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Earthing and grounding for the control of EMI in industrial instrumentation and control systems

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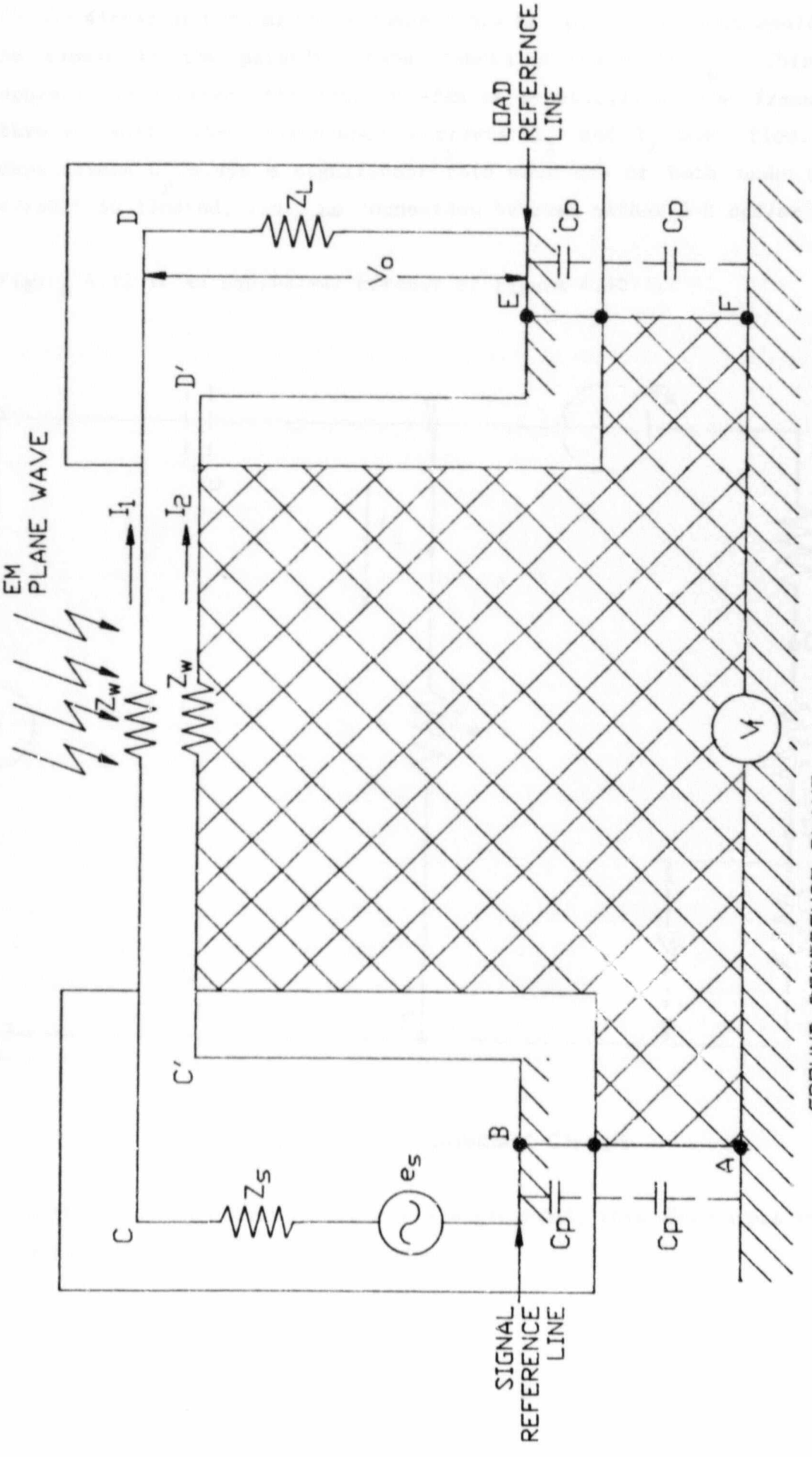


FIGURE 4.10 FIELD-TO-CABLE COMMON-MODE COUPLING

Should either or both of these connections be opened, the loop would still be closed by the parasitic capacitances indicated by C_p. This would appreciably increase the loop impedances especially at low frequencies through which the common-mode currents I_1 and I_2 must flow. The capacitance C_p plays a significant role when one or both ends of the circuit is floated, i.e., no connection between either A-B and/or E-F.

Figure 4.11 is an equivalent circuit of Figure 4.10.

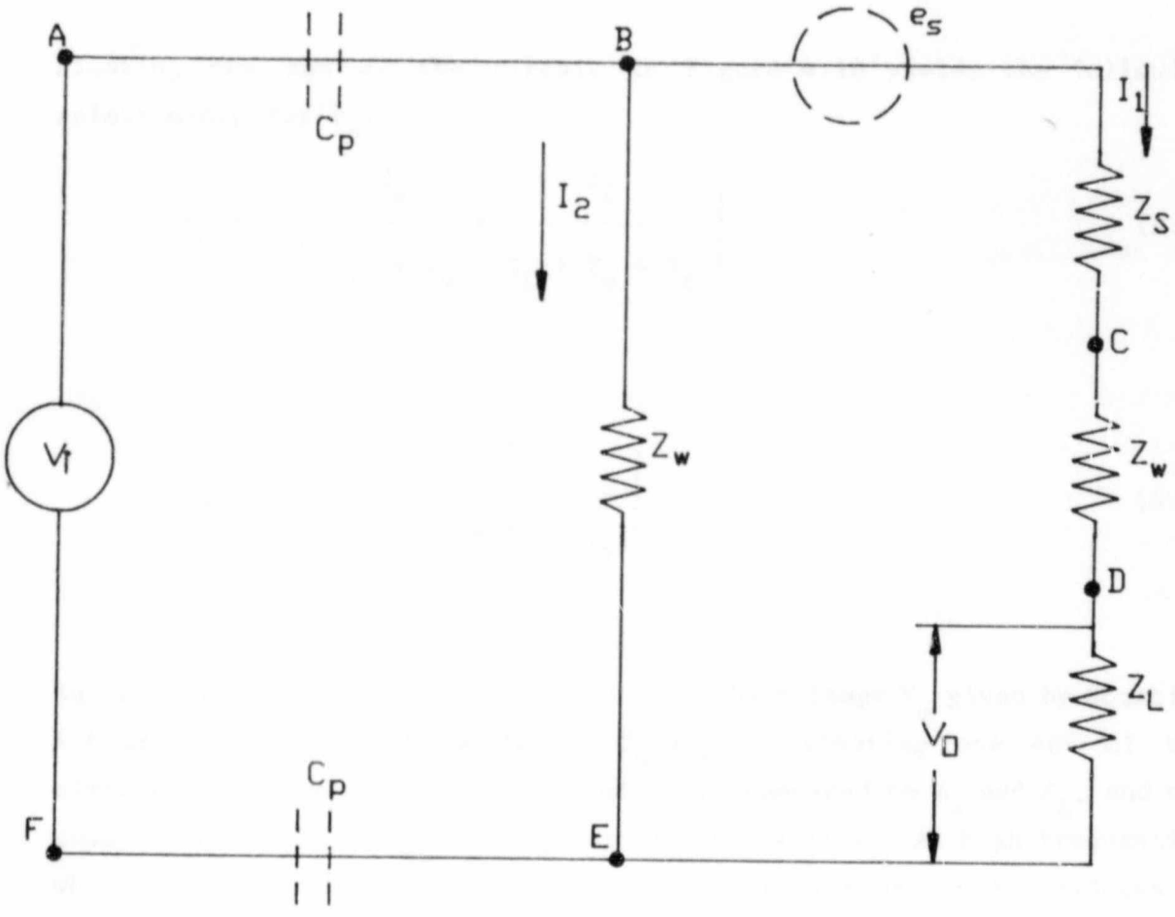


Figure 4.1[illegible]ent Circuit

If both signal and load referen[illegible] grounded, then the output voltage V_o across the load due to V_i becomes:

$$V_o = V_i \left(\frac{Z_L}{Z_s + Z_w + Z_L} \right) \tag{4.6}$$

The relation in Equation 4.6 results from circuit imbalances, i.e. the common-mode currents I_1 and I_2 are induced in phase through the transmission cables, but the impedances through which they flow are different due to circuit impedance imbalance. This suggests that one way to minimise common-mode effects is to balance the circuit and this is accomplished in practice by using differential drivers or receivers.

Floating one end of the circuit in Figure 4.10 yields the following relationship for V_o:

$$V_o \approx V_i \left(\frac{Z_w}{Z_{cp} + Z_w} \times \frac{Z_L}{Z_L + Z_w + Z_S} \right) \tag{4.7}$$

$$V_o \approx V_i \left(\frac{Z_w}{Z_{cp}} \times \frac{Z_L}{Z_L + Z_w + Z_s} \right) \tag{4.8}$$

Equation 4.8 indicates that, effectively, the voltage V_o given by Equation 4.6 has been reduced by a factor Z_w/Z_{cp} by floating one end of the circuit. Z_w is wiring impedance and small compared to Z_s and Z_L, and the capacitive impedance Z_{cp} is large at low frequencies. At high frequencies whereby the impedance of C_p drops significantly Equation 4.7 reduces to Equation 4.6. However, it should be noted that at high frequencies, other factors such as wiring inductance, must be considered whereby the circuit could begin to resonate (see Chapter 3).

4.4.2.2 Differential-Mode Radiation Coupling

Figure 4.12 illustrates the coupling of incident radiation directly into the wiring loop area between the signal transmission cables. This coupling path converts the incident field into a differential-mode voltage which appears across the input terminals of the load to produce the EMI threat. For unbalanced lines, such as a coaxial line, the coupling physics does not encompass a loop area, but it can be described in two parts:

1. A relationship between the incident field and the induced surface current on the cable, and

2. The cable transfer impedance relating the induced current to the EMI voltage appearing along the inner conductor. A portion of this appears across the load terminals.

It is beyond the scope of this study to go into a full circuit analysis and the interested reader to referred to the book by White "EMI Control Methodology and Procedures"[5] in which a complete analysis is done. Suffice to say that the induced surface current is a function of frequency and cable length, and the transfer impedance is a function of frequency and cable type.

Differential-mode reduction can be accomplished for balanced lines by using twisted wire pairs, reducing loop wire area, properly grounded single or multiple braided shields or solid homogeneous tubular shields or conduit. For unbalanced lines, such as coaxial cables, techniques include selecting coaxial cables with lower transfer impedance, triaxial cables with the outer braid grounded at one end (for low frequency application whereby the cable length is less than 1/15 of a wavelength), and using semi-rigid, homogeneous coaxial lines[2],[5].

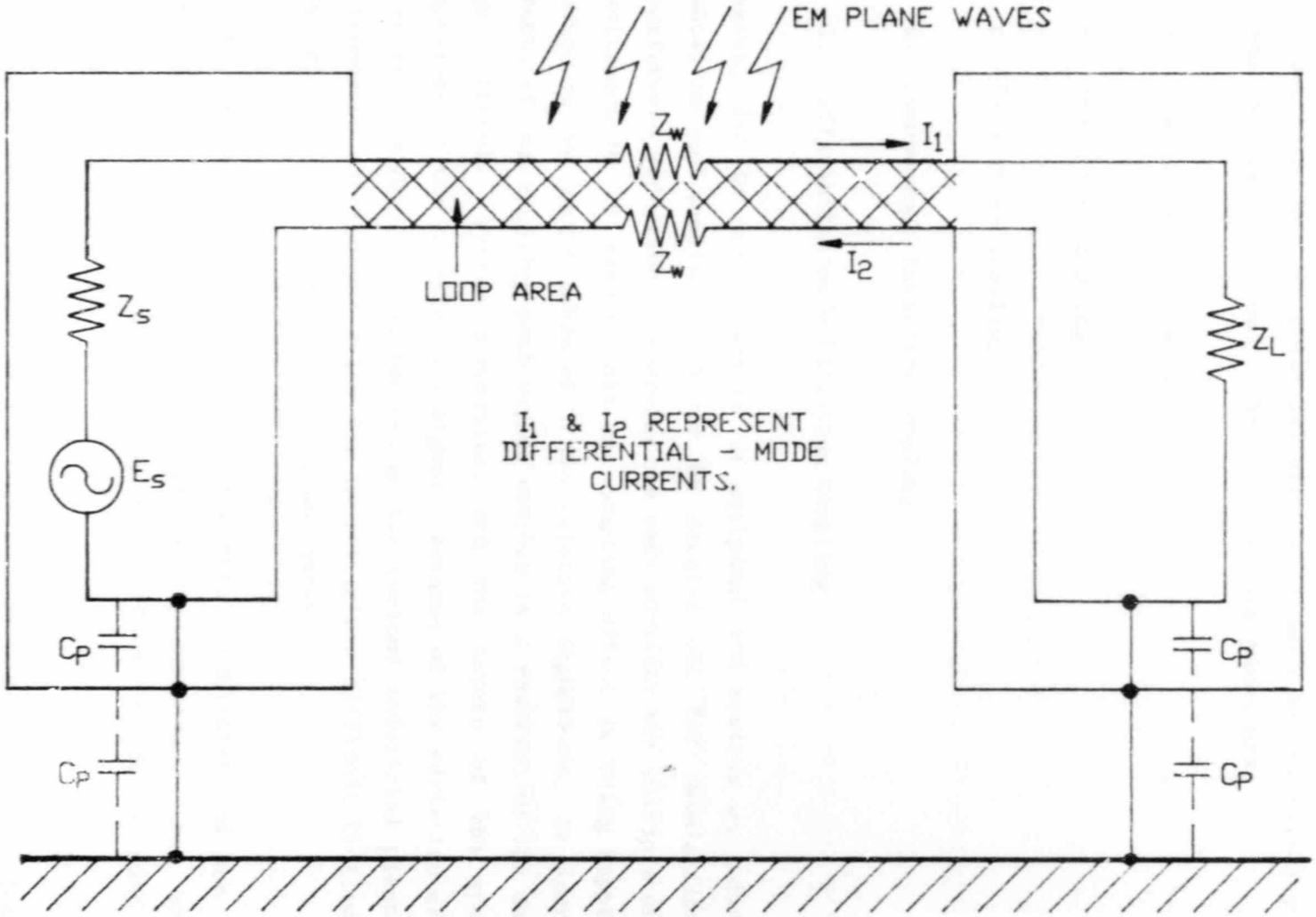


FIGURE 4.12 FIELD--TO--CABLE DIFFERENTIAL--MODE COUPLING

4.5 SUMMARY

In the preceding sections, five EMI ground related coupling paths have been identified and the potential effects of each on industrial process systems have been examined. The five coupling paths are:

a. Common-Mode Impedance Coupling

b. Inductive Coupling

c. Capacitive Coupling

d. Common-mode Radiation Coupling

e. Differential-mode Radiation Coupling

However, due to the diversity of equipment and systems on industrial plants, no one coupling path can be singled out for examination for interference reduction. Generally one must consider the multiple effects simultaneously to assure that one coupling effect is being suppressed another is not being enhanced. The relative importance, in terms of effect, of one coupling path versus another is a function of the desired signal circuit, system properties, and the nature of the spectral properties of the interference signal. Because of the variation of this inter-relationship with system design for various industrial plants and environments, stereotype rules for grounding are difficult to formulate which would be applicable to all circumstances.

However, certain design guidelines have been established and are being stressed for interference reduction in instrumentation and control systems. These are summarised below and form the basis for later Chapters.

1. Minimise the impedance of the reference ground plane, if indeed the ground plane must be used for the return path.

2. Individual separate ground returns are highly desirable to prevent common-mode impedance coupling.

3. Increase the separation between the coupled circuits (inductive and capacitive coupling).

4. Shield the susceptible circuit or the source.

5. Reduce the area of the signal loop.

6. Balance the signal transfer path.

7. Electrically break the signal transfer loop at the frequency of the interference.

8. Prevent the source and the load ends of the desired signal circuits from being connected to points of different potential.

9. Minimise the efficiency of ground leads acting as antennas, i.e. lead lengths should be less than 1/15 of a wavelength of the interfering signal.

10. Reduce the length of parallel runs of source and receptor cables.

11. Twist wires in opposite directions.

12. All circuit returns should conform to the following principles:

    a) The two leads of a given circuit should be routed together as close as possible.

    b) Leads should be routed as close to the ground reference plane as possible.

    c) Circuit returns should never be shielded separately or carried outside the shield used for the corresponding live conductor.

13. Attention should be given to the separation of the various circuits into compatible groups, especially when diverse functions are incorporated into a single package, and

14. Single end or multiple end grounding depending on frequency of interfering signal.

CHAPTER 5

5.0 EFFECTIVE SIGNAL AND SHIELD GROUNDING

5.1 INTRODUCTION

The subject of grounding has been extensively covered in the literature with respect to power systems and lightning protection and grounding techniques are well developed and have been standardised (See References). Electronic or signal ground systems, on the other hand, have not been standardised. This is so because signal grounding is frequently related to "black magic" and a thorough understanding of the principles of grounding for purposes other than meeting the minimum requirements of the electrical safety code has been lacking. As a consequence, undesirable interference situations results due to poor grounding practice. Such problems can only be avoided by very careful design of the ground system.

In this Chapter various signal ground network configurations are examined. These include floating grounds, single-point grounding, multiple-point grounding and nodal-point grounding where the prime concern is EMI control. It will be shown that all systems are a continuation of each other at higher frequencies, but that certain correct grounding practices should be followed. In addition, circuit and shield grounding guidelines are established based on frequency and sensitivity consideration. Practical techniques are also presented to counter the effects of ground loops. In addition, the aspects of preventing noise in grounded and ungrounded transducers is also considered. An important point to note is that the grounding principles covered here are just as applicable to individual circuits on a single printed circuit board as they to large complex electronic instrumentation and control systems.

5.2 THE IDEAL GROUND.

It has been stated that the purpose of signal grounding is to establish an equipotential reference to prevent interference and to dispose of unwanted excess energy. These objectives can only be achieved through the use of zero impedance conductors, which do not exist. Ideally, the purpose of signal grounds are to provide:

1. An equipotential reference plane to prevent unwanted coupling between circuits (common-mode impedance coupling);

2. Signal return paths at the circuit level;

3. A low impedance network to control static charge and stray capacitance effects (capacitive coupling); and

4. Fault protection for signal circuits.

In practical applications, where complex electronic systems extend throughout a large plant, the first of these objectives, i.e. an equipotential reference plane, cannot be achieved. The closest approximation to an ideal ground would be a very large sheet of conductor material, such as copper or aluminium, underlying the entire facility with large visors extending up to individual pieces of equipment - a prohibitively expensive approach. However, the other three objectives must, and can be accomplished to minimise noise problems.

On the question of providing a reference and a path to the reference, consider the following. Between any two points on a metallic path, a potential difference at some frequency will exist in the presence of an electric or a magnetic field. This potential V may be expressed as[2]

$$V = A \sin (2\pi \ell/\lambda) \qquad (5.1)$$

where

A = amplitude of induced voltage in the metal

ℓ = distance between the two points

λ = wavelength at the frequency concerned.

alternately, the impedance Z, between two points in a ground plane is given by

$$Z = R_{ac} (1 + |\tan 2\pi\ell/\lambda|) \quad (5.2)$$
$$= KR_{dc} (1 + |\tan 2\pi\ell/\lambda|)$$

$$(\text{for } \ell < \lambda/10) \quad Z \simeq KR_{dc}(1 + 2\pi\ell/\lambda) \quad (5.3)$$

$$(\text{for } \ell < \lambda/20) \quad Z \simeq KR_{dc} \quad (5.4)$$

$$(\text{for } \ell \simeq \lambda/8, 3\lambda/8) \quad Z \simeq 2KR_{dc} \quad (5.5)$$

$$\text{and } (\text{for } \ell = \lambda/4, 3\lambda/4) \quad Z = \infty \quad (5.6)$$

where

R_{dc} = dc resistance

R_{ac} = high frequency resistance

and $K = R_{ac}/R_{dc}$

Hence, it becomes apparent from the above equations that the impedance between two points on a ground plane can become substantial at frequencies higher than that corresponding to $\lambda/8$, thereby offering little equipotential value. However, at lower frequencies for which $\ell<\lambda/20$, the impedance between two points is proportional to R_{ac}.

5.3 FLOATING GROUNDS

The floating ground system, illustrated in Figure 5.1, is one possible configuration for the signal ground network when coupling to a common ground is to be avoided. This type of signal ground system in a facility is electrically isolated from building elements or ground and any other conductive object. Hence, interfering currents flowing in these conductive elements will not be conductively coupled into signal systems.

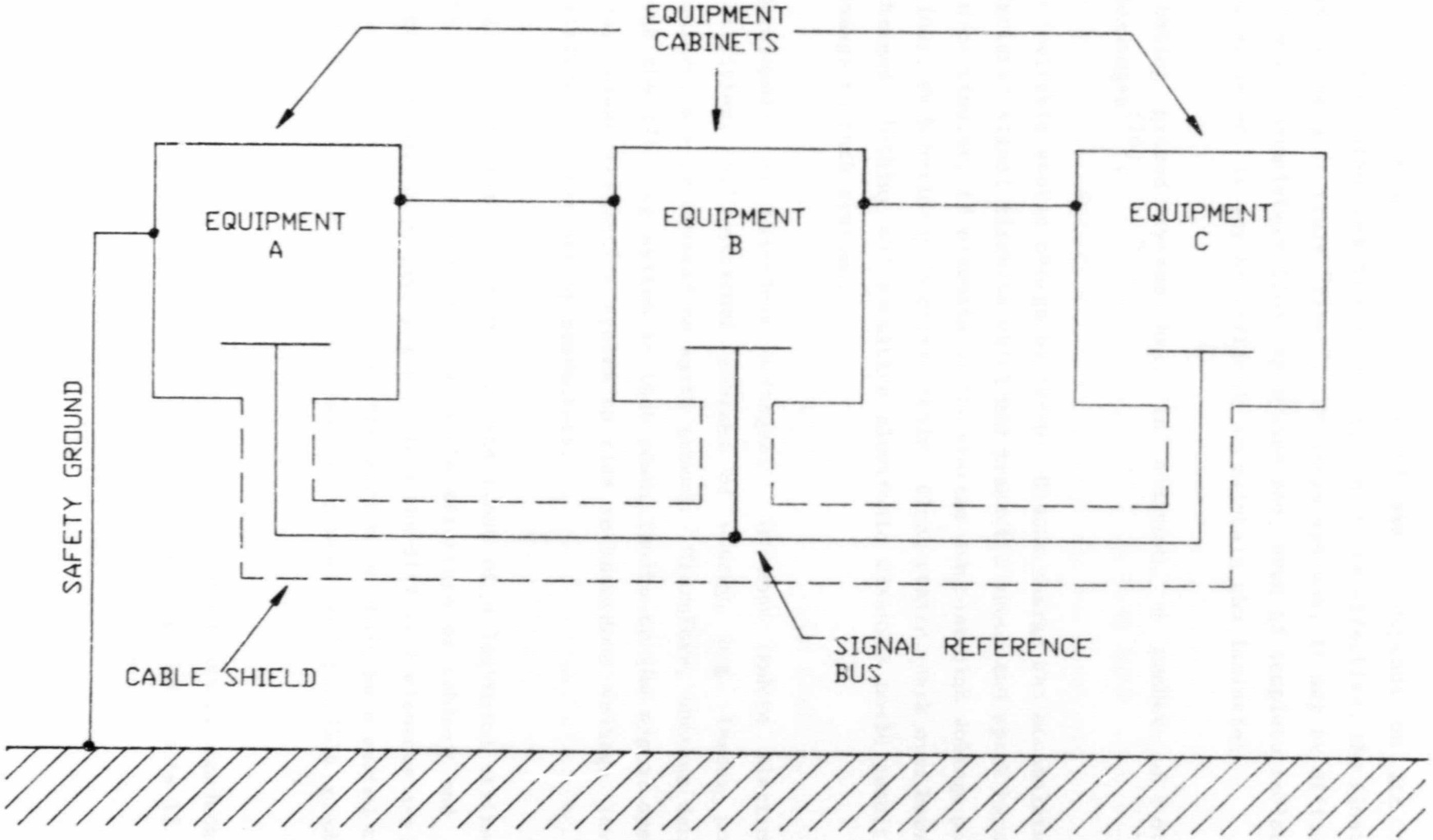


FIGURE 5.1 ILLUSTRATION OF FLOATING GROUND SYSTEM

In addition electromagnetic shields may be used to prevent magnetic coupling so as to maintain the isolated floating ground of the system.

The effectiveness of a floating ground system depends on its true isolation from other nearby conductors, i.e. to be effective, the floating ground system must truly "float". In large systems, it may be difficult to achieve a completely floating system and, even if complete isolation can be achieved, it may be difficult to maintain the isolation.

A floating ground system has, in addition, a number of other disadvantages[10]:

1. Undesirable static charge build-up. Static charge can accumulate an isolated signal circuits which may present a shock and spark hazard. In particular, if elements of the systems are near high voltage power lines, such build-up is quite likely. Also, static spark over between charged clothing and sensitive electronic circuits could result in damage to such systems.

2. Development of hazardous voltages. In most modern electronic facilities, all external sources of energy, e.g. feeder power sources, are referenced to earth ground. Therefore, another danger with the floating system is that power faults to the signal system would cause the entire system to rise to hazardous voltage levels relative to other nearby conductors.

3. Lightning flashover threat. In the event of a lightning strike to the facility a flashover between the structure or cabinet and the signal system could take place. Since the different elements are not conductively coupled together, the structure could be elevated to a high voltage relative to the signal ground and possibly produce flashover.

4. Capacitive coupling. Stray capacitance to other nearby conductive objects may produce unpredictable coupling to signal circuits if the signal ground network is not connected to these objects.

Hence, one concludes that floating systems can be practical only if a few circuits or a few pieces of equipment are involved and power is supplied from either batteries or dc-to-dc converters.

5.4 SINGLE-POINT GROUND SYSTEM

Figure 5.2 illustrates the concept of single-point grounding. In this case, the signal circuits are referenced to a single point or star-point and that point is then connected to the earth system. On a cabinet level, all circuits are tied to a ground which is insulated from the cabinet and building. These grounds are then tied to the one reference point, i.e. the earth system. This isolates the cabinets and prevents any conducted circulating currents in the building ground from producing potential drops within the equipment.

However, in larger systems it becomes increasingly difficult to maintain single-point ground paths. The ideal would be one in which separate ground conductors extend from one point on the earth system to the return side of each of the numerous circuits located throughout the plant. This type of ground system, however, requires an extremely large number of conductors which may be expensive and is vulnerable to conductive and induced interference coupling. Because of the interference problem and expense involved in the ideal configuration, various degrees of approximation to single-point grounding are commonly applied.

The configuration illustrated in Figure 5.3 represents one approach to a plant wide single-point ground. To mitigate interference, such as due to common-mode impedance coupling, as many separate ground buses are used. These buses extend from a single point on the facility ground to each individual electronic system. In each system, the various signal reference points in each electronic subsystem are individually connected at only one point to this ground bus.

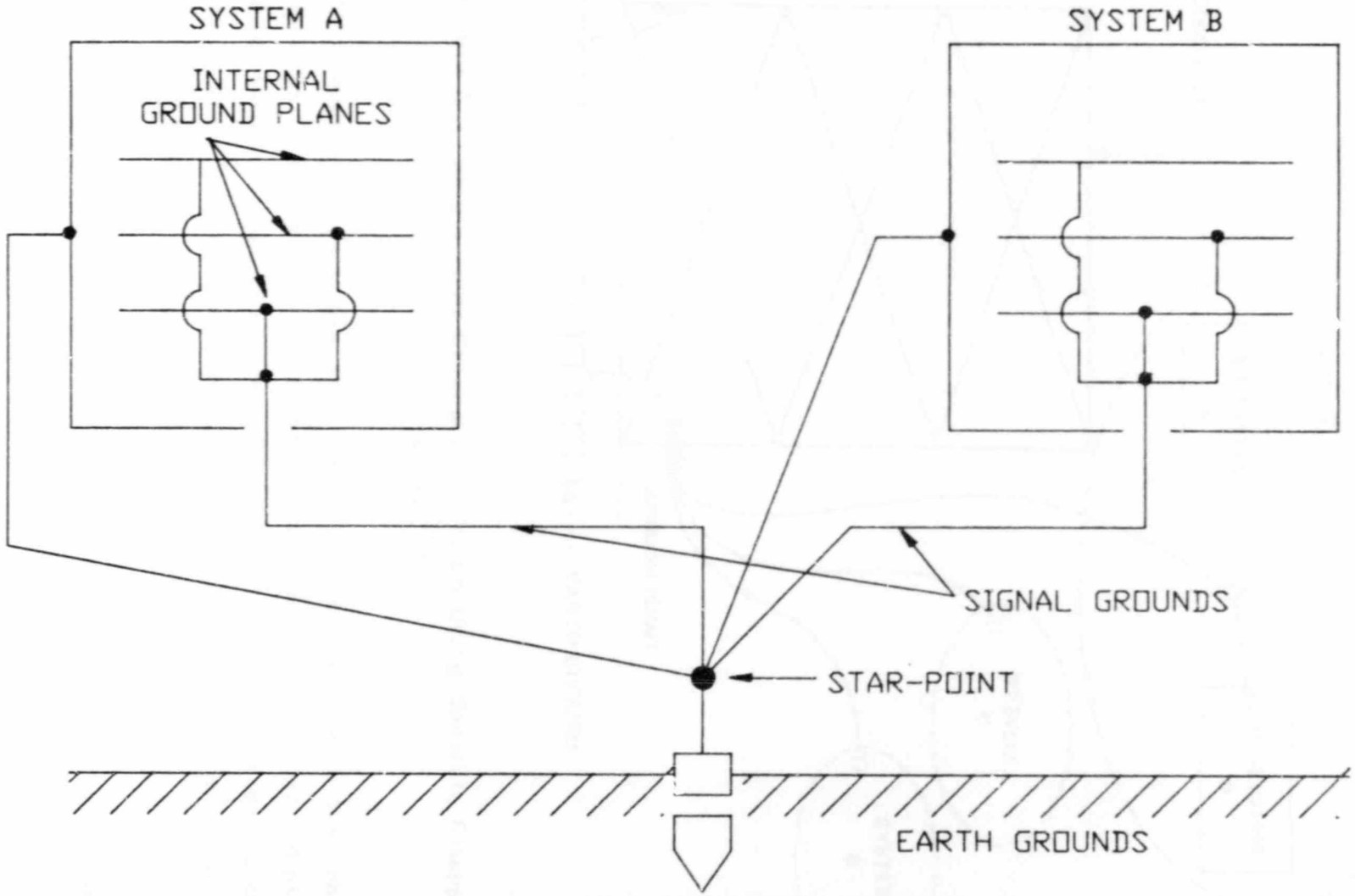


FIGURE 5.2 SINGLE-POINT GROUNDING

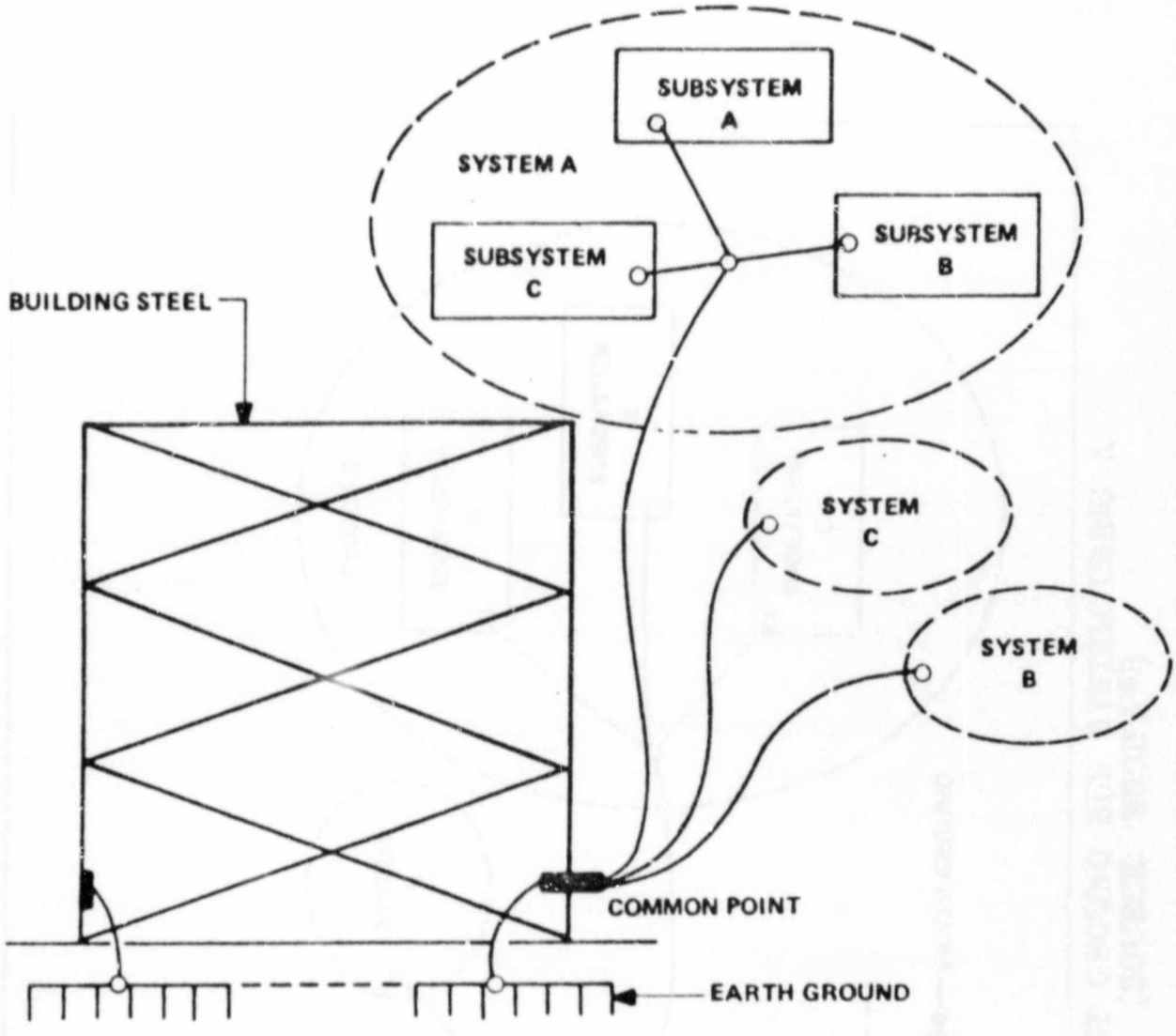


Figure 5.3 Single-Point Ground Bus System Using Separate Risers
(Source: Woody[10])

Another approach frequently used is illustrated in Figure 5.4, which assumes the form of a tree. Here, each system has a separate ground plane to which each subsystem is single-point grounded. These individual ground planes from each system is then connected by the shortest route to the tree ground bus with a single insulated conductor.

The configuration networks discussed thus far implied single ground circuits only. In general, modern electronic systems seldom have only one ground plane.

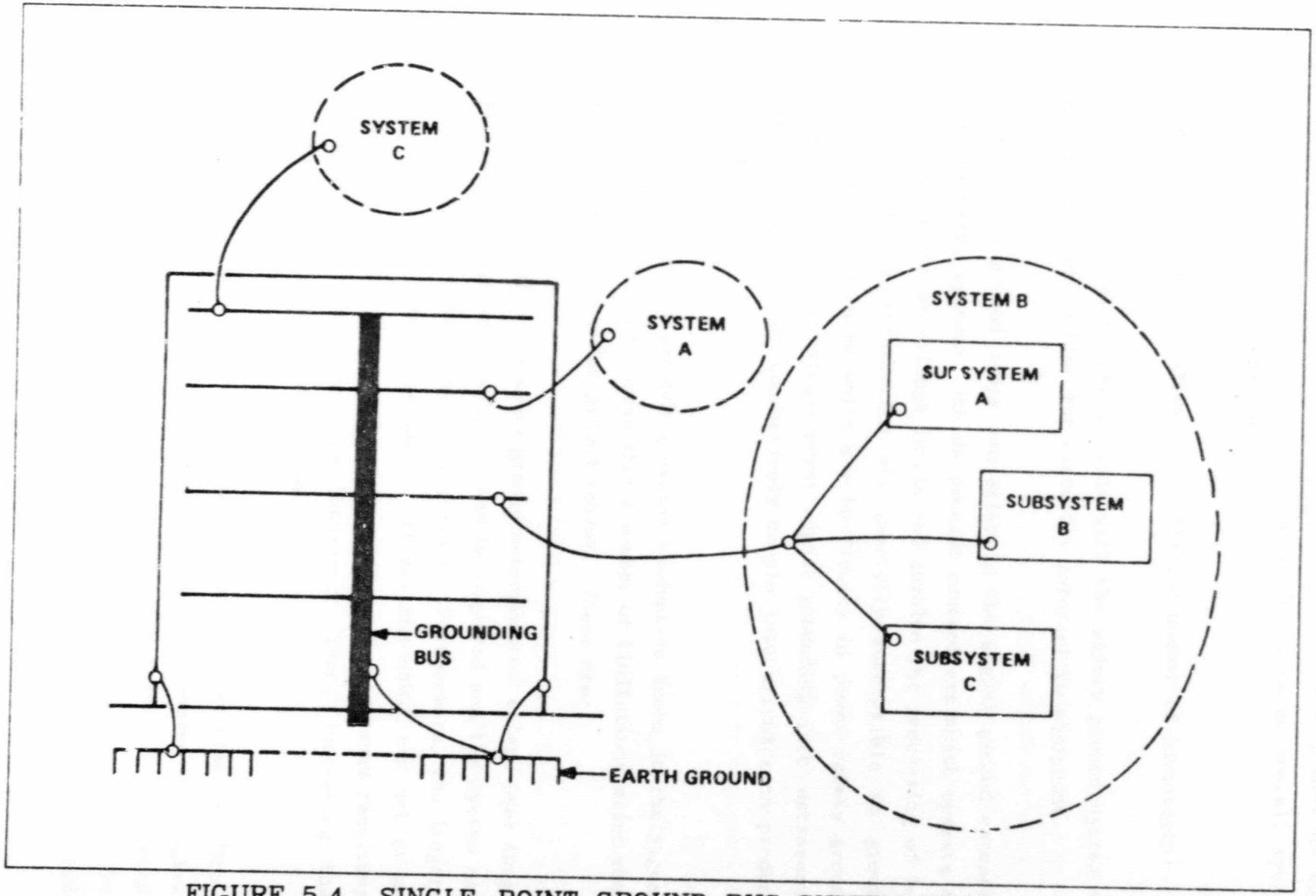


FIGURE 5.4 SINGLE–POINT GROUND BUS SYSTEM USING A COMMON BUS (SOURCE: WOODY[10])

To prevent interference and coupling, separate ground planes in each subsystem for structural grounds, signal grounds, shield grounds, and ac prime and secondary grounds are generally provided. These planes are then connected to the system ground point where they form an overall system potential reference (See Chapter 7).

The single-point ground configuration offers a number of advantages:

1. At least one connection is made with the safety ground system to provide fault protection for circuitry internal to equipment.

2. No conductive ground loops can exist in the signal ground network. In particular, systems such as process controllers which operate at very low current or voltage levels and involve the processing of low frequency analog information are generally susceptible to ground network noise currents which may be flowing in power safety ground systems. Thus, with single-point signal grounding such extraneous noise currents cannot conductively couple into circuits to produce interference.

Even though single-point grounding avoids conductive loops in the signal ground network, it should be noted that a number of limitations arise when implementing the single-point ground scheme. These are:

1. In complex installations where ground networks must extend over large distances, long ground conductors may be required and the system can get mechanically cumbersome and expensive. Furthermore, the lengths can be such as to cause resonance. If so, the cable can act as an efficient radiator of energy; or it can act as an antenna receiving radiated energy from some other sources. Thus, increasing the possibility of greater system noise.

2. The long conductors prevent the realisation of a satisfactory "low" impedance ground network at high frequencies because of higher self-impedance. At high frequencies, the inductance of the ground conductors increases the ground impedance and also contribute to large mutual coupling effects between the signal ground network and

power lines. Also, at higher frequencies the conductor impedance can get very high if the electrical length is longer than $\lambda/20$. (Equation 5.2). This could result in large potential differentials which could disrupt operations.

3. Another limitation is the possible existence of stray capacitances between ground and subsystems Such parasitic capacitances allows coupling at high frequences. These parasitic capacitive reactances represent low-impedance paths at high frequencies, while bond inductances result in higher impedances between subsystems and ground points. This leads to unequal potentials between subsystems and thus increasing the possibility of common-mode interference noise into these systems.

These points are appropriately illustrated graphically in Figure 5.5 which shows a degenerate single-point ground scheme. To realise the full advantages offered by single-point grounding, other interference reduction techniques must be supplemented such as the use of balanced circuits, opto couplers, twisted pair interfaces, and shielded cables. (See Section 5.8).

5.5 MULTIPLE-POINT GROUND SYSTEM

Another approach to signal grounding of systems is that of multiple-point grounding. This configuration intentionally provides as many shunt conductive paths as possible to various electronic systems or subsystems in the facility. Within each subsystem, equipment and circuit there exists multiple connections to a ground plane which in turn could be earthed for safety reasons. The ground plane might be an equipment chassis, or a ground wire that is carried throughout a system, or building structural members. Where large installations are involved the ground plane may take the form of a grid or network of interconnected conductors.

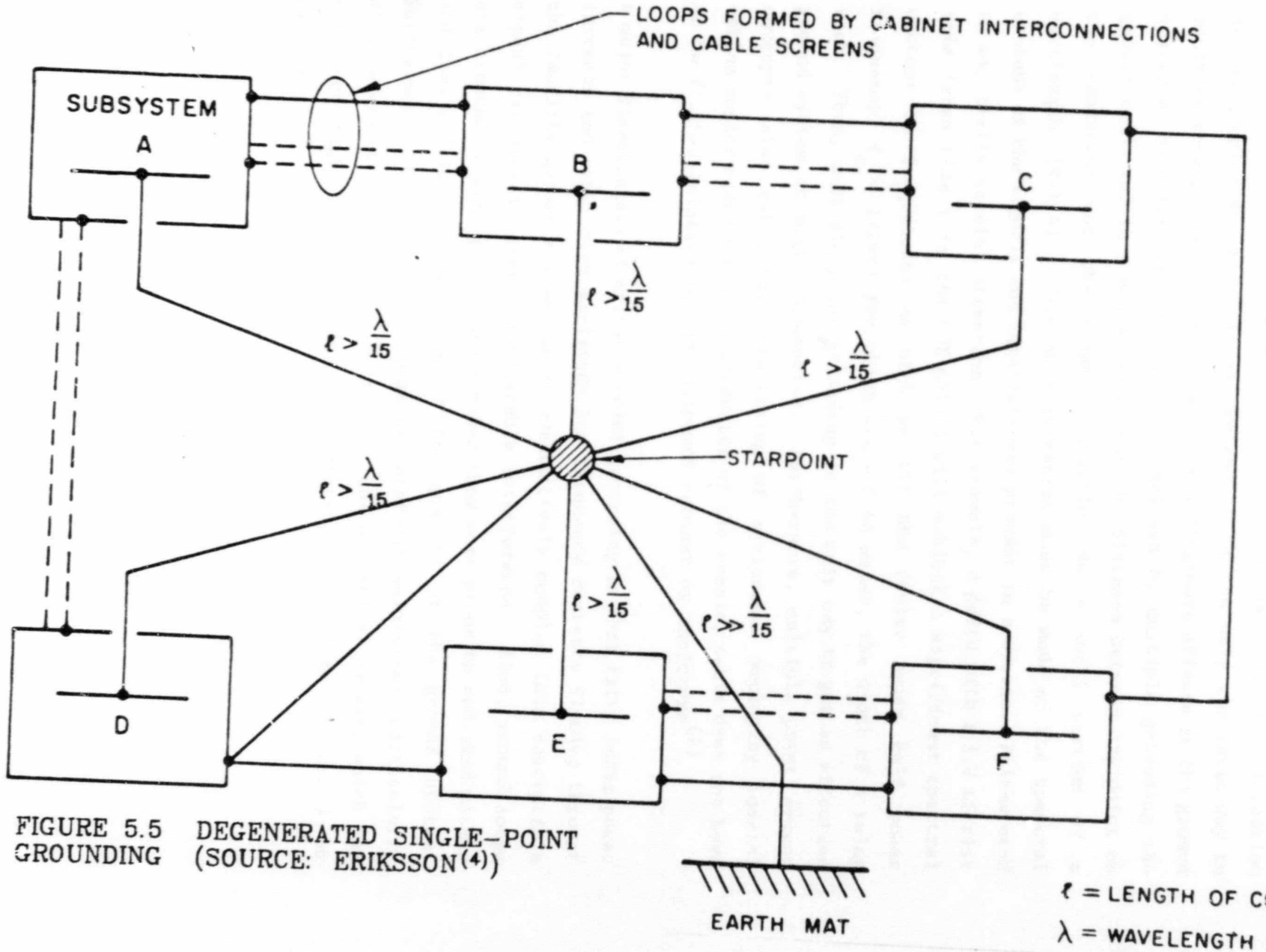


FIGURE 5.5 DEGENERATED SINGLE-POINT GROUNDING (SOURCE: ERIKSSON[4])

Thus, in any installation there are numerous parallel paths between any two points in a multiple-point ground network as shown in Figure 5.6.

The advantages of multiple-point grounding are that circuit construction inside complex equipment is easier and it is the only realistic way to minimise ground impedance and to avoid standing-wave effects in the ground system at high frequencies. This is realised by multiple grounding the ground conductor in a manner such that the distance between any point on the conductor and the ground connection is a small portion of a wavelength. ($\ell < \lambda/4$). Thus an examination must be made of the spectral content of the signals and interferences present in a system. Pulses need an especially careful attention. For example, a pulse with a 1.0 nS rise time (rise time τ to the 63% point) will exhibit a significant spectral content to frequencies as high as 157 MHz (pulse upper half power frequency, $f_u = 1/2\pi\tau$) for which $\lambda/4 = 0.48$ meter, the width of a relay rack. Thus, multiple point grounding is the only way to get an effective ground system at high frequencies. Furthermore, multiple point ground concepts also makes the interfacing of equipments employing coaxial cables easier since the outer conductor of the coaxial cable does not have to be floated relative to the equipment cabinet or enclosure[1].

A major disadvantage of multiple point grounding is that fifty hertz power currents and other high amplitude low frequency currents flowing through the facility ground system can be conductively coupled into susceptible signal circuits to create intolerable interference. Also, ground loops are created in many places which makes them more prone to radiated pickup and thus raising the question of the quality of the ground system. Furthermore, the ground plane must be carefully maintained, particularly with reference to corrosion, vibration, and mechanical damage, which can introduce high impedances into the ground system (See Chapter 9 on Bonding).

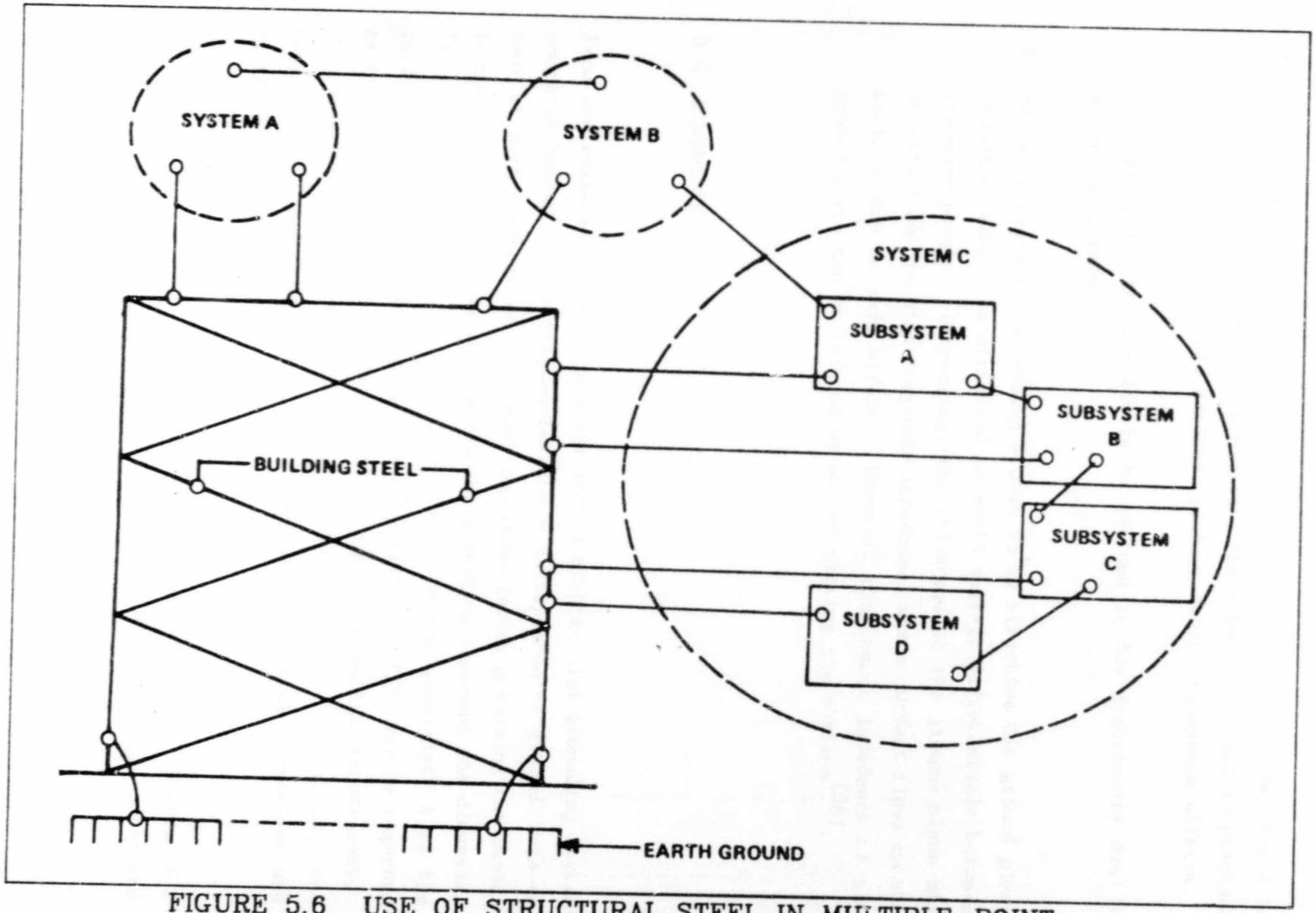


FIGURE 5.6 USE OF STRUCTURAL STEEL IN MULTIPLE-POINT GROUNDING (SOURCE: WOODY[10])

For multiple-point grounding to be affective the following points should be noted.

1. The connections between each circuit and the ground plane should be kept as short as possible to minimise their impedance, and to preclude development of possible antennae pickups and/or resonance effects.

2. Multiple-point grounds should be avoided at low frequencies due to ground loop problems.

3. For multiple-point grounding system to be effective the ground plane impedance should be minimised to avoid voltage differentials between grounded points. Increasing, the thickness of the ground plane has no effect on its high frequency impedance, since current flows on the surface due to skin effect. However, the common impedance of the ground plane can be reduced by silver plating the surface[28].

5.6 COMMENT

From preceding sections it is clear that a single-point grounding system operates better at low frequencies and a multiple-point ground behaves best at high frequencies. The most important factor governing the choice between single-point and multiple-point grounding concerns the dimension "ℓ" of Equations 5.1 to 5.6 in relation to the wavelength λ of the interfering signal. The region between $\ell=\lambda/10$ to $\ell=\lambda/20$ may be regarded as transitional between single and multiple-point grounding requirements. This means that for low frequency operation and small dimensions, use single-point grounding. For high frequency and large dimensions use multiple-point grounding.

Based on the separation criteria of $\ell=\lambda/20$ (Equation 5.2), Figure 5.7 may be used as a guideline indicating the border between single-point and multiple-point grounding situations.

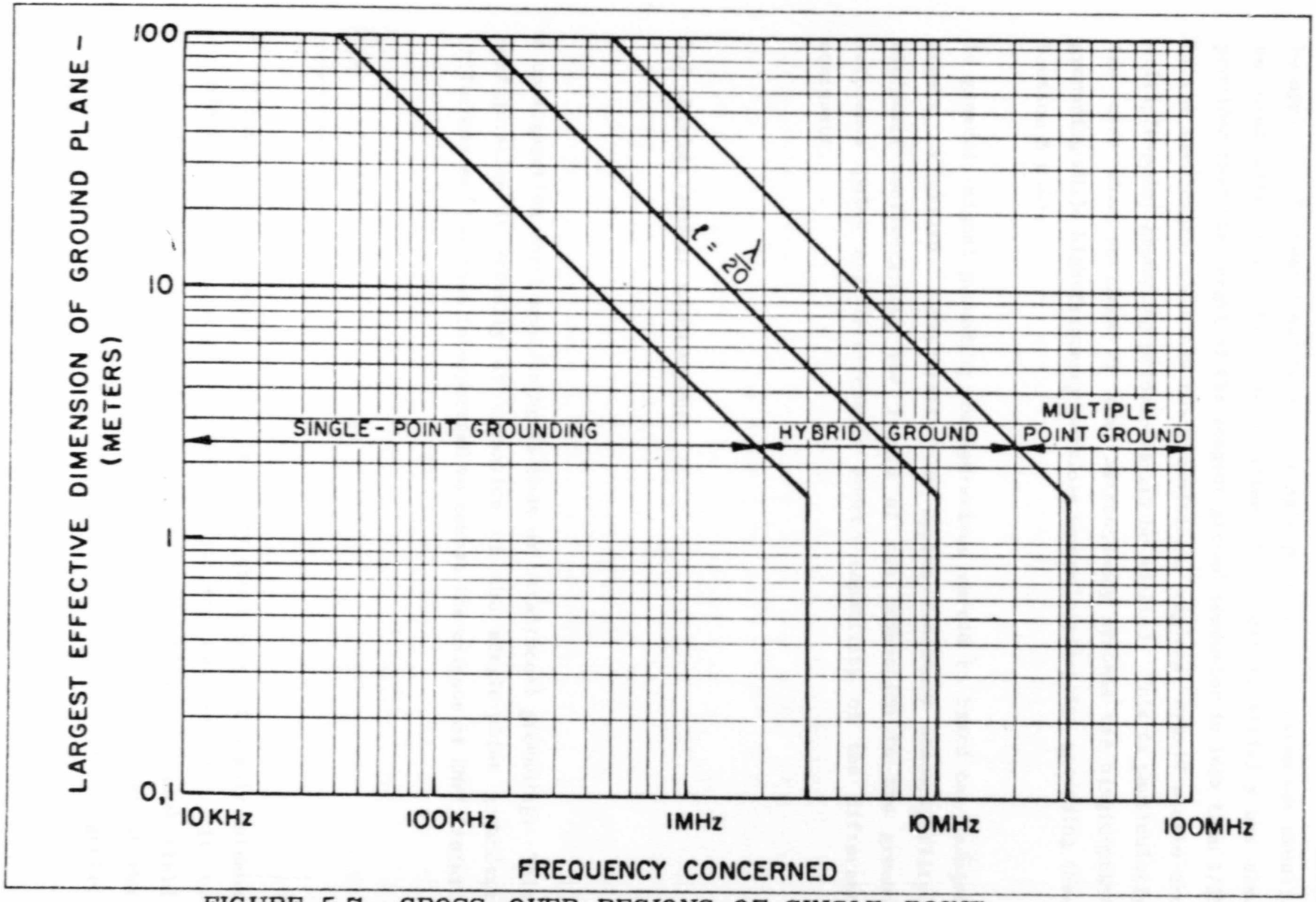


FIGURE 5.7 CROSS-OVER REGIONS OF SINGLE-POINT vs MULTIPLE-POINT GROUNDING (SOURCE: ERIKSSON[4])

Ott[28] suggests at frequencies below 1MHz, a single-point ground system should be applied and above 10 MHz a multiple-point ground system should be applied. Between 1 and 10 MHz a single-point ground system can usually be used after a careful consideration of circuit sensitivity and also provided that the length of the longest ground conductor is less than 1/15 of the wavelength. Also in the transitional regions, hybrid single and multiple-point grounding principles may be applied. This is particularly the case when portions of the low-frequency systems use single-point grounding while high-frequency portions use multiple-point grounding (See Section 5.8.4).

In general, signal grounding configurations should be based on, amongst others, a careful consideration of system frequency susceptibility, equipment configuration, the length of the connection to the ground reference point and interference source capability of the different equipment.

5.7 NODAL/ZONAL GROUNDING

A configuration worth mentioning is that of nodal/zonal grounding. This configuration is actually an extension of the single-point grounding philosophy and has been incorporated to combat the effects of EMP[2] fields.

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[2] Electromagnetic pulse - EMP - is a very short burst of highly intense electromagnetic energy produced by nuclear detonations. It is characterised by a very short (10 nSec) rise time, high peak field intensity (50 kV/m), and a short duration (250 nSec). Most of the energy is concentrated at frequencies below 10MHz, where magnetic field effects dominate.

This scheme prescribes the arrangement of grounding elements in a star or tree configuration in a manner that precludes the formation of ground loops susceptible to magnetic field interference. Figure 5.8 graphically illustrates this form of grounding scheme. This typically involves the organisation of classes of equipments and subsystems into nodes[9]. All of these entities should be connected together at a single point, a common denominator, called the station earth ground point (SEGP). Typically the primary node is the SEGP, a secondary node is an area feeder distribution point, and a quaternary node is a chassis distribution point. This hierarchy seldom goes beyond the point of a quaternary node.

An additional implementation is the concept of zoning or area allocation. This requires items to be grounded according to their noise generating or their susceptibility to noise characteristics. These areas, zones, or subsystems are each provided with a single grounding point, the secondary node. Tertiary nodes are racks or cabinet grounding distribution points, and quaternary nodes are chassis distribution points. This concept of zoning has been further developed by Vance[45] where systems are partitioned into "environmental zones". This idea is diagrammatical illustrated in Figure 5.9.

Basically different levels are created to separate the harsher lower level zonal area from the susceptible higher level zonal area. One and only one ground connection (nodal points) interconnects the zonal boundaries. No ground connection passes through a zonal boundary; it must terminate at the boundary and internal grounds to a zone begin at the boundary. Thus interference generated in a particular zonal area can be contained within that area. This concept is based on the postulate that any internal equipment must tolerate the ambient internal environment without upset or failure.

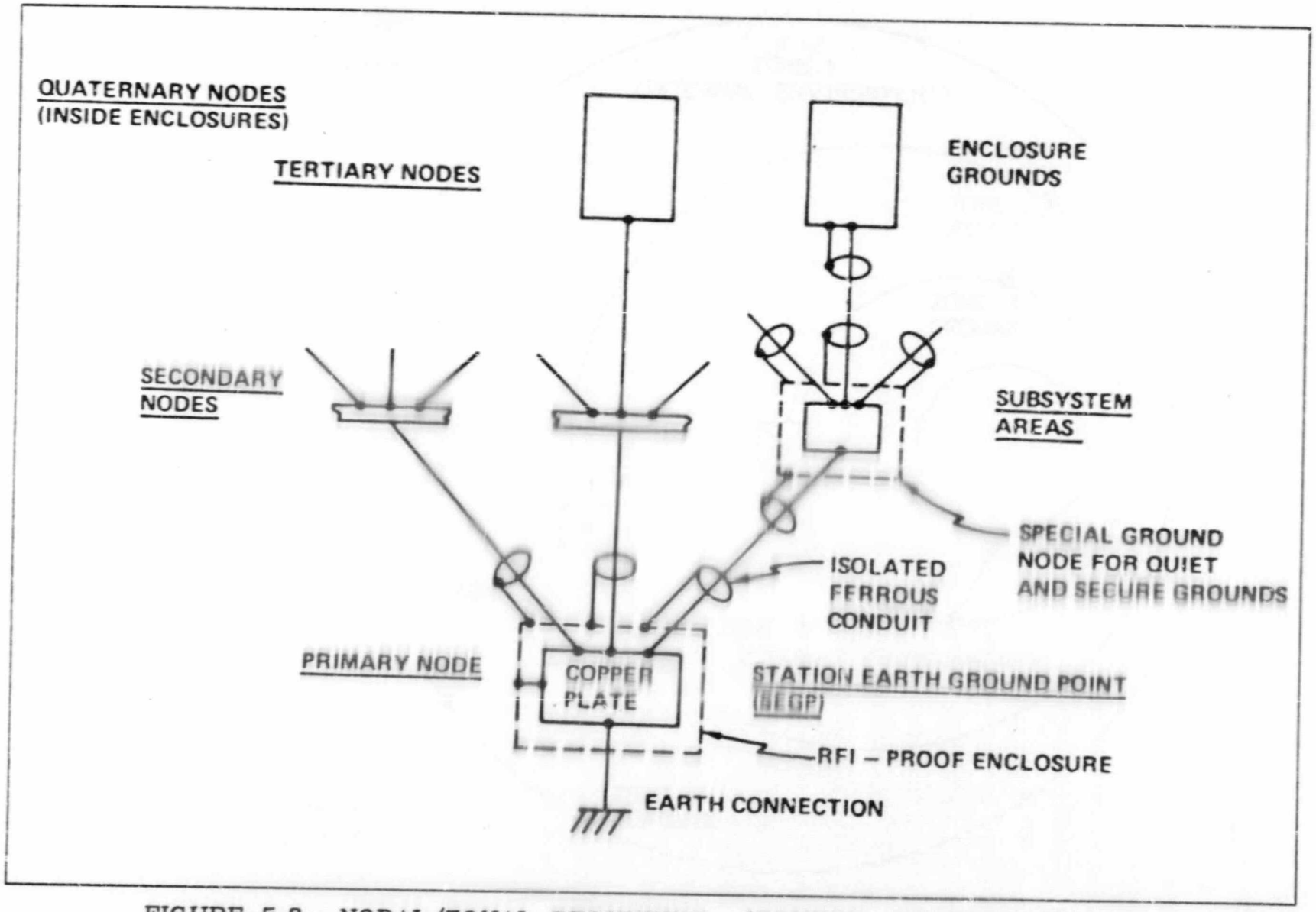


FIGURE 5.8 NODAL/ZONAL GROUNDING (SOURCE: CRAWFORD[9])

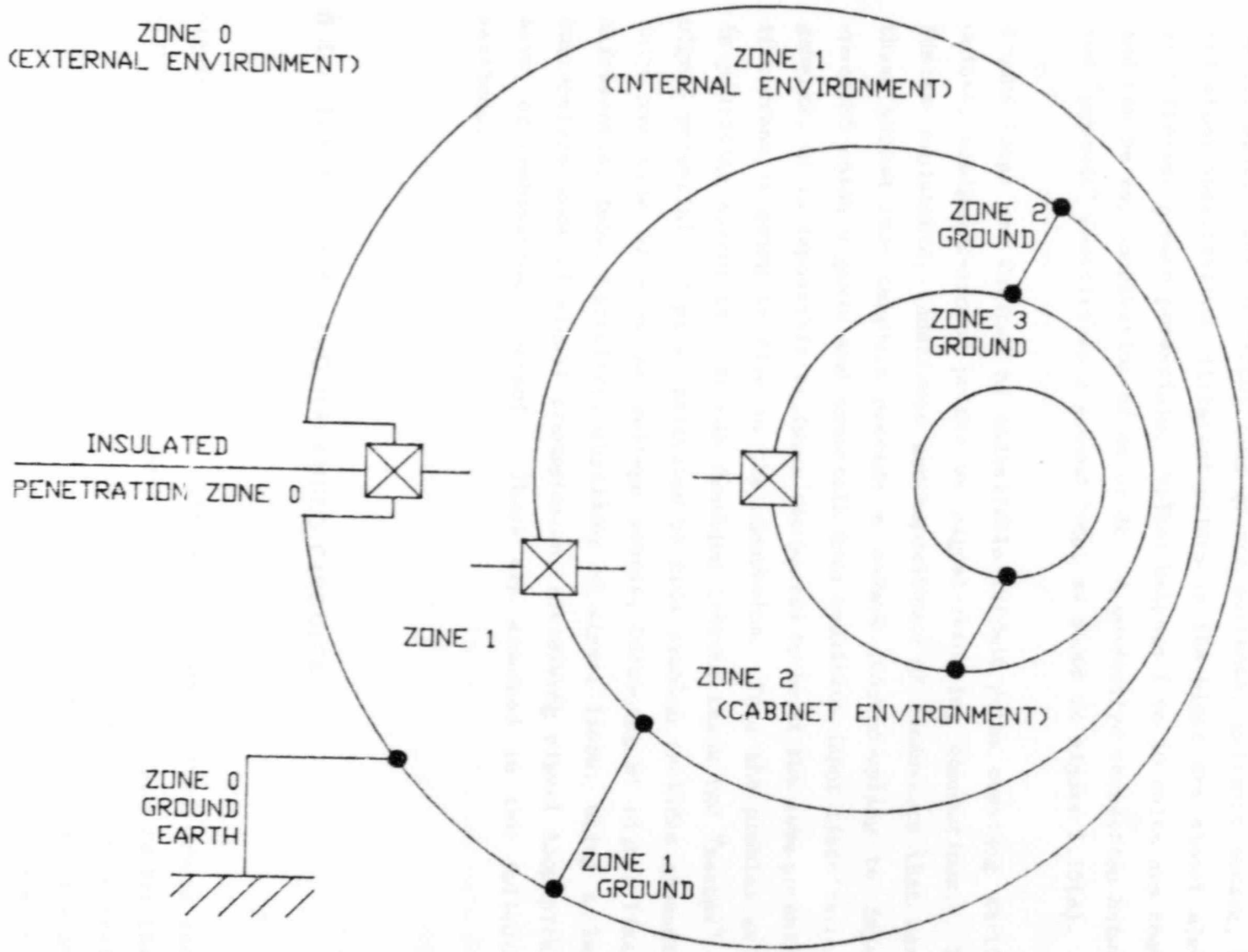


FIGURE 5.9 GROUNDING ZONES IN A COMPLEX FACILITY

5.8 BREAKING GROUND LOOPS

In an industrial plant, signals are frequently generated on one "grounded" environment and processed and terminated in a second "grounded" environment. Due to circulating ground currents, galvanic action, EMI and other interference, different points in the plant are almost always at different ground potentials. Values between 1 to 10 volts are common and can be any combination of ac or dc. A conductive connection between two "grounds" constitutes a ground loop, as shown in Figure 5.10(a).

Ground loops are defined as undesirable current paths coupling earthed points, equipment-ground points or signal-returning connections. The finite resistance, inductance and capacitance of conductors that carry these ground loop currents provide a common cross-coupling to inject unwanted noise signals and crosstalk into sensitive input circuits. In general, it is impossible to force two points to be at the same potential if current is going to flow in the connection. Thus the problem exist in providing circuitry that can function between these two "zeroes" of signal potential. Typical solutions to this problem includes grounding only one side of a noise voltage source, balancing of signal lines, differential input circuitry, shielding of signal lines, using a less susceptible mode of signal transmission, minimising signal loop pickup area, or combinations thereof. These are examined in the following sections.

5.8.1 DIFFERENTIAL AND BALANCED CIRCUITS

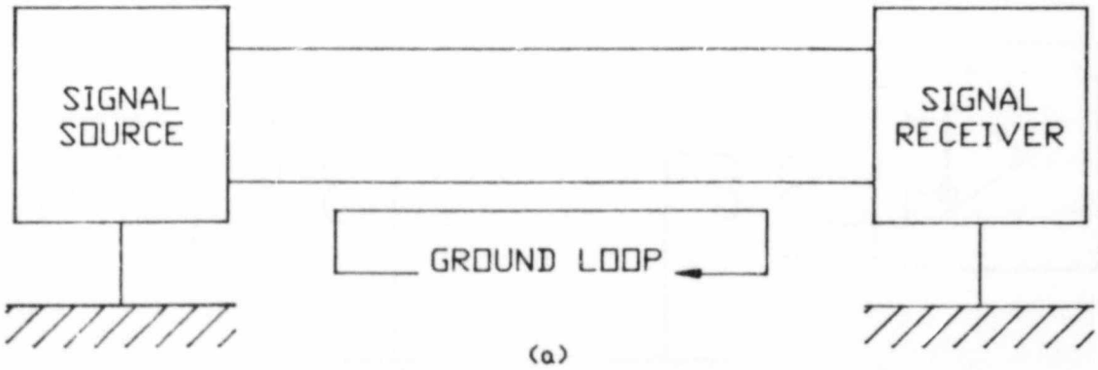
Figure 5.10(b) shows a balanced differential input circuit where each signal is a voltage differential between the two input points rather than with respect to ground. For the circuit to discriminate effectively against common-mode voltages and currents, perfect balance (resistive and reactive) between both legs of the circuit is required. The greater the degree of balance, the less the noise that will couple into the system.

Generally, a high degree of balance becomes more difficult with increasing frequency. Furthermore, the signal circuit should be grounded in one place only to avoid large common-mode voltages. However, it must be noted that there is no such thing as a completely differential input device and that the common-mode voltage on the input leads always has some effect on the devices' output - thus the need for a barrier or isolation in critical circuits.

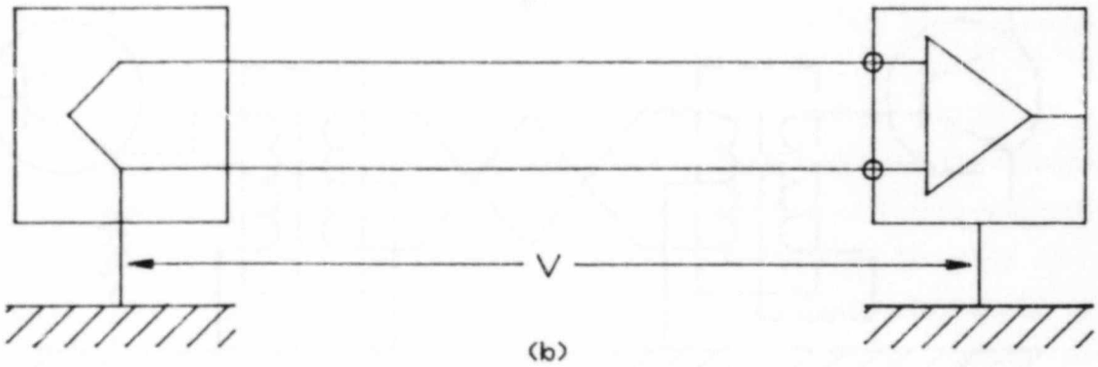
5.8.2 ISOLATION TRANSFORMERS

A common technique to break ground loops is by using isolation transformers, as shown in Figure 5.10(c). This method prevents circulating common-mode currents since the transformer (ideally) should not process common-mode signals. In some circuits, however, direct current or very low frequency continuity is required between the two circuits and an isolation transformer is not practical. Under these conditions a transformer can be used as a longitudinal choke (also called a neutralising transformer), as shown in Figure 5.10(d). A transformer connected in this manner presents a low impedance to the signal current and allows dc coupling.

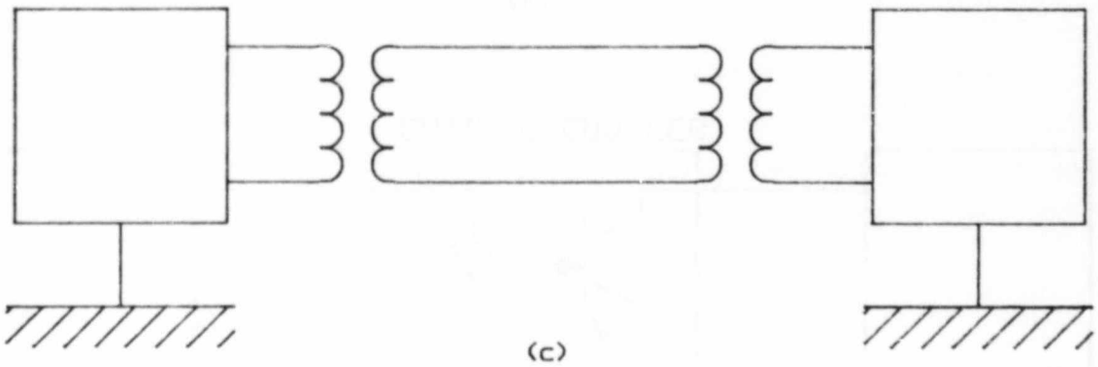
In Figure 5.10(e), the driver and receiver are balanced (they talk with + and - signals referred to 0 volt). Balanced operation between circuits can be achieved with balanced-to-unbalanced (BALUN) transformers, as shown in Figure 5.10(f). The BALUN has a shield to reduce the primary to secondary parasitic coupling, which has been grounded. Effective operations over broad frequency ranges can be achieved with adequate transformer coils and proper windings. The twisted pair, in addition, is recommended to avoid field pick-up by the pair itself.



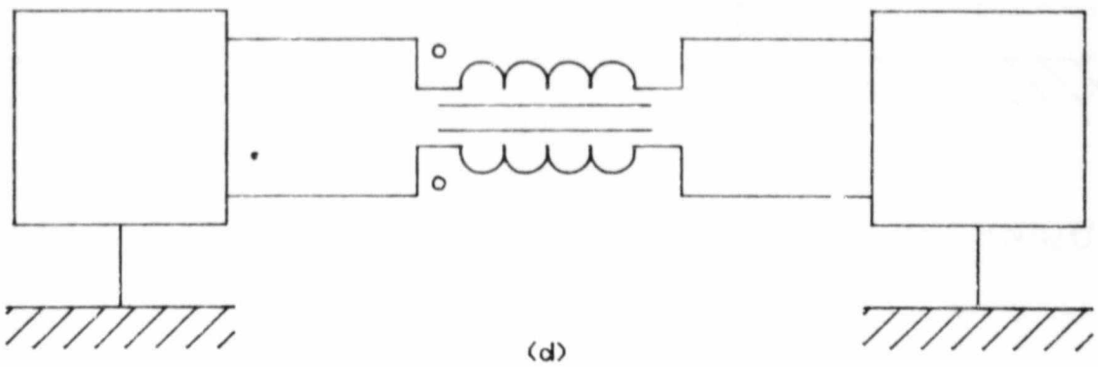
(a)



(b)



(c)



(d)

Author Ambelal Dependra
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