The Lenkurt® Demodulator

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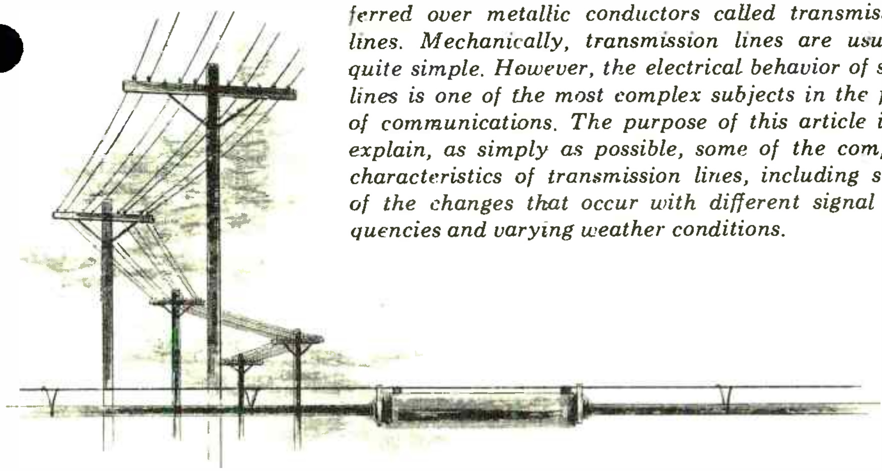
Characteristics of TRANSMISSION LINES



Signals in many communications systems are transferred over metallic conductors called transmission lines. Mechanically, transmission lines are usually quite simple. However, the electrical behavior of such lines is one of the most complex subjects in the field of communications. The purpose of this article is to explain, as simply as possible, some of the complex characteristics of transmission lines, including some of the changes that occur with different signal frequencies and varying weather conditions.

One of the most important elements in any communications system is the *transmission line* whose function is to transfer signals from one part of the system to another. The simplest transmission line consists of two parallel wire conductors with a power source at one end and a load at the opposite end. Since most transmission lines appear as relatively simple mechanical devices, their rather complex electrical behavior is not always fully appreciated. Because they are electrically complex, they can have a significant effect on the signals transmitted over them. For this reason, the effect of transmission lines must be determined and taken into account when evaluating the transmission performance of a communications system.

There are three general types of transmission lines used in communications systems: open wire, multipair cable, and coaxial cable. Open-wire lines consist of pairs of wire conductors suspended on poles. A multipair cable is an assembly of pairs of insulated wire conductors, wrapped in a protective sheath. A coaxial cable consists of two tubular-shaped conductors, one inside the other. The inner conductor is usually a small copper tube and is insulated from the outer conductor which is either a copper tube or copper braid. Multipair and coaxial cables are either suspended on poles, or buried underground or underwater. (The *waveguide,* a type of transmission line used to transmit signals at microwave frequencies, is not discussed in this article.)

Electrical Properties

Communications systems contain a number of different types of elements whose electrical properties (resistance, inductance, and capacitance) are considered to be *lumped*. The action of a so-called lumped element occurs at a concentrated point in the circuit—that is, at its location. The electrical properties of a transmission line, however, exist uniformly along its entire length and are considered to be *distributed* rather than lumped.

Each type of transmission line possesses four such distributed electrical properties which must be considered and properly adapted for operation with the different types of communications systems. These four properties are: (1) series resistance R, (2) series inductance L, (3) shunt capacitance C, and (4) shunt conductance G.

The particular values of these fundamental electrical properties depend primarily on the physical configuration of the transmission line and the material used in its construction. To a lesser degree, the values of these properties also depend on frequency, temperature, and weather conditions.

In analyzing the properties of a transmission line it is convenient to describe a line of infinite length consisting of sections of unit length (feet, yards, miles), each possessing the four fundamental electrical characteristics. The equivalent electrical circuit of such a line is shown in Figure 1. In this diagram, the distributed resistance, conductance, inductance, and capacitance are symbolized as *lumped* constants to show their effect more clearly.

Electromagnetic Waves

When power is first applied to a transmission line, energy from the power source does not appear all along the line simultaneously. Instead, it travels away from the source in the form of an electromagnetic wave, called the *incident wave,* and reaches the various sections of the line at different times. The time it takes to travel through each section depends upon the values of the four fundamental properties of the line. Since the series inductance and shunt capacitance of the line store energy for a period and then return it to the circuit, no loss of energy occurs as a result of these properties. (The losses in a line are caused mainly by its resistive properties which dissipate energy in the form of heat.)

Current that leaves the power source will start to charge the shunt capacitance of the first section. The charge is not instantaneous because the charging current is impeded by the series resistance and the series inductance of the section. When the shunt capacitance

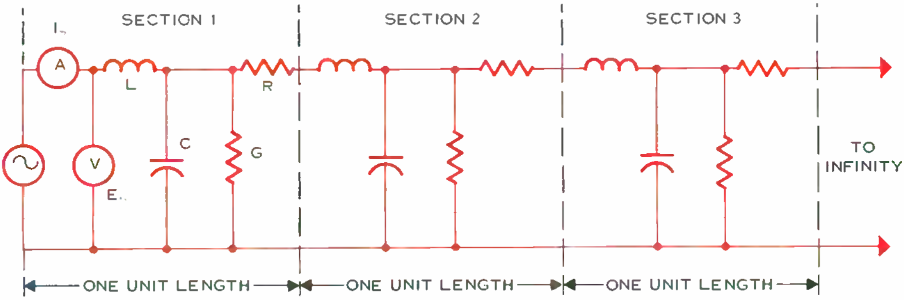


Figure 1. Equivalent circuit of transmission line of infinite length.

is fully charged, the current will begin to decrease. However, now the shunt capacitance in the second section begins to charge through the series inductance and resistance. The shunt capacitance in each succeeding section will add to the charging current as the current in the capacitance of the preceding section starts to decrease. The current, voltage, and the associated electromagnetic wave will progress down an infinite line in this manner until all the energy is diminished due to the resistance in the line. From an extension of Ohm's law, the amount of current that will flow in such a theoretical line is expressed mathematically as

$$I_s = \frac{E_s}{\sqrt{\frac{z}{y}}} \qquad (1)$$

where

I_s = sending end current
E_s = sending end voltage
z = series impedance per unit length
y = shunt admittance per unit length

Characteristic Impedance

It is important to note that in equation (1) the impedance, expressed as

$$\sqrt{\frac{z}{y}},$$

depends only on the four characteristic properties of the line, does *not* include any termination impedance, and is independent of length. An *infinite line* is used so that the effects of termination impedances can be ignored. Since the impedance includes reactance as well as resistance, it is also a function of frequency. This property of a transmission line is called its *characteristic impedance* Z_0, and is expressed mathematically* as

$$Z_0 = \sqrt{\frac{z}{y}} = \frac{E_s}{I_s} = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \qquad (2)$$

where

R = series resistance
G = shunt conductance
$j\omega L$ = series reactance
$j\omega C$ = shunt susceptance

The resistance R and conductance G in transmission lines used in carrier systems are usually so small compared to the series reactance $j\omega L$ and the shunt susceptance $j\omega C$ that they are sometimes omitted when calculating the characteristic impedance. In such a case, equation (2) can be simplified to

$$Z_0 = \sqrt{\frac{L}{C}}$$

*Z_0 is a complex impedance and a detailed explanation of this expression is beyond the scope of this article.

If the values of the four fundamental characteristics of a particular transmission line are not known, the characteristic impedance can be obtained by measurement. This is done by first measuring the impedance of the line with the receiving end open circuited (Z_{oc}) and then measuring the impedance of the line with the receiving end short circuited (Z_{sc}). The characteristic impedance can then be obtained from the following equation:

$$Z_o = \sqrt{Z_{oc} Z_{sc}}$$

There is, of course, no such thing as a line of infinite length. All transmission lines contain a power source at the sending end and are terminated in a load of some impedance value at the receiving end. As mentioned earlier, energy placed on the transmission line at the sending end travels in the form of an electromagnetic wave (incident wave) toward the opposite end of the line. The value of the load impedance is very important. To transfer all of the energy that reaches the receiving end of the transmission line to the load, the impedance of the load *must* equal the characteristic impedance of the line. In such a case, the input impedance of the line also equals the characteristic impedance, and, as far as the power source is concerned, the line *appears* to be infinitely long. Therefore, for a given frequency, the input impedance of a transmission line is constant, *regardless of its length,* if the line is terminated in its characteristic impedance. If the load and characteristic impedances are not equal, an impedance mismatch exists and all of the energy will *not* be transferred to the load. Instead, some of the energy in the form of a *reflected* wave will travel back toward the power source and will interfere with the incident wave.

The amount of energy reflected because of a mismatch can be expressed by the *reflection coefficient* which is derived from the following formula:

$$\text{Reflection Coefficient} = \frac{Z_L - Z_o}{Z_L + Z_o}$$

where

Z_o = characteristic impedance
Z_L = load impedance

In communications systems, a more common method of expressing the degree of mismatch between the characteristic impedances of a transmission line and the load impedance is the *return loss,* expressed in decibels, which is defined as

$$\text{Return Loss} = 20 \log_{10} \frac{1}{\text{Reflection Coefficient}}$$

Since it is impossible to have a perfect match between the characteristic impedance of a transmission line and the impedance of the load, there is always some reflection. In communications systems, undesirable effects such as echos and singing may result if the return loss is too low.

Standing Waves

The incident wave and the reflected wave on a transmission line travel in opposite directions. At certain points along the line the voltages in the two waves will be in phase and will add, while at other points they will be out of phase and will subtract. The points along the line where the two voltages are in phase are points of maximum voltage and minimum current and are spaced one-half wavelength apart. The points along the line where the two voltages are 180° out of phase are points of minimum voltage and maximum current and are also spaced one-half wavelength apart. The distance between alternate points is one-quarter wavelength.

If the receiving end of the line is either a short circuit or an open circuit, all of the energy in the incident wave will be reflected back towards the power source (total reflection). In such a case, the voltage and current at minimum points are zero. When the receiving end is an open circuit, it is a point of maximum voltage and zero current. On the other hand, if the receiving end is a short circuit, it is a point of maximum current and zero voltage. Figure 2 is a plot of the rms voltage and current maximum and minimum points along transmission lines with various terminations.

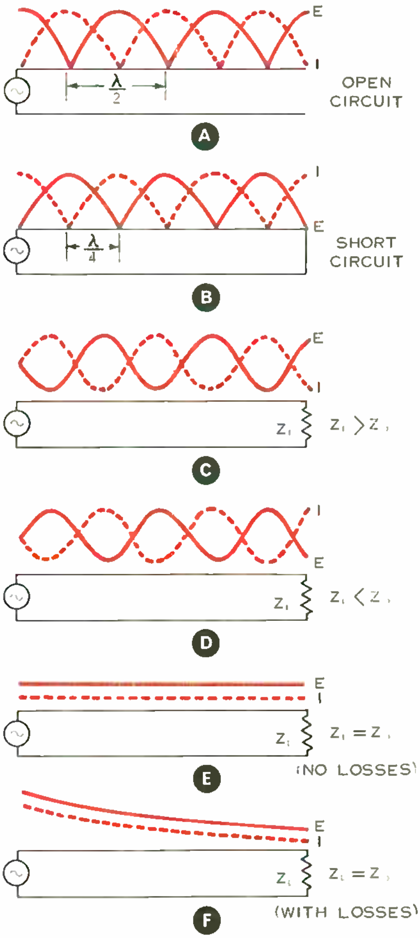


Figure 2. Diagrams A through D are plots of the rms voltage and current of lossless transmission lines with various terminations. Diagrams E and F are plots of rms voltage and current along transmission lines terminated in their characteristic impedances.

When the load impedance is greater than the characteristic impedance, the receiving end of the line will be somewhat like an open circuit, except that the rms current at minimum points will not reach zero. Conversely, when the load impedance is less than the characteristic impedance, the receiving end will be somewhat like a short circuit, except that the rms voltage at minimum points will not reach zero.

It can be seen in Figure 2 that when the line is not terminated in its characteristic impedance, the plots of the rms voltage and current appear as waves and, for this reason, are referred to as *standing waves*. Because they are motionless, however, they are not true waves in the same sense as the incident and reflected waves.

The ratio of the rms voltage or current at a maximum point to the rms voltage or current at a minimum point is referred to as the *standing wave ratio*. A standing wave ratio of 1:1 implies that there are no standing waves, and that the line is terminated in its characteristic impedance.

When a transmission line is terminated in its characteristic impedance, the current and voltage all along the line are in phase. If the line is considered to be lossless, a plot of the rms voltage and current is a straight line as shown in Figure 2E. However, there are always some losses which cause the energy to diminish as it travels down a line. A plot of the rms voltage and current along a properly terminated line with losses is shown in Figure 2F.

Attenuation and Frequency Effects

The amplitude of the current that flows through a transmission line is continuously diminishing with distance from the power source because of the shunt conductance of the line. The voltage is also diminishing because of the series resistance of the line. Because the voltage and current are diminishing, the energy in the associated electromagnetic wave is also diminishing.

The series resistance of a transmission line increases with frequency as a result of the expanding and contracting magnetic field within the line which forces current to flow toward the outer surface of the wire. This action, known as the *skin effect,* reduces the total effective cross-sectional area of the wire, thereby increasing the series resistance.

In multipair cable where the individual wires of each pair are very close together, series resistance is further increased by *proximity effect.* The interlinking magnetic fields of the two wires force the current to flow in that portion of each wire that is closest to the other wire, causing a further reduction of the effective cross-sectional area of the conductors. Like skin effect, proximity effect in cable circuits increases with frequency. The external magnetic fields and current distribution in a cable pair are shown in Figure 3.

A slight reduction of the series inductance with increasing frequency is caused by the change in current distribution which reduces the net strength of the magnetic field within the wire.

Shunt capacitance changes so slightly with increasing frequency that the change is negligible at all frequencies below the microwave region.

Shunt conductance increases considerably with increasing frequency. The total shunt conductance consists of two parts. The first and most familiar part is the conductance of the line insulation. The second part is an apparent conductance caused by internal heating of the line insulation. When an alternating voltage is impressed across the line, the insulation is stressed first

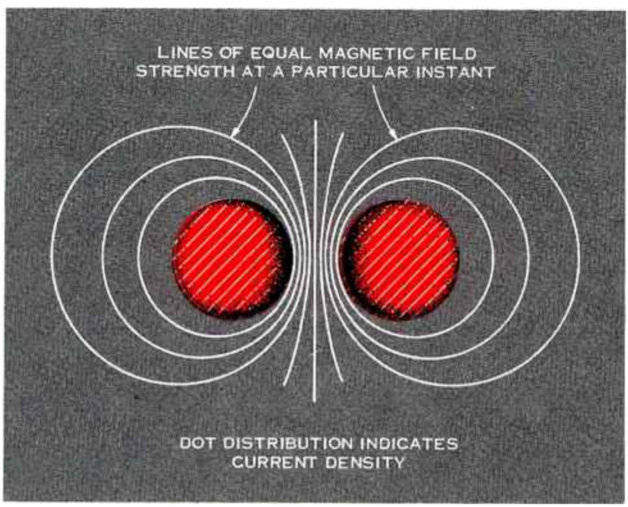


Figure 3. Increased line attenuation at high frequencies in cable pairs is partly caused by an increase in series resistance due to higher current density near the surface.

Figure 4. Current flow in a conductor covered with ice. Dot distribution indicates density of current flow.

in one direction and then the other. The heating that results is a power loss and appears to the line input voltage as an increase of the shunt conductance.

Influence of Weather

Transmission lines are often subject to a wide range of weather conditions. Cable lines are not usually affected by precipitation, although they are affected by temperature changes. Weather variations have significant effects on the properties of open-wire lines. The series resistance of an open-wire line is increased under high temperature conditions and also under wet weather conditions because of increased skin effect. During wet weather conditions, the film of moisture on the wires is slightly conductive. Since the magnetic field within the wires forces the current to flow more toward the surface, part of the current leaves the wire and flows in the film of water. The resistance of the water film is many times greater than the resistance of the copper wire. Therefore, the losses incurred by the current flowing in the water film are appreciable. During frosty or icy conditions, the coating of ice on the wires can become very thick with a considerable part of the current leaving the wire and flowing in the ice coating as shown in Figure 4.

Moisture and ice also affect the shunt conductance of the line. When the weather is dry, the shunt conductance is low and the loss is relatively low. During wet weather, dirt and dust collected on the insulators become much more conductive and the shunt conductance increases allowing more current to flow through the shunt leakage paths and thus increasing the attenuation. Under severe icing conditions the attenuation caused by skin effect and shunt conductance may be increased by as much as six or more times normal dry weather attenuation.

Conclusion

Transmission lines play an integral role in communications systems of all types. A good transmission line delivers as much of the signal energy as possible from the power source to its destination. The line should also be very stable and uniform. This means that each of the fundamental characteristics of the line must be the same throughout its entire length. It is also important that transmission lines be as free as possible from the effects of weather conditions such as temperature extremes, humidity, wind, rain, and snow.

Although transmission lines are being replaced by microwave radios in many medium- and long-haul communications systems, their usefulness has certainly not diminished. Transmission lines are essential in many types of communications systems and are capable of excellent service provided their characteristics are recognized and properly adapted for operation at the frequencies intended. •

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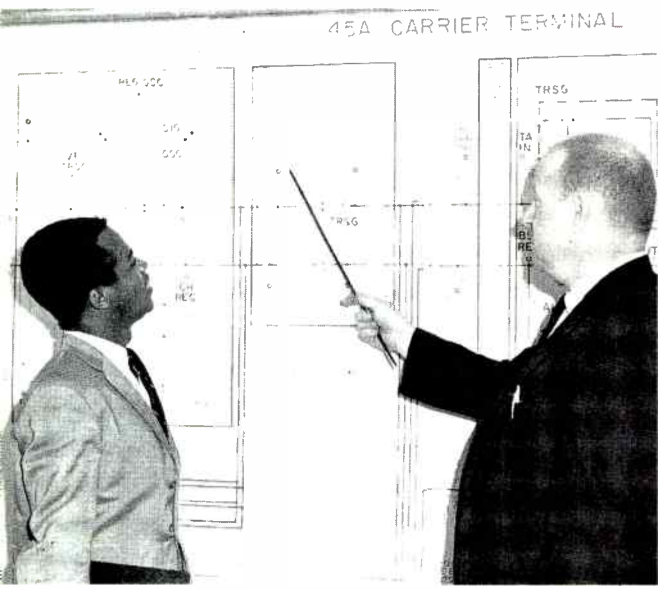

MILESTONE

The 3000th student to attend a class at Lenkurt's Customer Training School, is Peter A. Ukaegbu, from Nigeria. Ukaegbu, a graduate of Purdue University, is an electrical engineer employed by the Nigerian Post and Telegraph. The training school, which offers specialized courses in the operation and maintenance of multiplex and microwave systems, has been an integral part of Lenkurt's customer services program since 1952.

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