Forward and Reflected Power: What Does It Mean?

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Overview

Measurements made in the RF domain are steeped in tradition. Like most traditions, RF concepts are passed on by word of mouth as well as by written legend. Also like most traditions, the concepts are imperfectly understood by many who need to know better. In particular, reflected power is often misunderstood. Most users have the impression that its presence is bad and so it should be minimized. This paper is intended to increase knowledge and dispel myths surrounding RF measurements and practice.

Origins

The use of radio frequencies in the first half and more of this century was centered on radio communication, as the very name implies. In a radio station, power is generated by a transmitter, usually housed comfortably in a shack, and the RF power is led to the (usually) remote antenna by a cable, or *transmission line*, which in short wave stations can be several wavelengths long. An antenna tuner is generally placed at the antenna end of this line. The function of this circuit is to match the antenna, which means that the complex impedance represented by the antenna is transformed by this circuit to a fixed real impedance. This is desirable for two reasons; the first relates to the transmitter and the second to the line.

First, every transmitter has some impedance into which it can deliver the most real power (usually set by design to 50 Ω). If the antenna's impedance is different from this ideal value, more voltage and/or current will be required of the transmitter to get a given radiated power than if the load was matched to the transmitter. This limits the maximum power of the transmitter.

Secondly, if a line is terminated in its characteristic impedance (also usually 50 Ω), the RF voltage along that line will be uniform. If it is not so terminated, a standing wave will be set up along the line. A standing wave of current also exists along the line. This can result in overheating, or hot spots in the cable, at places where the current is at a maximum.

> A standing wave is a distribution of RF voltage that rises and falls along the line. This can stress the line because the voltage peaks for a given power are higher than the voltage on a matched line and the line could arc over at these voltage maxima.

For both reasons, radio engineers match the antenna, meaning that they adjust the antenna tuner until the transformed impedance is equal to the line impedance, which is generally also the transmitter's ideal load resistance. To detect when the antenna is matched, radio engineers do not physically walk along the line to measure the actual standing wave. Rather more conveniently, they use a device known as a directional wattmeter, which they can place at any convenient point in the cable. This device measures the voltage, current, and their relative phase. It reports on its dials quantities called *forward power* and *reflected power*.

Where do such terms come from and what do they mean?

Forward and Reflected Power

A standing wave on a transmission line can be thought of as being composed of two traveling waves, one moving toward the load (the forward wave) and one moving in the opposite direction (the reflected wave). These waves, moving through the transmission line, interfere with one another to produce the standing wave. Each of these waves have a voltage amplitude — the forward voltage V_f and the reflected voltage V_r. The conceptual problem comes from the dials of the directional wattmeter, which are not calibrated in volts but rather in watts. How do we get watts from volts?

The coupler (or wattmeter) assumes that the forward wave is terminated in a 50 Ω resistor, calculates $|V_f|^2/50$, and presents the result as forward power. Similarly, it assumes the reflected wave is also terminated in a 50 Ω resistor, calculates $|V_r|^2/50$, and presents the result as reflected power. This can cause serious confusion because usually the waves are not impressed on any such resistor.

If the antenna and tuner are replaced by a 50 Ω resistor, then the forward wave is terminated in this resistor, and the indicated forward power actually will be the power dissipated in the load resistor. Because the 50 Ω line is terminated in its characteristic impedance, there will be no reflected wave and no standing wave, because the line is matched, and V_r and the reflected power are zero. (If the tuner is adjusted to transform the antenna impedance to exactly 50 Ω, the same thing occurs, except that the power is radiated from the antenna instead of being dissipated in a resistor.) If the load at the end of the line is not equal to 50 Ω, then there will be a standing wave, and so a reflected wave. Since the forward power is defined as the power in a 50 Ω load, and since the load is no longer 50 Ω, the forward power no longer represents the load power. What about the reflected power? What does it represent?

One very common misconception is that the reflected power represents the power that must be absorbed by the generator. That this is not the case can be easily seen if one looks at an extreme case. Suppose a lossless line is terminated by a pure open circuit, and suppose that the line is exactly one wavelength long at the operating frequency. In this case, the current at the generator will be zero, and so the current in its internal impedance will be zero, so there is no power dissipated in it. Yet there is a standing wave on the line, so there are forward and reflected waves. The directional wattmeter will show a forward and reflected power, and in fact they will be equal to one another and equal to the power that would be dissipated in a 50 Ω resistor if the voltage at the generator were impressed upon it. But there is no such resistor and so there is no power lost anywhere (again assuming no line loss).

Is there any measure of sense that we can get from the forward and reflected power readings? What do they really mean, anyway, if forward power doesn't represent the power delivered to the load and reflected power doesn't represent power absorbed by the transmitter?

FORWARD AND REFLECTED POWER: WHAT DOES IT MEAN?

First of all, the difference between the forward and reflected power has a concrete meaning: it is the power delivered to the load (see Appendix A). In this sense, one can imagine that the forward power is being impressed upon the load, which is rejecting the reflected part and absorbing the balance. We have to be careful not to take this imagery too far. It must not be inferred, for example, that the generator actually has to generate the forward power. The generator has to produce the power lost in the load, the line, and its internal impedance, and no more, because any power produced must be delivered somewhere, and these are the only places for it to be lost. In the case of the open lossless line, there is no power lost in the load, line, or the generator, and so there is no real power lost anywhere, but there are forward and reflected power figures. These powers are not real energy flows, but rather are calculated figures that represent the power that would be generated in a 50 Ω resistor if the forward and reflected waves were impressed upon it. Since there is no such resistor, there is no such power.

Let's recap. What can be inferred from the forward and reflected power readings on our directional wattmeter and what cannot?

1. If the reflected power is zero, there will be no standing wave on the line and no excess stresses on it.
2. If the reflected power is zero, the generator can deliver its maximum rated power into the load.
3. The difference between the forward and reflected powers is the real power delivered to the load, but:
4. the generator does not actually generate a power equal to the forward power, and
5. the reflected power figure is not absorbed by the generator.

If number 5 above is true, then why are generators rated to handle some maximum reflected power? The answer relates to the maximum voltage and current the generator can deliver. If a generator is rated to deliver, say, 1000 watts, this does not mean that it can do so into any load. As the load resistance is increased, to get 1000 W, one needs more and more voltage ($P = V^2/R$, so $V = \sqrt{PR}$) and sooner or later the generator has produced all the voltage it can, and the power is limited. Similarly, as the load resistance is decreased, the current goes up ($P = I^2R$, so $I = \sqrt{P/R}$). Sooner or later, the generator cannot deliver any more current. Appendix A defines reflected voltage as

$$V_r = \frac{\mathbf{V} - Z_0 \cdot \mathbf{I}}{2}$$

This quantity increases as V differs from Z_0I, and the difference is limited by the maximum voltage and current the generator can create.

Finally, those who used to work with tube-type generators remember that a mismatched load can cause the plate of the tube to glow red. Does this not mean that excess power is being dissipated there, and doesn't this indicate that reflected power is being absorbed by the tube?

Certainly, the higher temperature of the anode indicated that the plate power was increased, but this does not mean that the reason was absorption of some kind of power coming in from the outside. In a tube-type transmitter, the tube has a substantial voltage across it during conduction, resulting in large conduction losses. The actual losses depend upon the design mode (A, AB, B, C, etc.) but can easily be larger than, and are rarely less than 1/3 of, the output power. To achieve high efficiency, the tube must be biased well beyond cutoff and must be operated on a tight load line. If there is reflected power as a result of a reactive load, the load line becomes an open curve. This means that for a portion of the cycle, substantial voltage exists across the tube at the same time high current is being drawn through it. This results in the large plate dissipation.

In the case of modern FET amplifiers, the output field effect transistors are operated as switches. The FET, operated as a switch, is nearly an ideal one, with typical "on" resistance of considerably less than 1 Ω, and properly designed amplifiers of this type have losses well under 10% of the output power. These losses can increase or decrease, depending upon the load impedance, and in some cases, the presence of reflected power can even result in decreased dissipation. Modern protection circuits for such amplifiers look only at the power lost in the output device and the voltage across it, and reflected power is not measured.

Appendix A

The directional coupler samples the voltage and current at the point in the line where it is inserted and produces from them two quantities called the forward and reflected voltages, which are the amplitudes of the two traveling waves that make up the standing wave on the line. These are defined as follows:

(1) $$V_f = \frac{\mathbf{V} + Z_0 \cdot \mathbf{I}}{2}$$ for the forward voltage, and

(2) $$V_r = \frac{\mathbf{V} - Z_0 \cdot \mathbf{I}}{2}$$ for the reflected voltage

Here, the voltages and currents are in bold print to emphasize that they are vectors (i.e., they have a phase angle) and the addition and subtraction must be done with vector, or complex algebra. The quantity Z_0 is arbitrary; if there is a transmission line and if the voltages are to represent the amplitudes of the traveling waves that make up the standing wave on the line, Z_0 must be equal to the characteristic impedance of the transmission line. The directional wattmeter must assume a value for Z_0 and so is calibrated for use at only one impedance level.

Voltage and current exist in a circuit with no transmission line, of course, and equations (1) and (2) may still be used to calculate a forward voltage and a reflected voltage, even though there is no line to have a standing wave. These figures then represent the amplitudes of waves that would exist on a line of impedance Z_0 if it did exist in the circuit.

Let's assume we are using a 50 Ω coupler. If we look closely at equation (2), we see that the reflected voltage is zero if the voltage is exactly fifty times the current (and in phase with it). Zero reflected voltage means no reflected power, since the reflected power is defined as:

(3) $$P_r = \frac{|\mathbf{V}_r|^2}{Z_0} \quad ,$$

which is zero when V_r=0 (i.e., when $V = Z_0 I$).

The forward power is similarly defined, as $P_f = |V_f^2|/Z_0$, and the difference between the two powers is the load power:

(4) $$P_{load} = P_f - P_r \quad .$$

This can be shown by substituting the defining equations (1) and (2) for V_f and V_r into equation (4), yielding:

$$P_{load} = \left[\frac{|\mathbf{V}_f|^2}{Z_0} - \frac{|\mathbf{V}_r|^2}{Z_0}\right] = \frac{1}{Z_0}\left[\mathbf{V}_f \cdot \mathbf{V}_f - \mathbf{V}_r \cdot \mathbf{V}_r\right] = \mathbf{V} \cdot \mathbf{I} = |\mathbf{V}| \cdot \mathrm{I} \cdot \cos\theta \qquad ,$$

which is the true power in the load. Here • is indicating the "vector dot product" of the voltage and current vectors.

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