Basics for Beginners

The Whys of Transmission Lines

Part I

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To radiate effectively, an antenna ought to be up in the air as high as it can be put. Also, it should not be close to houses, power lines and the like. You may not have an ideal spot, but even so you probably won't have to bring the antenna right into your operating room. So in most cases the situation is this: The antenna is "out there" and the transmitter is "in here"; how is the r.f. power to get from the transmitter to the antenna?

The answer, of course, is a transmission line. Your 60-cycle power comes to you through a transmission line, too. However, there is a difference in the way r.f. lines and 60-cycle lines operate. The reason is the difference in wavelengths. One wavelength at 60 cycles is over 3000 miles. If we wanted to build a half-wave antenna for that frequency it would have to extend more than half way across the United States. So even though you may be 20 miles from a power station, you're only a very small fraction of a wavelength away. The time it takes for power to reach you is so short, compared with $^1/_{60}$ second (one cycle), that the standing-wave effects discussed earlier[1] are negligible.

But in transmitting power at a frequency of, say, 7 Mc., the time taken for the power to travel 50 feet isn't at all negligible compared with the duration of one cycle. This means that we can't look upon a transmission line as a simple electrical circuit, which we *can* do at 60 cycles. What is happening at the "far" or "output" end of the line may be quite different from what is happening at the "near" or "input" end at the same instant.

The "Infinite" Line

A useful concept in explaining transmission-line operation is the **infinite line.** This is an imaginary line consisting of two conductors, side by side and close together, extending so far that we can never reach the end.

If an r.f. voltage is applied to the input end of such a line, one terminal will be negative whenever the other is positive, and vice versa. This causes the current to flow in one direction in one wire and in the other direction in the second, as in Fig. 1. Because the currents flow in opposite directions, the electromagnetic fields set up by them are also opposite. The fields therefore cancel each other's effects, or nearly do so (there is always a *little* uncancelled field, because the two wires can't actually occupy the same spot). Since the fields cancel, there is no radiation from the line.

Thus all the energy put into the line travels away from the generator, following the line at almost the speed of light. And since the line is infinitely long, none of the energy ever comes back.

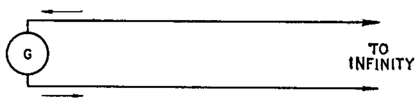

Fig. 1—An imaginary two-conductor line extending to infinity. Arrows show that the current in one wire flows in the opposite direction to current in the other; this relationship is true throughout the entire length of the line, although the actual currents periodically reverse direction as the polarity of the generator's voltage reverses each half cycle.

Characteristic Resistance

Probably the first question you'd ask at this point is this: If the generator voltage is known, how much current will flow in the line? From the discussion of the meaning of resistance in Part II[2] you would be right to infer that such a line must act like a resistance, since energy is being taken continuously from the generator. But how many ohms?

This resistance, called the **characteristic resistance** of the line, has nothing to do with the actual resistance of the conductors. While it may seem odd, the fact is that it is a function of the inductance and capacitance per unit length of line. The resistance actually is determined by the line's L/C ratio. This ratio depends on the diameters of the conductors and the spacing between them. The smaller the conductor diameter and the wider the spacing, the higher the characteristic resistance. Practical values of resistance lie between about 150 and 800 ohms for a

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[1] "Antennas and Feeders," Part I, *QST*, October, 1963.

[2] "Antennas and Feeders," Part II, *QST*, November 1963.

"two-wire" or **parallel-conductor** line as shown in Fig. 1.

It is important to realize that this characteristic resistance does not itself consume any power. The power is merely *following* the line on its way to infinity. The characteristic resistance is simply the ratio of voltage to current all along the line. Since the line is imaginary anyway, we can imagine further that the conductors have no actual resistance and there is no other energy loss along the line. Thus all the power put into the line is delivered to infinity, wherever that may be. This means that the characteristic resistance is "pure" resistance — no reactive effects at all.

Characteristic Impedance

But what if the conductors do have resistance of their own? Practically, of course, they must have. Also, the practical insulation between the two conductors is not perfect; there is some leakage between the two wires. This leakage is equivalent to a resistance (a high value) shunted across the two conductors. In the topsy-turvy world of transmission lines the presence of these two components of resistance gives rise to *reactance.* So if the line is a practical one having losses, the generator doesn't see a pure resistance but sees an impedance containing both resistance and reactance. This is called the **characteristic impedance** of the line.

Because things get complicated at this stage we like to ignore the reactive part of the characteristic impedance, and do so by assuming that the line has no losses. As long as the losses per unit length are small we can get away with it. Fortunately, this is the case with lines used by amateurs at frequencies below 30 Mc. It is even a good-enough assumption in the lower v.h.f. range. When the losses are small the characteristic impedance is *very nearly* a pure resistance equal to the characteristic resistance. The term characteristic impedance is widely used to mean the characteristic resistance of a lossless line. We'll use it that way here, too.

The Terminated Line

An infinite line, even if we could have one, wouldn't be of any practical use. It happens, though, that a line can be tricked into *thinking* that it's infinitely long.

In Fig. 2A, suppose that the line is cut at *XX*. If the generator is moved up to this point it will still see the same characteristic impedance (which is commonly designated Z_0), since what remains of the line to the right of *XX* is still infinitely long. In the same way, the section of line to the left of *XX* "sees" the section to the right of *XX* as a resistance equal to the characteristic impedance. This is true anywhere along the line. It suggests the idea that the line section to the left of *XX* wouldn't know the difference if a resistor having the same value as the characteristic impedance were substituted for all the line to the right of *XX*.

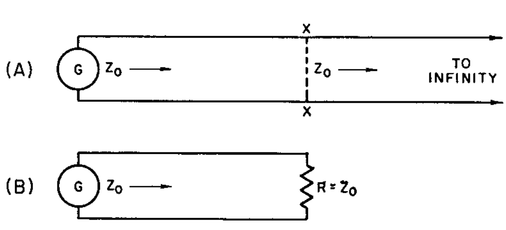

Fig. 2—An infinitely-long line can be simulated by terminating an actual line in its characteristic impedance.

This is actually so. If a line of any length is **terminated** in a resistance equal to its characteristic impedance the voltages and currents are just the same in that section as they would be if the line were infinitely long. If the line has no losses, all the power put into it at the generator end is delivered to the terminating resistance.

Matching

The terminating resistance doesn't have to be a resistor. It can be any device, such as an antenna, that uses up power and thus has an equivalent resistance. If the power-consuming device doesn't inherently have the right value of resistance to match the line, its resistance can be transformed by means of circuits (such as those described earlier[3]) that will make it "look like" the proper value. Matching of this sort is done more often than not; only occasionally does the load have the right value of resistance, in itself, to match a practical line impedance.

One final point about a **matched line:** If the line has negligible losses, an ammeter inserted anywhere along its length will give the same reading. Also, a voltmeter connected across it at any point will give the same reading. There are no standing waves of current or voltage such as we find along an antenna, even though the line may be many times longer than the antenna. But this is true *only* when the line is terminated in its characteristic impedance.

Standing Waves on Lines

Now let's look at a line that *doesn't* simulate one that is infinitely long. The length of a matched line didn't matter, because all the power kept going in the same direction — to the load. If the line is not matched, its length becomes quite important.

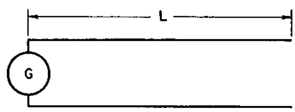

Fig. 3—A line with no termination—simply an open circuit.

To take an extreme case, suppose the line just stops, as in Fig. 3. The power goes out from the generator to the open end, at which point it has no path left to follow except to turn back and head toward the generator. This it does, just

[3] "A.C. in Radio Circuits," Part III, *QST*, May 1963.

as in the case of the antenna discussed in Part I. In coming back it sets up standing waves of voltage and current, just as it did along the antenna.

Here, too, the current and voltage distribute themselves along the line according to the wavelength. If the line length L is just one-quarter wavelength, the current and voltage distribution are as shown in Fig. 4A. If you will imagine the line to be unfolded so that the wires extend in opposite directions from the generator, you can see that this is the same voltage and current distribution that we found along a half-wave antenna (Fig. 3, Part I). The line, too, is resonant to the generator's frequency. The total length for both wires is still a half wavelength, although the line as a whole is only a quarter wave long.

Odd Lengths

If the line is less than a quarter wave, as in Fig. 4B, there is room only for the outer sections of the standing waves. The line is not resonant in this case. The generator sees it as a reactance, and in order to put maximum current into the line the reactance must be tuned out by adding reactance of the opposite kind. Inductive reactance is needed here for **loading** the line.

In Fig. 4C the line is more than a quarter wave long. Here we have not only the standing waves we had along the quarter-wave line but the beginning of another set, too. This line is not resonant, either, and again it looks like a reactance to the generator. However, in this case its reactance must be tuned out by using capacitance for loading.

Finally, Fig. 4D shows a line a half wavelength long. Each wire is like a half-wave antenna. Since one terminal of the generator is always positive when the other is negative, and vice versa, the voltages and currents are always opposite in polarity along the wires, just as in the other cases. The half-wave line is also resonant at the applied frequency, since each wire will accommodate exactly a complete standing wave, no more and no less.

This could be continued on for still longer lines. In doing so we should find that the line is always resonant when its length is exactly a multiple of one-quarter wavelength. It is *not* resonant at any other lengths.

Quarter- and Half-Wave Resonance

Comparing A and D in Fig. 4, you can see that there is a difference even though both can be considered to be resonant. In A the voltage is zero at the generator, but the current has its highest value. In D the current is zero and the voltage has its highest value. Since the impedance seen by the generator is equal to voltage divided by current, the impedance at the input end of the line must be extremely low in A and extremely high in D. If there were no power lost in the line the impedance values would be zero and infinity, respectively. However, no line can be completely free from loss, so we don't have to worry about what might be meant by zero and infinity. Practically, the impedance is a very

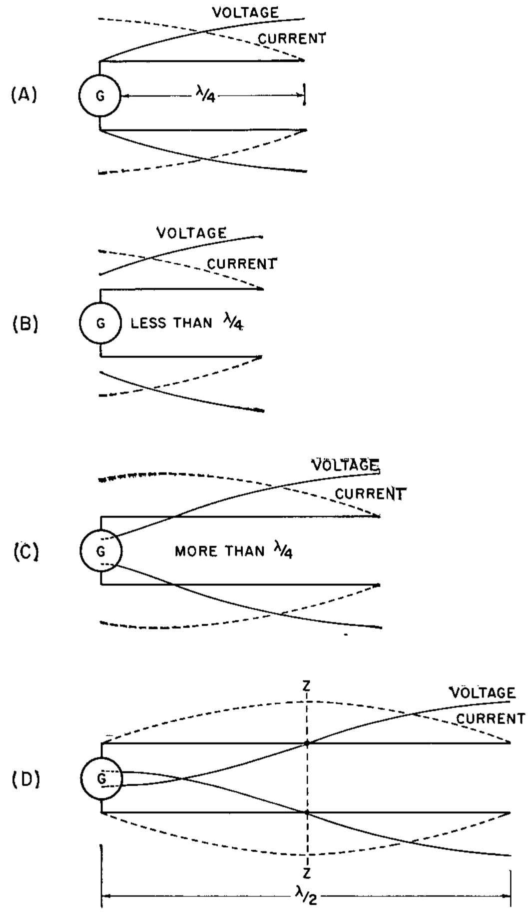

Fig. 4—Standing waves along open-circuited lines.

low resistance in A and a very high resistance in D.

A quarter-wave line open-circuited at the far end acts like a series-resonant circuit. A half-wave line open at the far end acts like a parallel-resonant circuit.

The Short-Circuited Line

Instead of being left open at the far end as in Fig. 3 the line could be short-circuited as in Fig. 5. Once again, energy traveling out from the generator must turn back when it reaches the short circuit. However, in this case there can be no voltage across the short circuit, although the current can be large. This is just the reverse of the open-circuited case of Fig. 3.

If you will look at Fig. 4D, you will see that just the same condition exists at the point ZZ,

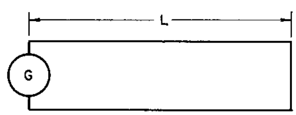

Fig. 5—Short-circuited line.

one quarter wavelength from the end of the open line. The voltage between conductors is zero (if there are no losses) at this point. This means that a short-circuit could be placed across the line at ZZ without disturbing the currents or voltages. Since it is a quarter wavelength from ZZ back to the input end of the line, this section of line also is resonant.

It is apparent from this that what the generator sees when looking into a quarter-wave short-circuited line is the same as what it sees when looking into a half-wave open-circuited line. That is, a quarter-wave short-circuited line is equivalent to a parallel-resonant circuit. The voltage and current distribution are as shown in Fig. 6A.

By carrying on this line of thought it is easy to demonstrate that a half-wave short-circuited line is equivalent to a series-resonant circuit. The current and voltage distribution are given in Fig. 6B. Lines of other lengths are not resonant, and will act like almost pure reactances. Table I summarizes this.

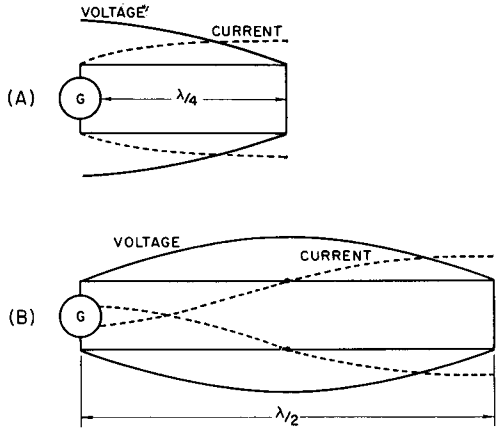

Fig. 6—Voltage and current distribution along resonant short-circuited lines.

Table I
Transmission-Line Behavior

Length	Open-Circuited Line	Short-Circuited Line
Less than ¼ wave-length	Capacitive Reactance	Inductive Reactance
¼ wave-length	Series-resonant circuit	Parallel-resonant circuit
Between ¼ and ½ wave-length	Inductive Reactance	Capacitive Reactance
½ wave-length	Parallel-resonant circuit	Series-resonant circuit

The line behavior goes through the same series of changes with each added quarter wavelength.

Why Open- and Short-Circuited Lines?

Offhand, you might think that open- and short-circuited lines are about as useless, practically speaking, as an infinitely-long line. However, the fact is that they are quite useful.

In the first place, a resonant line can be substituted for a resonant circuit, and often is. The resonant line is especially useful at v.h.f. and u.h.f., where it may offer the only resonant-circuit structure that it is physically possible to use. Here is where the multiple resonance that goes with a series of quarter-wave sections often saves the day. A conventional *LC* circuit does not have this feature, and there is a limit to how large, physically, such a circuit can be made for a given frequency.

Second, nonresonant sections of line can be used in place of coils and capacitors, simply by adjusting the length to give a desired value of inductive or capacitive reactance. This is frequently done in antenna matching systems.

Finally, there are applications where multiple resonance in a line lets us do things like short-circuiting a harmonic of the transmitter while the fundamental frequency goes through unaffected. For example, a short-circuited line having a length of one-quarter wavelength at the fundamental frequency has a very high impedance — nearly an open circuit — and can be connected across another transmission line with little effect on the power flowing through it. But at the second harmonic it is a half wavelength long, and it will act as a short circuit across the other line at that harmonic (and all other even harmonics). QST

Strays

WA9FMQ operates the Twoer and K9YBC and WA9AVZ look on during a recent v.h.f.pedition to Bunker Hill, Wisconsin. Bovine s.w.l.s. in the background are unnamed.