Ground - A Path for Current Flow

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A signal ground is normally defined as an equipotential point or plane that serves as a reference potential for a circuit or system. This definition, however, does not emphasize the importance of the actual path taken by the current in returning to the source. It is often important that the design engineer know the actual path taken by the ground current. Only by knowing this can the designer accurately estimate the radiated emission from a circuit, or the susceptibility of a circuit to electromagnetic energy.

An alternative definition for a single ground is: *A low impedance path for current to return to the source.* This definition emphasizes the importance of the current flow in the ground system. It implies that since current is flowing through some low, but finite, impedance there will be a difference in potential between the two ends. This *current* concept of a ground is also useful in order to determine where decoupling capacitors should be connected, and explains why, in some cases, eliminating a ground may make a circuit less susceptible to electromagnetic interference.

Introduction

There are two primary reasons for grounding a circuit or system. One is for safety and the other is to provide a *signal common* or reference for the circuitry. This paper is concerned with the latter. The word *ground* as used here refers to a *signal common* used in electronic systems. This common may or may not be connected to earth potential.

The most important part about grounding that a designer should keep in mind is that **a good ground system must be designed**, just like any other portion of the circuit. It is wishful thinking to expect a ground system to perform well if no thought is given to its design. The larger the system and the faster (higher frequency or shorter rise time) the system, the more important a well designed ground becomes. However, even a low frequency or dc system normally requires a well designed ground to provide optimum performance.

One big advantage of a good ground system is that it can provide protection against unwanted electromagnetic interference (EMI), without any additional per unit cost to the product. The only cost is the additional engineering time required to design the system properly. In comparison an improperly designed ground may be a primary source of electromagnetic interference and still require considerable engineering time to eliminate the problem. Properly designed ground systems are, therefore, very cost effective.

Signal Ground

A signal ground or common is usually defined as an equipotential point or plane which is a source or sink for current, and serves as a reference potential for a circuit or system. As a result of this *equipotential* definition, designers often do not concern themselves with what happens to the current after it enters the ground system. In particular, what path does the current actually take in returning to the source? The above definition leads one to believe that if a sufficiently low ground impedance is obtained, the actual path taken by the current is not important. However, as shown later, it is often important to know the path taken by the ground current.

An alternative definition which overcomes the limitations mentioned above is that a signal ground is **a low impedance (hopefully) path for current to return to the source.** This *current concept* of a ground emphasizes the importance of current flow. It further implies that since current is flowing through some low, but finite, impedance there will be a difference of potential between two physically separated points in the ground system. The equipotential concept defines what a ground *ideally* should be, while the current concept defines what a ground actually is.

The actual return path taken by the ground current is important in determining the magnetic coupling between two circuits. The magnetic or inductive coupling is proportional to the area of the loop formed by the receptor circuit. But what is the area of the loop in a system containing multiple ground paths? The area of interest is the total area enclosed by the **actual** current flow in the receptor circuit. An important consideration in determining this area is the ground path taken by the current in returning to the source. Quite often this is not the path intended by the designer.

This *current concept* of a ground is also useful in determining where and how decoupling capacitors should be connected. Additionally, it can be useful in explaining why in some cases eliminating a ground connection may make a circuit less susceptible to interference as well as reduce the radiated emission from the circuit.

The advantages of considering a ground as a path for signal current to return to the source, rather than an equipotential, will be demonstrated with the following two examples.

Example #1—Coaxial Cable

Consider the simple circuit shown in Fig. 1, which consists of a single conductor above a ground plane. In this case the signal current (I_1) flows down the conductor to the load

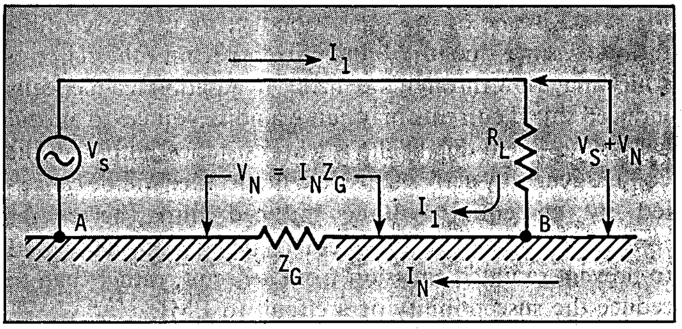

Figure 1—Single Conductor Above Ground Plane.

R_L and returns to the source through the ground plane, since there is no other path. If additional circuits were connected to the ground plane, another current (I_N) may also be flowing in the ground. Since the ground has a finite impedance, this current will produce a noise voltage ($V_N = I_N Z_G$) between points A and B in Fig. 1. The voltage across the load will then be $V_S + V_N$.

Due to the loop formed by the center conductor and the ground, the circuit of Fig. 1 will radiate a magnetic field. In addition the circuit will be susceptible to interference from an external magnetic field. This susceptibility will be proportional to the area of the loop formed by the center conductor and the ground. Placing the conductor closer to the ground plane will decrease the area of the loop, and will therefore decrease the amount of radiated emission and make the circuit less susceptible to EMI.

If a shield is now added around the conductor and grounded at both ends the circuit of Fig. 2 would result. The shield is now part of the ground system. In this case the signal current (I_1) flows down the center conductor of the coax to the load resistor. The current then has a choice in returning to the source. It can either flow through the ground plane or it can return on the shield or some combination of both. If the current returns through the ground plane the circuit will radiate a magnetic field due to the signal current flow around the loop consisting of the center conductor and the ground. The amount of radiation would be the same as that of Fig. 1, assuming the loop areas are the same.

If on the other hand the current returns on the shield the amount of radiated emission and the susceptibility to EMI will be reduced, due to the decreased loop area formed by this current path. The coaxial cable provides a very small loop area since the shield can be represented as an equivalent conductor located on its longitudinal axis. This effectively locates the shield and center conductor at the same place in space.

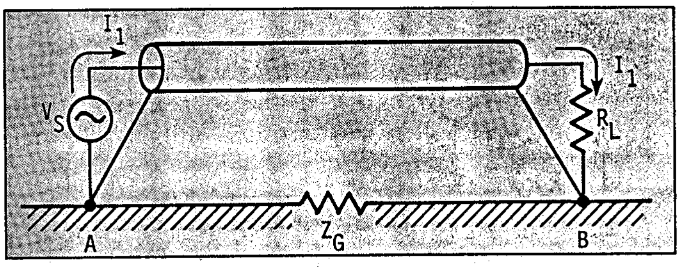

Figure 2—Coaxial Cable with Shield Grounded at Both Ends.

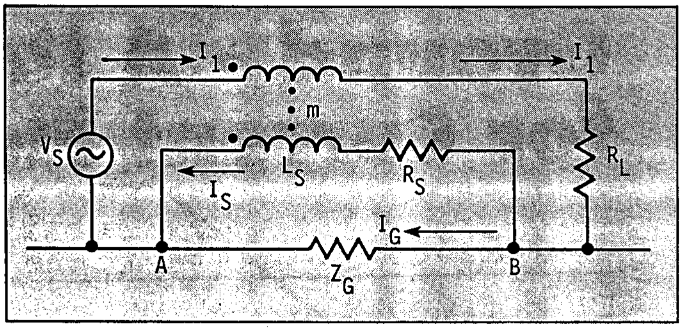

Figure 3—Equivalent Circuit of Figure 2.

It is, therefore, important to know under what conditions the current will return on the shield rather than through the ground plane. To do this one can use the equivalent circuit shown in Fig. 3 where L_S and R_S are the shield inductance and resistance, respectively, and M is the mutual inductance between the shield and the center conductor. Let the current that returns to the shield be I_S and the current that flows in the ground plane be I_G. Then,

$$I_G = I_1 - I_S. \tag{1}$$

Writing a mesh equation around the loop $A - L_S - R_S - B$ gives

$$0 = -I_S(j\omega L_S + R_S) + I_1(j\omega M) + I_G Z_G. \tag{2}$$

Substituting Equation 1 for I_G and solving for I_s gives

$$I_S = \left[\frac{j\omega M}{j\omega L_S + R_S + Z_G} + \frac{Z_G}{j\omega L_S + R_S + Z_G}\right] I_1. \tag{3}$$

It can be shown that for a coaxial cable $M = L_S$.[1] Therefore,

$$\frac{I_S}{I_1} = \left[\frac{j\omega}{j\omega + \dfrac{R_S + Z_G}{L_S}}\right] + \left[\frac{Z_G/L_S}{j\omega + \dfrac{R_S + Z_G}{L_S}}\right]. \tag{4}$$

Figure 4 is an asymptotic plot of Equation (4). It shows that at frequencies considerably above

$$\omega = \frac{R_S + Z_G}{L_S} \tag{5}$$

virtually all of the signal current will return on the shield instead of in the ground plane. As the frequency is decreased below that of Equation (5) a larger percentage of the signal current returns through the ground plane, thus decreasing the effectiveness of the shield. Even at very low frequencies a current equal to

$$I_S = \frac{Z_G}{Z_G + R_S} I_1 \tag{6}$$

returns on the shield. This is due to the existence of the ground impedance Z_G.

If the ideal case is now considered, where the ground impedance Z_G approaches zero, the shield current I_S will also ap-

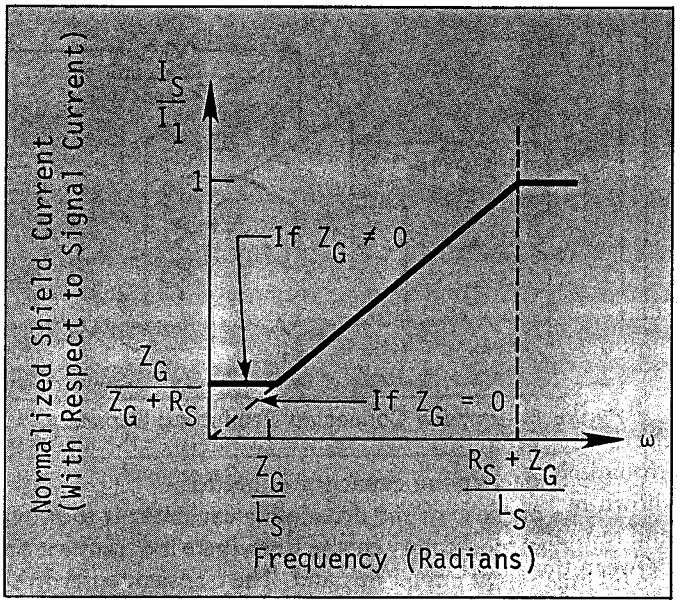

Figure 4—Asymptotic Plot of Normalized Shield Current.

proach zero at low frequencies. This is shown as the dotted curve in Fig. 4. In this case Equation (4) can be rewritten as:

$$\frac{I_S}{I_1} = j\omega/[j\omega + R_S/L_S]. \qquad (7)$$

Therefore, even for the case of zeroground impedance almost all the signal current will return on the shield if the frequency is above

$$\omega_c = \frac{R_S}{L_S} . \qquad (8)$$

This makes ω_c an important parameter of the system. It is dependent only on the parameters of the shield, its inductance and resistance, and is called the shield cutoff frequency. The actual value of the shield cutoff frequency is of considerable usefulness to the circuit designer since it determines which path the return current wil take. Values for typical cables[2] vary from about 0.5 to 8 kHz.

Therefore, at frequencies above the audio band the configuration of Fig. 2 will be useful in reducing the radiated emission from a circuit, and in reducing the susceptibility of the circuit to magnetic induction. This improvement is due to the reduction in loop area caused by current returning on the shield and **not** by any magnetic shielding properties of the shield itself.

The circuit of Fig. 2, however, has other problems. Since the shield is one of the signal conductors it is susceptible to interference due to ground currents from other circuits which may flow through the shield. In addition magnetically induced shield currents may cause a noise voltage to appear across the shield due to the shield resistance, although the voltage generally across the shield inductance will be cancelled by an equal voltage induced into the center conductor.[3] Therefore, the circuit of Fig. 2 is normally used to prevent radiated emission from a circuit, rather than to reduce the susceptibility of a circuit to EMI.

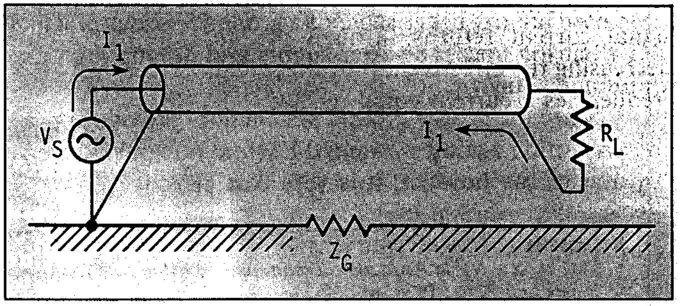

Figure 5—Coaxial Cable with Shield Grounded at One End Only.

Figure 5 shows a circuit where load (R_L) is not connected to the ground plane. In this case the signal current must return on the shield regardless of the frequency. Therefore, radiation will be minimized and interference reduced even at frequencies below the shield cutoff frequency. In addition, external ground currents and magnetically induced currents cannot flow on the shield. The use of the circuit shown in Fig. 5 is limited by the fact that in some cases it is not possible to eliminate the ground at the load end of the circuit. An example of this is at high frequencies where parasitic capacitances tend to force a ground connection at the load end.

In the case of the circuit of Fig. 5 the absence of a ground connection at the load end provides equal or better performance than the circuit of Fig. 2 which has grounds at both ends.

Example #2—Power Connection and Decoupling Capacitor

Consider the generalized amplifier circuit configured as shown in Fig. 6. A transient or high frequency load current must be supplied from the power supply (V_{dc}) through the impedance of the wiring. This current must flow from the power supply through the amplifier to the load R_L and into the ground. In the ground it must return through the ground impedances Z_3, Z_2, and Z_1 back to the power supply.

The arrangement in Fig. 6 causes two problems. The transient current (ΔI) flowing through the ground impedance Z_2 produces a noise voltage (ΔV) at the input of the amplifier. This voltage is then amplified and appears as an undesirable output voltage across the load R_L.

The second problem with the configuration of Fig. 6 is that the power supply voltage (V_{cc}) at the amplifier terminals

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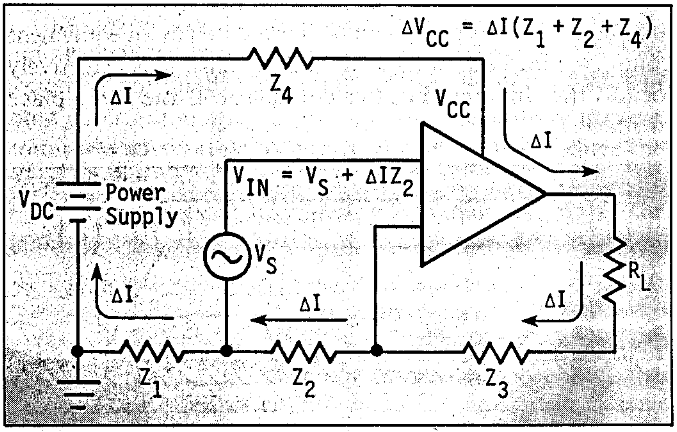

Figure 6—Generalized Amplifier Circuit-Improper Power Connection.

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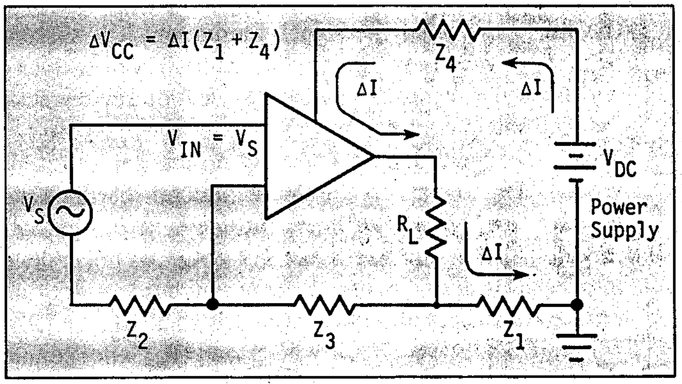

Figure 7—Generalized Amplifier Circuit-Proper Power Connection.

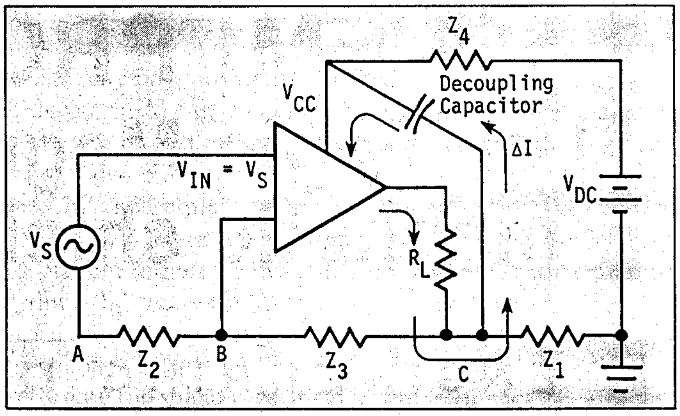

Figure 8—Properly Connected Decoupling Capacitor.

will drop due to the transient current flowing through the impedances Z_1, Z_2, and Z_4. The effect of this supply voltage change on the amplifier output will depend upon the supply voltage rejection ratio of the amplifier. The supply voltage rejection ratio of the amplifier is the ratio of the change in output offset voltage to the change in the supply voltage that caused it, usually in units of microvolts/volt.

If the power supply is reconnected as shown in Fig. 7 the transient current coupling to the input is eliminated. The current ΔI no longer must flow through the impedance Z_2 and an input noise voltage is not produced. The problem of a sudden reduction in power supply voltage (ΔV_{cc}) at the amplifier terminals is still present, however. To eliminate this, a decoupling capacitor is needed.

The purpose of the decoupling capacitor is to provide a source of momentary charge when there is a transient change in the current circuit demand. The transient current is supplied by the capacitor instead of being drawn by the power supply through the inductance of the circuit wiring.

The bypass or decoupling capacitor should be connected to provide the most direct path for this transient current. Since the transient current is normally drawn by the load, this means connecting the capacitor between the load common, or ground, and the amplifier V_{cc} terminal.

In Fig. 8 the decoupling capacitor is shown properly connected between V_{cc} and point C, the common of the load resistor. The transient current does not flow through any of the ground impedances in returning back to the V_{cc} terminal.

If the capacitor had been connected to point B an output noise voltage would be generated due to the transient current flow through the ground impedance Z_3. Connecting the capacitor to point A is even more detrimental, since the transient current must now also flow through the impedance Z_2, thus generating an input noise voltage.

Conclusion

Considering ground as *a low impedance path for current to return to the source,* instead of as an equipotential, emphasizes the importance of current flow in the ground system. Since this ground current flows through a finite, but hopefully small impedance any two ground points that are physically separated will be at different potentials.

In addition, knowing the actual path taken by the ground current is helpful in analyzing the performance of a circuit or system from a radiated emission and/or EMI point of view. The *current concept* of a ground is also useful in determining the proper power supply and decoupling capacitor connections.

Since the proper ground system does provide appreciable protection against unwanted EMI, at no additional cost per unit of the product, it is very cost effective. Ω

References

1. Ott, H.W., *Noise Reduction Techniques in Electronic Systems,* John Wiley and Sons, 1976, pp. 32-35.
2. Ibid., p. 37.
3. Ibid., p. 42.