_{FWD} = 25 dBm, P_{REFL} = 4 dBm
(F) P_{FWD} = 12 dBm, P_{REFL} = 6 dBm
(G) P_{FWD} = 10 dBW, P_{REFL} = 1 dBW
(H) P_{FWD} = 1 dBW, P_{REFL} = –20 dBW

Both power measurements must have the same units (dBm, dBW, etc) for the subtraction to yield the correct results. For example, one can't subtract dBW from dBm directly. Bonus exercise — what if P_{FWD} is 10 dBW and P_{REFL} is 20 dBm? (1 W = 1000 × 1 mW, so to convert dBW to dBm, add $\log_{10}(1000)$ = 30 dB. The answer to the bonus exercise is then 20 dBm – 40 dBm = –20 dB.)

As you can see, the more negative the value of RL, the smaller the fraction of forward power that is reflected towards the source. More negative values of RL are "better" in the same sense that lower values of SWR are "better."

SWR to Return Loss Conversion

If SWR and RL measure the same thing — reflected power as a fraction of forward power — can one be converted to the other? Of course. There are tables of those conversions, but how about an equation instead?

Start by converting RL back to a power ratio as follows:

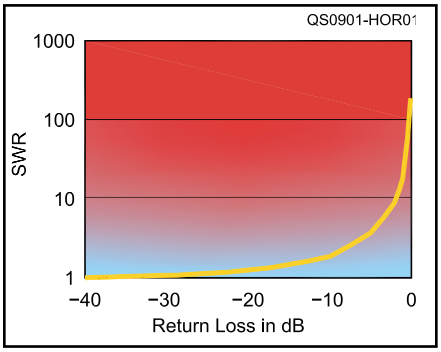

Figure 1 — A graph of SWR versus return loss (RL) shows that RL, measured in dB, is more useful at low values of SWR.

$$P_{REFL}/P_{FWD} = \log^{-1}(0.1 \times RL) \quad [2]$$

Now use the equation for computing SWR from forward and reflected power:

$$SWR = \left[1 + \sqrt{P_{REFL}/P_{FWD}}\right] / \left[1 - \sqrt{P_{REFL}/P_{FWD}}\right] \quad [3]$$

Table 2 contains a series of values that show the relationship between P_{REFL}/P_{FWD}, RL, and SWR that is also graphed in Figure 1.

What about going the other way, from SWR to RL? Start with the equation for power ratio in terms of SWR:

$$P_{REFL}/P_{FWD} = [(SWR - 1)/(SWR + 1)]^2 \quad [4]$$

Then convert that to RL using equation [1]. Table 3 shows a series of values for P_{REFL}/P_{FWD} and RL based on the value of SWR. You can use the equations above to make your own table or automatic RL to SWR converter in a spreadsheet!

Two-Port Devices

Why do RF engineers prefer to work in terms of RL and dB instead of the more familiar SWR? Most instrumentation used professionally is calibrated in dB (and related units, such as dBm) for amplitude such as on spectrum analyzers, a common instrument in the professional world. A measurement in dB "fits better" than a measurement such as SWR that is calculated linearly, without logarithms. Figure 1 gives another good reason — at large negative values of RL, SWR becomes very close to 1.0 and changes in value become smaller and smaller. It's much easier to work with the larger values of RL in dB, just as hams do for gain and attenuation.

Another reason is that RF engineers tend to think of their systems as a network of "black boxes" called *two-port devices* as shown in Figure 2. (Power supply connections are ignored in this model.) Each two-port device has an input (Port 1) and an output (Port 2). The behavior of the device is then described mathematically by the relationships between signals at the various ports.

There are a number of techniques to describe the relationships and each technique relies on a set of mathematical constructions called *parameters*. There are Z-parameters, H-parameters, T-parameters, and so forth, all designed to describe the device in a way that is of most use to the designer for a specific type of product or system. For example, T-parameters describe the device in terms that relate to the transmission of signals. Z-parameters describe the device in terms of impedances. Each type of parameter is a mathematical tool to be applied in the appropriate environment.

S-Parameters

In the RF design world, the most common set of parameters is that of the *s-parameters*, or "scattering parameters." The word scattering is used because s-parameters describe what happens when a signal is applied to one port and "scatters" to the other port, or even from the port to which the signal is applied.

There are four s-parameters: S_{11}, S_{12}, S_{21} and S_{22} shown in Figure 2. The numbers indicate the direction of the scattering. The first number is the port at which the scattered signal is measured and the second number the port at which the signal was applied. So S_{21}, for example, describes the signal at port 2 that results from a signal being applied at port 1. Hmmm...does that ring a bell? If the device is a circuit, then S_{21} describes its gain! If the device is a transmission line, S_{21} describes its loss.

Table 2
SWR Versus Return Loss

P_{REFL}/P_{FWD}	RL (dB)	SWR
0.0001	–40	1.02
0.0010	–30	1.07
0.0100	–20	1.22
0.0316	–15	1.43
0.1000	–10	1.92
0.3162	–5	3.57
0.6310	–2	8.72
0.7943	–1	17.39
0.9772	–0.1	173.72

Table 3
P_{REFL}/P_{FWD} Versus SWR

SWR	P_{REFL}/P_{FWD}	RL (dB)
1.01	0.005	–23.0
1.1	0.048	–13.2
1.2	0.091	–10.4
1.5	0.200	–7.0
2	0.333	–4.8
3	0.500	–3.0
5	0.667	–1.8
10	0.818	–0.9
100	0.980	–0.1

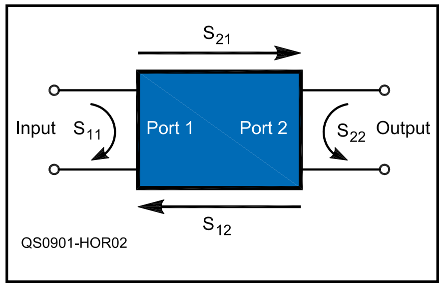

Figure 2 — A two-port device with its associated s-parameters. The s-parameters describe what happens at a port when a signal is applied to the same or the other port.

Well, why didn't they just call it *gain* or *loss*, I hear you asking. It's because the math involved with these four parameters often operates on all four at once (as a matrix) and it's easier to keep everything straight if a consistent symbol naming convention is used as opposed to common language names.

In an amplifier, S_{12} describes the isolation between the output and input ports. S_{11} describes what happens when a signal is applied to port 1 and then the resulting signal that comes back from port 1 is measured. Ah, hah! That's our definition of return loss, isn't it? (Similarly, there is an equivalent return loss at the output port, S_{22}.) So the set of four s-parameters — gain, isolation and two return losses — describes an amplifier (or filter or transmission line or...) pretty well. And now you know what you're looking at in those data sheets!

Exercise Answers

(A) –6 dB, (B) –20 dB, (C) –13 dB, (D) –17 dB, (E) –21 dB, (F) –6 dB, (G) –9 dB, (H) –21 dB

Recommended Reading

There are detailed discussions of return loss and scattering parameters on Wikipedia. Browse to **www.en.wikipedia.com** and enter either of those terms. Unfamiliar terms are often hyperlinked from Wikipedia pages for even more information.

Next Month

If you browse the tables of op-amp data in the Component Data and References chapter of *The ARRL Handbook* or in an electronic distributor's catalog, you'll discover a cornucopia of devices types. Next month, we'll talk about op-amp parameters and how to decide which common op-amps are right for your project.