Basics for Beginners

The Whys of Transmission Lines

Part II — Standing-Wave Ratio and Line Losses

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You have seen, in Part I,[1] that the power put into a matched line nearly all gets to the load at the output end. A small amount is used up by the losses in the line itself; this is converted into heat. We are assuming here, of course, that the line conductors are so close together that there is no radiation because of incomplete cancellation of the fields. If the spacing between the conductors is of the order of 1/100 wavelength this is a good assumption, providing the currents and voltages in the line are **balanced.** Line balance means that the current and voltage in one wire are exactly duplicated in the other, except for reversed polarity.

But what if the load connected to the far end of the line does not exactly match the line's characteristic impedance? A case like this falls somewhere between the perfectly-matched condition and the extremes of the open- and short-circuited lines. Some of the power reaching the far end of the line is absorbed by the load, but some of it also bounces back toward the input end. A **mismatch** is said to exist when the load resistance isn't the same as the line's characteristic impedance. The worse the mismatch, the greater the proportion of power reflected back.

Losses

The principal effect here, at least in transmitting, is that the line uses up a little of the power on both the outgoing and return trips. Aside from this, the power that is reflected from the load is by no means "lost". It's like the change you get when you pay for a 69-cent item by handing the clerk a dollar bill. The money returned goes back in your pocket. The reflected power on a transmission line, too, is unused: it simply subtracts from the power the transmitter put *into* the line, and the power input to the final stage is correspondingly reduced.

Even though some of the power is handed back to the generator (the transmitter) we can still put the full output of the transmitter into the antenna. This is simply a matter of the coupling between the transmitter and line. The coupling that would deliver the transmitter's output to a matched line won't do it if the line isn't matched. But by changing the coupling as required, the transmitter can be loaded just as well. A little less power will reach the load than would get there if the load matched the line properly, because of the extra line loss. But the difference on this account is too small to cause any worry, if a low-loss line is used. Even with lines which, when matched, have fairly high losses, the *extra* loss caused by mismatching isn't much if you aren't mismatched by a factor of more than 3 or so.

On a perfectly-matched line there are no standing waves because no power is reflected from the load end. On open- or short-circuited lines there are large standing waves. Along such lines the voltage and current go to zero, or very close to it, at the nodes.

When a line is mismatched, but not open- or short-circuited, there are standing waves because some of the power is reflected. But only *some* of it. The reflected voltage and current can't completely balance out the **incident** voltage and current (the voltage and current traveling *to* the load) at the nodal points unless there is just as much coming back as is going out. Since this is not the case, there are no points of zero voltage and current along the line. Instead, there will be points of *minimum* current and points of *minimum* voltage. Likewise, there will be points where the voltage and current will be maximum.

Standing Waves on Mismatched Lines

If we went along a mismatched line measuring the amplitudes of the current and voltage, without paying any attention to polarity, we would find that both vary along the line. Fig. 1 is typical of what might be measured. The points of maximum and minimum are still one-quarter wavelength apart, as in the cases discussed before. The ratio of the current at *B*, a maximum point, to the current at *A*, a minimum point, is called the **standing-wave ratio.** Measurement of the maximum and minimum voltages would give the same ratio as measurement of current.

If very little power is reflected from the load — i.e., the line is nearly matched — there is relatively little variation in the current and voltage along the line, so the standing-wave ratio — usually abbreviated to **s.w.r.** — is low. The greater the mismatch the greater the reflected power and the larger the **s.w.r.**

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[1] "The Whys of Transmission Lines", Part I, *QST*, January, 1965.

S.W.R. and the Load

It happens that the standing-wave ratio can be measured more readily than the current or voltage, or even the load resistance. So it is customary to measure the s.w.r. in order to find out whether the line is matched. There is a very simple relationship between load resistance, the characteristic impedance of the line, and the s.w.r.:

$$S.W.R. = \frac{R}{Z_o} \text{ or } \frac{Z_o}{R}$$

where R stands for the load resistance and Z_0 stands for the line's characteristic impedance. The reason for the choice in this formula is that it is customary to put the larger number on top, so that the s.w.r. is expressed as, for example, 5 to 1, rather than 1 to 5.

Actually, you don't need to know R at all in making most adjustments of load resistance. If you're shooting for no reflected power — that is, an s.w.r. of 1 to 1, meaning that the maximum and minimum values are the same — you adjust for the smallest possible s.w.r. When you have it you know you're right.

Fig. 1 shows the voltage high and the current low at the load. It could be the opposite. The drawing is for the case where the load resistance is larger than Z_0. The reverse would be true for a load resistance smaller than Z_0. The first case approaches the open-circuited line as R is made larger, and the second approaches the short-circuited line as R is made smaller.

With a mismatched load resistance, as in the cases discussed earlier, the generator sees a pure resistance when the line is some multiple of a quarter wave in length. Thus this same length indicates resonance. At all other lengths the generator will see reactance along with resistance. Table 1 in Part I can be used to find the *kind* of reactance, if the short-circuited column is used for loads less than Z_0 and the open-circuit column is used for loads greater than Z_0.

Resistance Only

Finally, a warning: To avoid confusing you with a lot of qualifications, in what was said above we have omitted one very important point. *The load has to be a pure resistance if any of this is to be true.*

Mostly, you will be working with loads that are "pure," or nearly so. You can't get an s.w.r. of 1 to 1 unless the load *is* a pure resistance; any reactance in it throws the whole thing off. So if you've been able to get the s.w.r. to 1 to 1 or close to it, you can take it for granted that the line behavior will be as described.

Practical Lines

Quite a few varieties of manufactured transmission lines are available. The ones that are of interest to amateurs are usually in stock at radio supply stores, since they are also used for television receivers. There are two general types. One is the parallel-conductor type we used for purposes of discussion in Part I. The other is the **coaxial line.** This also has two conductors, but one of them is a tube and the other is a wire centered in it.

The coaxial line, familiarly known as "coax" (pronounced with two syllables), obeys the same laws as the parallel-conductor line. All we have said so far applies to both types of line. However, the coax line has some distinctive features. The current is carried by the inner conductor and the *inside surface* of the tubular outer conductor. The *outside* surface is "cold" for r.f., if the line is properly used. In other words, the active part of the line is shielded from outside influences. This means, too, that there can be no radiation from the inside of the line.

Substantially all coaxial line in use by amateurs is the flexible type having a braided-wire tube for the outer conductor. Multistrand wire is often used for the inner conductor, although in some small-diameter lines a solid wire can be used without affecting the flexing. The insulation between the two conductors is a flexible solid plastic — polyethylene.

Velocity Factor

The presence of this solid insulation does two things: It increases the power loss, as compared with air insulation, and it reduces the speed at which power can go through the line. This means that the wavelength in coax cable is shorter, for the same frequency, than in air. The formula for

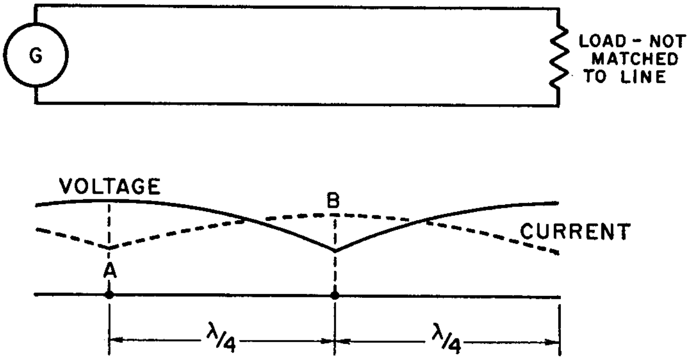

Fig. 1—The standing-wave ratio is the ratio of the current amplitude at B to that at A, or of the voltage amplitude at A to that at B.

Table I
Transmission Lines

Type	*Description*	*Characteristic Impedance, Ohms.*	*Velocity Factor*	*Matched Loss in Db. per 100 Feet*						
				3.5 Mc.	*7 Mc.*	*14 Mc.*	*21 Mc.*	*28 Mc.*	*50 Mc.*	*144 Mc.*
RG-58/U	Small coaxial	53.5	0.66	0.68	1.0	1.5	1.9	2.2	3.1	5.7
RG-59/U	Small coaxial	73	0.66	0.64	0.9	1.3	1.6	1.8	2.4	4.2
RG-8/U	Medium coaxial	52	0.66	0.3	0.45	0.66	0.83	0.98	1.35	2.5
TV Twin Line, Standard	Parallel-cond., solid insulation	300	0.82	0.18	0.28	0.41	0.52	0.6	0.85	1.55
TV Ladder Line, 1-in. spacing	Parallel-cond. air-insulated with spacers	450	*	*	*	*	*	*	*	*

* Not known. Velocity factor approx. 95 per cent. Losses very low in comparison with solid-insulation types.

wavelength given earlier has to be modified by a correction factor, called the **velocity factor,** on this account. For polyethylene-insulated solid-dielectric coax the velocity factor is 0.66. A line one-half wavelength long at 7.1 Mc., for example, would be 0.66 times 69.4 feet (a half wavelength in space), or 45.8 feet long.

Line Losses

If we should divide a line into sections of equal length and measure the power going in and coming out of each, we should find that there is the same *percentage* loss in each section. Suppose that 100 watts goes into the first section and 10 per cent of it is dissipated in heat in that section. Then 90 watts comes out to go into the second section. In the second section 10 per cent represents 9 watts, so now we have 81 watts left to go into the third section. This section loses 8.1 watts, and so on. This sort of power change is exactly what the decibel represents so nicely, so we can express line loss as so many decibels per unit length. The custom is to give the loss in decibels per 100 feet of line.

The loss becomes greater as we go higher in frequency. Losses in db. per 100 feet for the lines most used by amateurs are given in Table I. These losses are for lines that are properly matched by the load. If there is a mismatch the loss will be higher. However, as we said earlier, the additional loss isn't usually serious unless the mismatch is 3 to 1 — that is, an s.w.r. of 3 to 1 — or more. Even then it is not considerable unless the line has high loss when matched.

Parallel-Conductor Line

The most common type of parallel conductor line is TV lead-in, consisting of two wires separated by a web of polyethylene approximately ⅜ inch wide. It is sold under several trade names, and has a characteristic impedance of about 300 ohms. As shown by Table I, its losses are lower than the losses in coax. This is true of good-quality line, which you can be sure of getting only when you buy a well-known brand. Some of the "bargain" unbranded line is very poor, so it is best to steer clear of it.

The lowest-loss line available is the ladder type, consisting of parallel wires separated about an inch. The wires are held apart by small rods of polyethylene at intervals of a few inches. Thus most of the insulation is air, which has negligible loss.

There are many other types of line, both coaxial and parallel-wire, than those listed. Some have different characteristic impedances, and a few varieties have lower losses or greater power-handling ability. However, the types mentioned are easy to get, and are satisfactory for most amateur installations of medium power.