Coaxial cable contains a signal through equal and opposite currents in its two conductors

by John E. Cunningham, Editor THE ELECTRON

Many people seem to think that a shield contains a signal in much the same way a pipe contains water or a tin can contains tomatoes. The grounded shield is supposed to act like an impenetrable barrier to the signal carried by the shielded conductor.

This concept is incorrect. The proper explanation of how a coaxial cable works involves the electric and magnetic fields associated with the currents in both the inner and outer conductors. Fig. 1 shows a cross sectional sketch of a coaxial cable. The radial lines which represent the electric field terminate on the outside of the inner conductor and on the inside of the outer conductor. The dashed concentric circles between the two conductors represent the magnetic field associated with the currents in the conductors.

A little reflection, or a lot of mathematics, will show that if the currents in the two conductors are equal in magnitude and opposite in direction, there will be no fields outside the outer conductor. Thus the shielding effect of a coaxial cable depends on the currents in the two conductors being equal in magnitude and opposite in direction.

Now look at the situation in Fig. 2 which is rather common in practice. Here the outer conductor is grounded at both ends. In this situation the ground path is in parallel with the outer conductor. It seems logical that some of the current will flow in the ground which may have a lower resistance than the outer conductor. If this happens, the currents in the inner and outer conductors are no longer equal. What happens to the shielding?

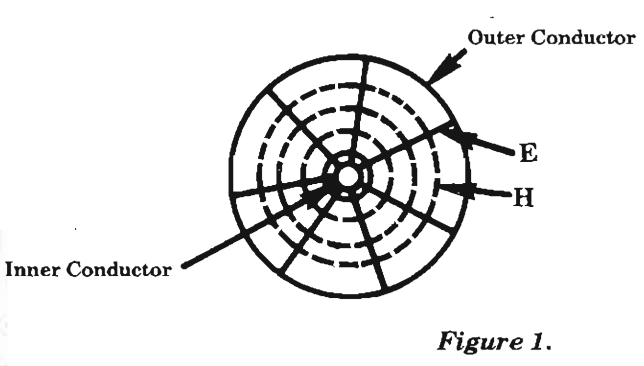

Figure 1.

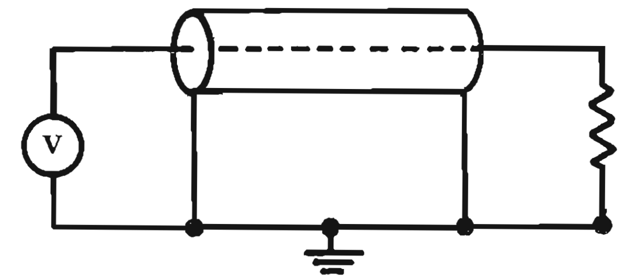

Figure 2.

As many technicians have found when faced with a situation like that shown in Fig. 2, the shielding isn't very good at low audio frequencies, but is usually good at higher frequencies. Why?

This situation may be analyzed by means of an equivalent circuit for a coaxial cable which the author learned about many years ago from Dick Mohr who worked for AIL at the time. It is shown in Fig. 3.

In this circuit L_1 is the self-inductance of the inner conductor, L_2 is the self-inductance of the outer conductor, and L_m is the mutual inductance between them.

The fact that all of the magnetic flux from the current in the outer conductor links the inner conductor means that the self-inductance L_2 of the outer conductor is equal to the mutual inductance L_m between the conductors.

In Fig. 3, I_1 is the current in the inner conductor, I_2 is the current in the outer conductor, and I_3 is the ground current which is the difference between I_1 and I_2.

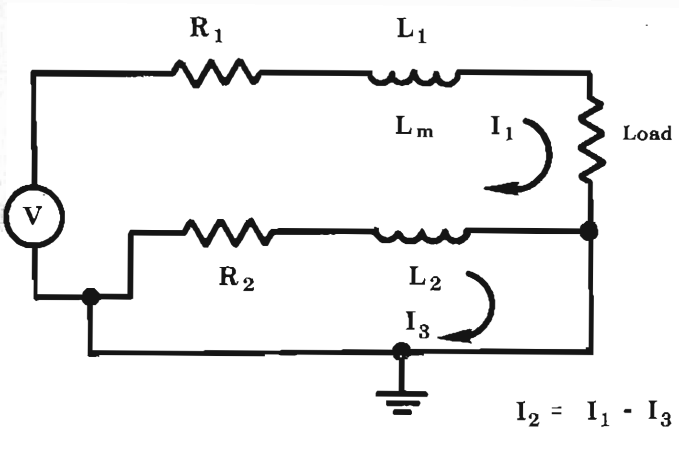

Figure 3.

This current may be found by writing the mesh equation for the bottom loop in Fig. 3. This is equation (1) of Fig. 4. Solving this equation shows that the ground current, I_3 is given by equation (2).

Equation (2) shows that the ground current depends among other things on the frequency of the signal. At the frequency given by equation (3) half of the return current flows in the outer conductor and the other half flows through the ground. At this and at lower frequencies, the coaxial cable provides practically no shielding.

$$0 = I_1 (j_\omega L \;\; -j_\omega L_2 - \;\; R_2) + I_3 (j_\omega L_2 + R_2)$$

$$L_m = \;\; L_2$$

Solving for I_3

$$I_3 = I_1 \left(\frac{1}{1 + \frac{j\omega L_2}{R_2}} \right)$$

$$f = R_2 / 2\pi L_2$$

Figure 4.

The frequency given by equation (3) is usually in the low to mid audio frequency range depending on the construction of the cable.

This analysis, which applied specifically to shielded cables applies in a general way to all sorts of shielding. For a shield to be effective the mutual inductance between the shield and the current being shielded must be equal to the effective self inductance of the shield.

The above analysis shows why a cable that is "air tight" at radio frequencies doesn't do much of a job of shielding at the 60 Hz power line frequency.