

https://dspace.org/

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

**Ambelal, Dependra**

**2014-09-12**
http://hdl.handle.net/10539/15535

Downloaded from a DSpace repository. https://dspace.org/

$$F(t) = \frac{ET_0}{T} + \sum_{n=1}^{\infty} \frac{2E}{n\pi} \sin\frac{n\omega T_0}{2} \cos(n\omega t) \qquad (2.2)$$

$$F(t) = \frac{ET_0}{T} + \sum_{n=1}^{\infty} S(\omega,n) \cos(n\omega t) \qquad (2.3)$$

where $\omega = 2\pi/T$

The plot of $S(\omega,n)$ as a function of frequency $f$ is the spectrum of the function F(t) in the frequency domain. Broadband digital and analog circuits are sensitive to interference over a much wider spectrum than tuned receiver circuits. Furthermore, digital and analog circuits are very often close to other high-speed (fast pulse) devices such as printers, teletypewriters and the like . Generally, industrial broadband interference fields are 50 to 60 dBs stronger than those inside a communications centre. Thus, clearly the 100:1 sensitivity advantage of digital circuitry can be wiped out by a 1000:1 increase in environmental interference level.

### 2.4.3 TRANSIENT EMI

In many cases, electrical transients are the main cause of control system malfunction, either destructive or nondestructive. These transients have irregular waveshape and they occur at random. Three illustrations of such electrical transients are shown in Figure 2.15. Figure 2.15(a) illustrates a rectangular pulse which is sometimes used as an approximation of actual transients for the sake of simplicity in analytical work. Figure 2.15(b) is a standard transient voltage specified in military specifications. The duration of the first loop is 10 μs. The front time is not specified.

Figure 2.15(c) is an industry standard transient voltage. It has a front time of 1,2 μs and the time to half value of 50 μs and is designated as

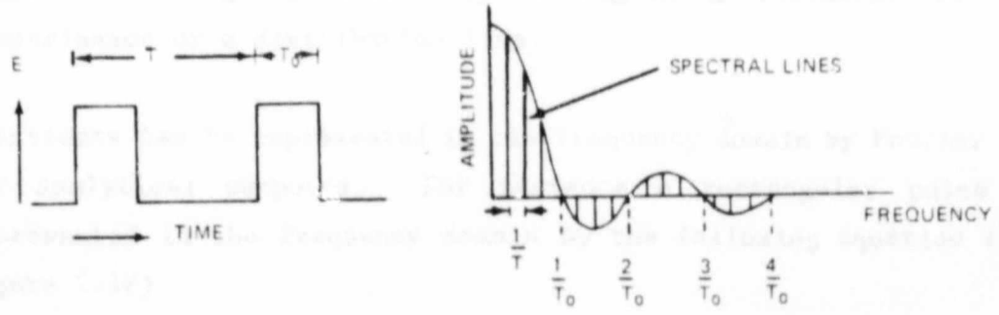



FIGURE 2.14 SPECTRUM OF RECTANGULAR PULSES (IEEE 518–1982[30])

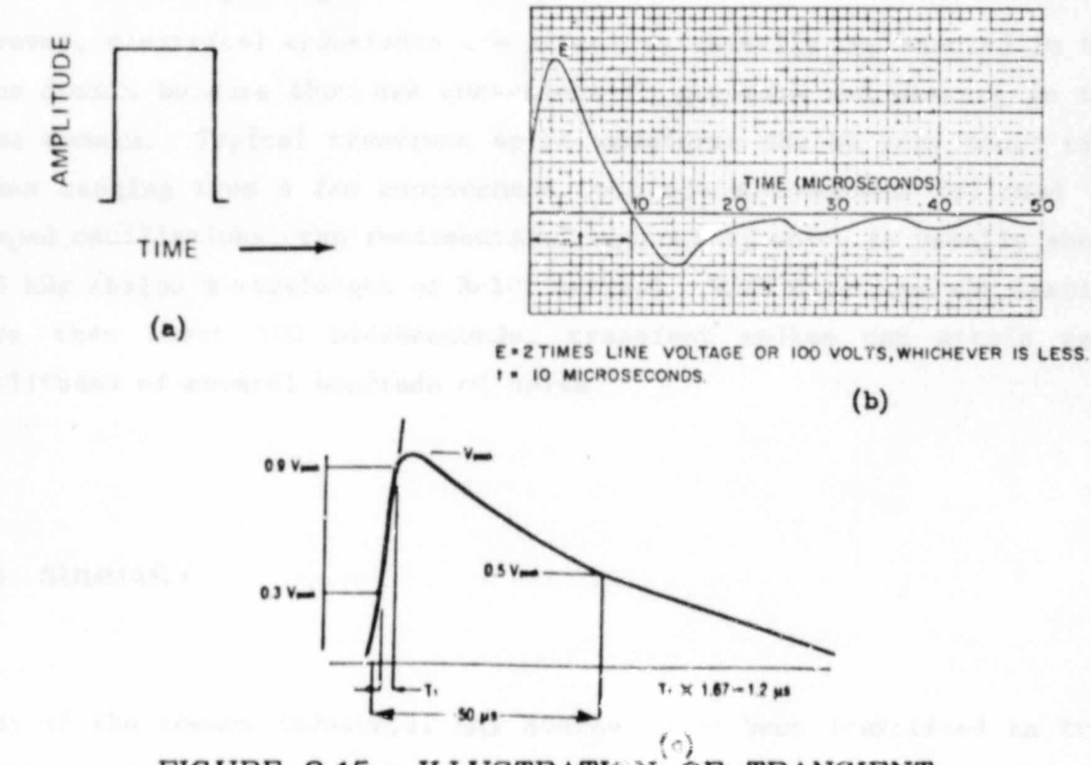



FIGURE 2.15 ILLUSTRATION OF TRANSIENT EMI (SOURCE: IEEE 518–1982[30])

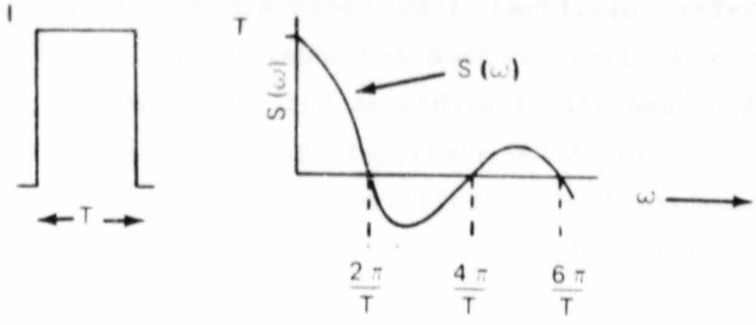



FIGURE 2.16 SPECTRAL DENSITY OF RECTANGULAR PULSES (SOURCE: IEEE 518–1982[30])

the 1,2/50 μs wave[39]. This wave shape is an approximation of the transient voltage generated by a lightning discharge on a power transmission or a distribution line.

Transients can be represented in the frequency domain by Fourier Integral for analytical purposes. For instance a rectangular pulse can be represented in the frequency domain by the following equation (Refer to Figure 2.16)

$$S(\omega) = \frac{2}{\omega} \sin \frac{\omega T}{2} \qquad (2.4)$$

However, electrical transients are almost universally represented in the time domain because they are convenient to generate and measure in the time domain. Typical transient spike waveforms can be very short rise times ranging from a few nanoseconds upto one microsecond followed by damped oscillations, the fundamental frequency of which is usually above 100 kHz (below a wavelength of $3\times10^3$ metres). With durations not lasting more than about 100 microseconds, transient spikes can attain peak amplitudes of several hundreds of volts.

## 2.5 SUMMARY

Some of the common industrial EMI sources have been identified in this chapter; the means by which they couple into different circuits and the victim receptor elements have been identified. Also, the nature of EMI has been illustrated and discussed with particular reference to the industrial situation. Interference has been categorised according to its spectral extent, or bandwidth, according to its amplitude behaviour, be it continuous or transient. An important point which surfaces is that in any EMI control programme identification and characterisation of disturbing signals is an essential and desirable phase so that proper grounding techniques can be devised.

# CHAPTER 3

# 3.0 CHARACTERISTICS OF GROUND CIRCUITS

## 3.1 INTRODUCTION

The term grounding has already been defined to mean the connection of something to an unipotential array of metal (or earth). When installed for safety or power fault hazards, the requirements are clear and there is substantial agreement on the means of implementation. When installed to prevent interference, the requirements are unclear, and experience has shown that many confusing and contradictory problems can arise in practice.

Many of the problems of grounding began when the early telegraphers sought to save copper by using the ground as the common return wire. However, as systems became more complex, the ground (or an artificial metal ground plane) was less used as a return-wire unit, and "two-wire" circuits become more common. Unfortunately, the myth of the unipotential ground conductor or plane developed, not only as a concept but also as a desirable practical aim. The fallacy of such a view is simply due to the fact that a ground circuit conductor possesses resistance, inductance and capacitance and thus no two points on a common conductor can be at a common stable potential at all frequencies.

In this chapter the characteristics of ground circuit conductors are examined by considering the impedance due to the resistive (R), inductive (L) and capacitive (C) components. The components due to skin and proximity effects are also examined. Considering these characteristics, a simplified projection of the frequency dependent behaviour of a grounding circuit is made, and general conclusions are drawn for different types of conductors. The problem of establishing a good common ground or reference plane as return paths for complex networks is described. Ground plane or circuit resonant behaviour is analysed and relationships developed to illustrate the non-ideal, high-frequency behaviour of grounding conductors.

## 3.2 THE GROUND INTERFERENCE PROBLEM

Practical electronic circuits typically are collections of several source-load combinations, such as:

- one source driving multiple loads, or
- separate source-load pairs connected to a common ground plane.

Throughout this study, frequent reference is made to this source-load combination, as shown in Figure 3.1.

Figure 3.1 shows a load $Z_L$ driven by a signal generator, with one side of the load and generator grounded at point G by a common conductor. In this idealised situation all lines are considered to be pure conductors, and any point on the grounded conductor is assumed to serve equally well as a common reference.

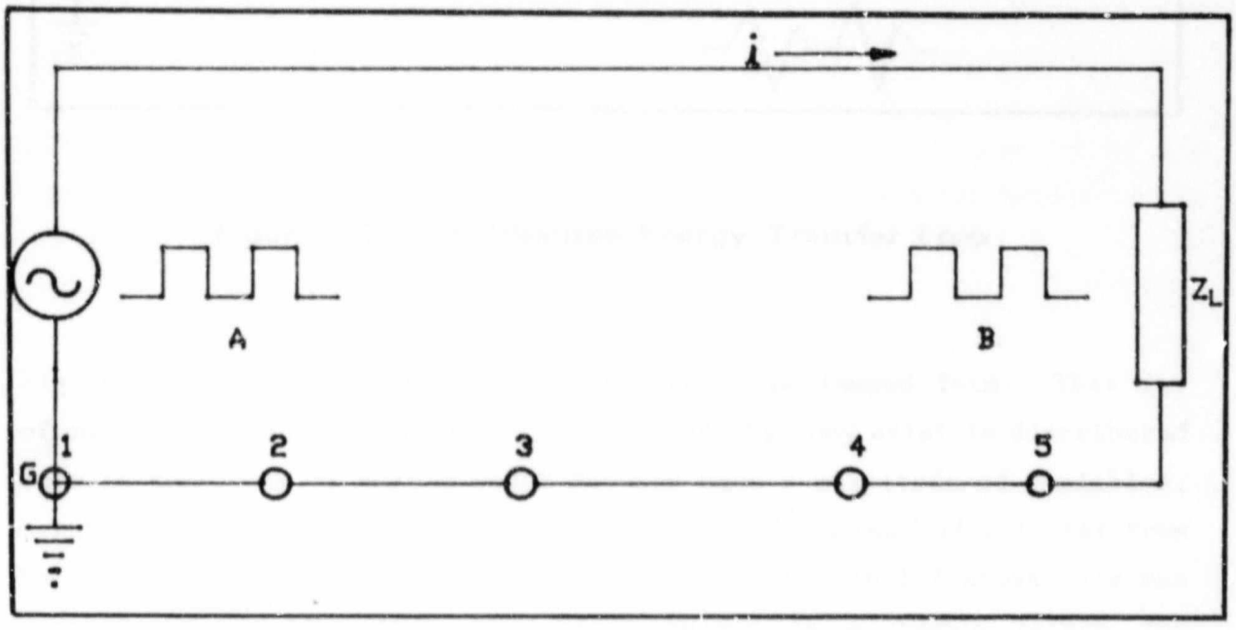



Figure 3.1 Idealised Energy Transfer Loop

But real circuits do not behave like the idealised circuit of Figure 3.1. Figure 3.2 shows the same simple circuit in its more realistic form with

all of the extraneous properties inherent in conductors. These include inductance L, skin-effect resistance $R_{skin}$, capacitance C, transformer coupling T, and dc resistance $R_{dc}$. Although the existence of these extraneous properties is well known, their effects are generally assumed to be negligible. This is far from being the case, as will be illustrated in this, and the following chapters.

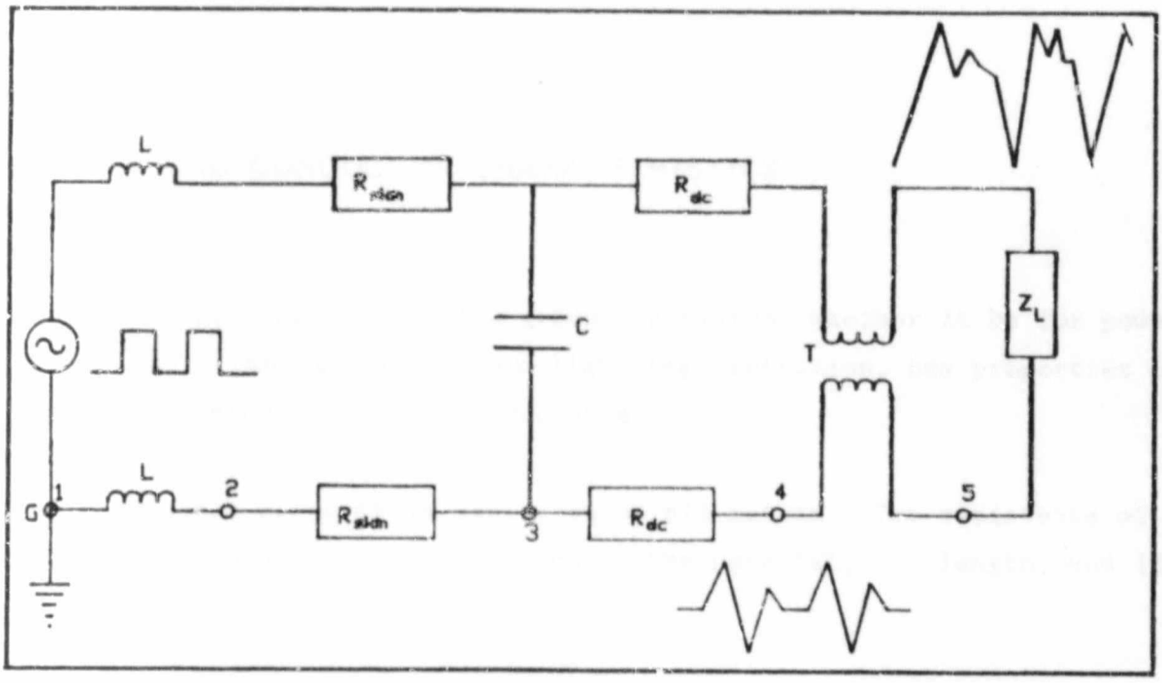



**Figure 3.2 Non-Idealised Energy Transfer Loop**

Figure 3.2 shows these extraneous properties in lumped form. This is, of course, an oversimplification, for in reality they exist in distributed form in some complex manner which depends upon a multitude of variables. Figure 3.2 does make the point, however, that the ground line is far from being a pure, simple conductor. Furthermore, Figure 3.2 shows only one circuit, in practice this line often serves as a common return for hundreds of circuits, each adding in its own particular brand of transient currents, and each reacting with the stray impedances of the extraneous conductor properties to generate a transient voltage.

It must be noted that this discussion and subsequent discussions of grounds is not limited to wires and cables. Instead, it is meant to cover the entire physical environment in which the control system operates, and includes structural members of the building, pipes, machine frames, metal housings and cabinets, and even the earth. All such items, which are generally considered to be electrical equipment, are in fact strong sources of interference noise.

## 3.3 GROUND CONDUCTOR CHARACTERISTICS

Every element (conductor) of a grounding system, whether it be for power grounding, signal grounding, or lightning protection, has properties of resistance, capacitance and inductance.

The resistance property is exhibited by all metals. The resistance of a ground path conductor is a function of the material, its length, and its cross-sectional area.

The capacitance associated with a ground conductor is determined by its geometric shape, its proximity to other conductors, and the nature of the intervening dielectric.

The inductance is a function of its size, geometry length and, to a limited extent, the relative permeability of the metal.

The following sections examines these characteristics in more detail.[1]

---

[1] Substantial portions of the succeeding sections have been sourced from Eriksson et al[4], Terman[6], ITT Handbook[14].

### 3.3.1 THE DC RESISTANCE

In the case of a rectangular conductor of length $\ell$(m), cross-sectional area A($m^2$) and resistivity $\rho$ ohm-meter, the dc resistance, $R_{dc}$, is given by:

$$R_{dc} = \frac{\rho \ell}{A} \tag{3.1}$$

For circular conductors

$$R_{dc} = \frac{\rho \ell}{\pi r^2} \tag{3.2}$$

For straps

$$R_{dc} = \frac{\rho \ell}{(w \times t)} \tag{3.3}$$

where

r = cross-sectional radius of the wire in meters

w = width in meters.

t = thickness in meters

Resistivity values in ohm-cm of common metals include

$\rho_c = 1{,}724 \times 10^{-6}$ ohm-cm for copper

$\rho_a = 2{,}69 \times 10^{-6}$ ohm-cm for aluminium

$\rho_s = 10{,}142 \times 10^{-6}$ ohm-cm for cold rolled steel

$\rho_b = 6{,}37 \times 10^{-6}$ ohm-cm for brass

$\rho_{sl} = 1{,}62 \times 10^{-6}$ ohm-cm for silver

Table 3.1 lists the per unit length resistance, $R/\ell$, of representative grounding/bonding straps as calculated from Equation 3.3.

| Strap Size | Unit Length in μΩ/cm | | |
|---|---|---|---|
| (cm) | Copper | Aluminium | Steel |
| 0.05×0.5 | 68.96 | 104.80 | 405.67 |
| 0.05×1.0 | 34.48 | 52.40 | 202.84 |
| 0.05×2.0 | 17.24 | 26.20 | 101.42 |
| 0.05×5.0 | 6.90 | 10.48 | 40.57 |
| 0.05×10.0 | 3.45 | 5.24 | 20.28 |
| 0.10×0.5 | 34.48 | 52.40 | 202.84 |
| 0.10×1.0 | 17.24 | 26.20 | 101.42 |
| 0.10×2.0 | 8.62 | 13.10 | 50.71 |
| 0.10×5.0 | 3.45 | 5.24 | 20.28 |
| 0.10×10.0 | 1.72 | 2.62 | 10.14 |

**Table 3.1 Per Unit Length Resistance of Grounding Straps**

An examination of the parameters of Equation 3.1 reveals that a low dc resistance can be obtained by using a short conductor with a low resistivity and a large cross-sectional area. However, the actual ratio between the width and thickness is of less importance at low frequencies. Furthermore, the resistance also varies with temperature. For temperature ranges that are not too great, this variation may be represented approximately by the following equation

$$R_T = R_0[1 + \alpha(T-T_0)] \tag{3.4}$$

where

$R_T$ = resistance at temperature T

$R_0$ = resistance at temperature $T_0$, usually 20°C

$\alpha$ = temperature coefficient of resistivity

$\alpha_c$ = 0,00393 for copper

$\alpha_a$ = 0,0039 for aluminium

### 3.3.2 INDUCTANCE

As the current flowing through the conductor increases in frequency, the inductive reactance of the wire will increase the impedance. The conductor begins to look like a L-R circuit instead of just a resistor. The inductance for a rectangular conductor at low frequencies can be calculated from the following equation

$$L = 2\times10^{-4}\ell\left[2.303\ \log\frac{2\ell}{w+t} + 0.5 + 0.2235\frac{w+t}{\ell}\right]\ \mu H \qquad (3.5)$$

where

L = inductance of the conductor in μH

w = width of the conductor in mm

t = thickness of the conductor in mm

ℓ = length in mm

For circular wire, Equation 3.5 reduces to

$$L = 2\times10^{-4}\ell\left[2.303\ \log\frac{4\ell}{d} - 1 + \frac{\mu}{4}\right]\ \mu H \qquad (3.6)$$

for l=1000d

where

d = diameter of the wire in mm

μ = permeability of conductor material

Generally, Equation 3.6 can be approximated for paramagnetic material such as copper and aluminium by

$$L = 2\times10^{-4}\ell\left[2.303\ \log\frac{4\ell}{d} - 0.75\right]\ \mu H \qquad (3.7)$$

Figure 3.3 shows a plot of inductance of various wire lengths and diameters at high frequencies. Observe that the inductance decreases with increasing diameter and increases with increasing length.

The impedance of a copper wire can be obtained by converting Equation 3.7 to inductive reactance ($X_L = 2\pi fL$) and adding vectorially the resistance

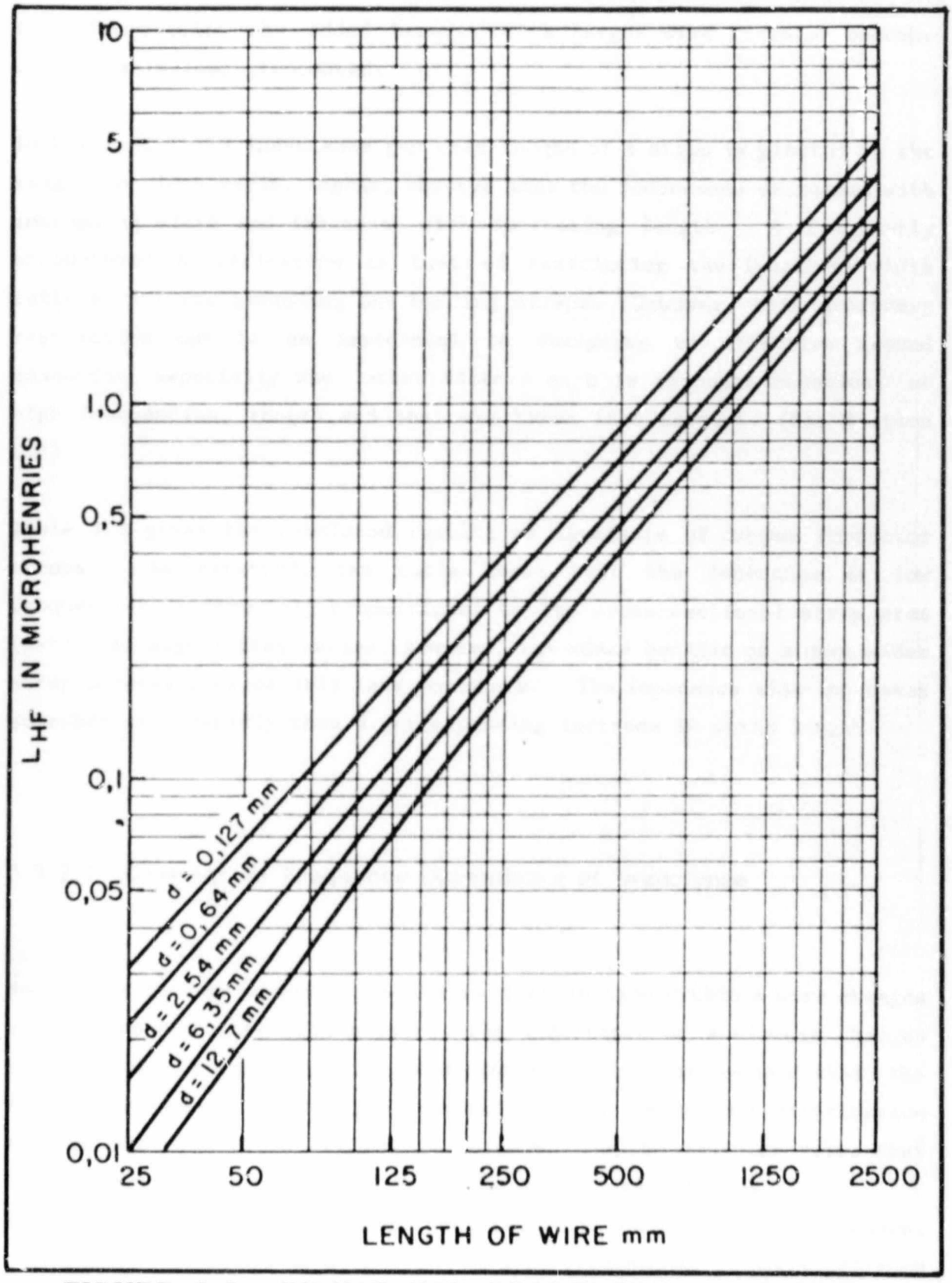



FIGURE 3.3 INDUCTANCE PROPERTIES OF ROUND WIRE AT HIGH FREQUENCIES (SOURCE: ERIKSSON[4])

of Equation 3.3. This impedance is tabulated in Table 3.2 for different gauge copper wires. Observe that the impedance at low frequencies is inversely proportional to the wire area (diameter squared). However, at high frequencies the added benefit of a larger wire diameter becomes considerably less pronounced.

In Figure 3.4 the inductance per unit length of a strap is plotted vs the length to width ratio. Again, observe that the inductance decreases with increasing width and increases with increasing length. A frequently encountered specification is that of restricting the length-to-width ratio to 5:1 for grounding and bonding straps. However, this arbitrary restriction can be an impediment to designing an effective ground conductor, especially when other factors such as resonant behaviour at high frequencies, length and cost are taken into account. (See Section 3.7)

Table 3.3 gives the tabulated results of impedance of copper conductor straps. As expected, the table shows that the impedance at low frequencies is inversely proportional to the cross-sectional strap area (w×t). At higher frequencies, however, the added benefit of a much wider strap becomes considerably less pronounced. The impedance also increases somewhat more rapidly than a corresponding increase in strap length.

### 3.3.2.1 Comment on Frequency Dependence of Inductance

Because of the way in which the current distribution within a wire changes with frequency (see skin effect), the inductance of a circuit changes somewhat with frequency. Of most interest are the values that the inductance assumes at very low frequencies when the current distribution through the wire cross section is uniform, and the limiting value that the inductance assumes as the frequency approaches infinity.
This latter inductance is always less than the low-frequency inductance, since the redistribution of current at high frequencies is always of such

| | AWG#=2, D=6.54mm | | | | AWG#=10, D=2.59mm | | | | AWG#=22, D=.64 mm | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FREQ. | t=1cm | t=10cm | t=1m | t=10m | t=1cm | t=10cm | t=1m | t=10m | t=1cm | t=10cm | t=1m | t=10m |
| 10Hz | 5.13μ | 51.4μ | 517μ | 5.22m | 32.7μ | 327μ | 3.28m | 32.8m | 529μ | 5.29m | 52.9m | 529m |
| 20Hz | 5.14μ | 52.0μ | 532μ | 5.50m | 32.7μ | 328μ | 3.28m | 32.8m | 529μ | 5.29m | 53.0m | 530m |
| 30Hz | 5.15μ | 52.8μ | 555μ | 5.94m | 32.8μ | 328μ | 3.28m | 32.9m | 529μ | 5.30m | 53.0m | 530m |
| 50Hz | 5.20μ | 55.5μ | 624μ | 7.16m | 32.8μ | 329μ | 3.30m | 33.2m | 530μ | 5.30m | 53.0m | 530m |
| 70Hz | 5.27μ | 59.3μ | 715μ | 8.68m | 32.8μ | 330μ | 3.33m | 33.7m | 530μ | 5.30m | 53.0m | 530m |
| 100Hz | 5.41μ | 66.7μ | 877μ | 11.2m | 32.9μ | 332μ | 3.38m | 34.6m | 530μ | 5.30m | 53.0m | 530m |
| 200Hz | 6.20μ | 99.5μ | 1.51m | 20.6m | 33.2μ | 345μ | 3.67m | 39.6m | 530μ | 5.30m | 53.0m | 530m |
| 300Hz | 7.32μ | 137μ | 2.19m | 30.4m | 33.7μ | 365μ | 4.11m | 46.9m | 530μ | 5.30m | 53.0m | 531m |
| 500Hz | 10.1μ | 219μ | 3.59m | 50.3m | 35.3μ | 425μ | 5.28m | 64.8m | 530μ | 5.31m | 53.2m | 533m |
| 700Hz | 13.2μ | 303μ | 5.01m | 70.2m | 37.7μ | 500μ | 6.66m | 84.8m | 530μ | 5.32m | 53.4m | 537m |
| 1kHz | 18.1μ | 429μ | 7.14m | 100m | 42.2μ | 632μ | 8.91m | 116m | 531μ | 5.34m | 53.9m | 545m |
| 2kHz | 35.2μ | 855μ | 14.2m | 200m | 62.5μ | 1.13m | 16.8m | 225m | 536μ | 5.48m | 56.6m | 589m |
| 3kHz | 57.5μ | 1.28m | 21.3m | 300m | 86.3μ | 1.65m | 25.0m | 336m | 545μ | 5.71m | 60.9m | 656m |
| 5kHz | 87.3μ | 2.13m | 35.6m | 500m | 137μ | 2.72m | 41.5m | 559m | 571μ | 6.39m | 72.9m | 835m |
| 7kHz | 122μ | 2.98m | 49.8m | 700m | 189μ | 3.79m | 58.1m | 783m | 609μ | 7.28m | 87.9m | 1.04Ω |
| 10kHz | 174μ | 4.26m | 71.2m | 1.00Ω | 268μ | 5.41m | 82.9m | 1.11Ω | 681μ | 8.89m | 113m | 1.39Ω |
| 20kHz | 348μ | 8.53m | 142m | 2.00Ω | 533μ | 10.8m | 165m | 2.23Ω | 1.00m | 15.2m | 207m | 2.63Ω |
| 30kHz | 523μ | 12.8m | 213m | 3.00Ω | 799μ | 16.2m | 248m | 3.35Ω | 1.39m | 22.0m | 305m | 3.91Ω |
| 50kHz | 871μ | 21.3m | 356m | 5.00Ω | 1.33m | 27.0m | 414m | 5.58Ω | 2.20m | 36.1m | 504m | 6.48Ω |
| 70kHz | 1.22m | 29.8m | 498m | 7.00Ω | 1.86m | 37.8m | 580m | 7.82Ω | 3.04m | 50.2m | 704m | 9.06Ω |
| 100kHz | 1.74m | 42.6m | 712m | 10.0Ω | 2.66m | 54.0m | 828m | 11.1Ω | 4.31m | 71.6m | 1.00Ω | 12.9Ω |
| 200kHz | 3.48m | 85.3m | 1.42Ω | 20.0Ω | 5.32m | 108m | 1.65Ω | 22.3Ω | 8.59m | 142m | 2.00Ω | 25.8Ω |
| 300kHz | 5.23m | 128m | 2.13Ω | 30.0Ω | 7.98m | 162m | 2.48Ω | 33.5Ω | 12.8m | 214m | 3.01Ω | 38.7Ω |
| 500kHz | 8.71m | 213m | 3.56Ω | 50.0Ω | 13.3m | 270m | 4.14Ω | 55.8Ω | 21.4m | 357m | 5.01Ω | 64.6Ω |
| 700kHz | 12.2m | 298m | 4.98Ω | 70.0Ω | 18.6m | 378m | 5.80Ω | 78.2Ω | 30.0m | 500m | 7.02Ω | 90.4Ω |
| 1MHz | 17.4m | 426m | 7.12Ω | 100Ω | 26.6m | 540m | 8.28Ω | 111Ω | 42.8m | 714m | 10.0Ω | 129Ω |
| 2MHz | 34.8m | 853m | 14.2Ω | 200Ω | 53.2m | 1.08Ω | 16.5Ω | 223Ω | 85.7m | 1.42Ω | 20.0Ω | 258Ω |
| 3MHz | 52.3m | 1.28Ω | 21.3Ω | 300Ω | 79.8m | 1.62Ω | 24.8Ω | 335Ω | 128m | 2.14Ω | 30.1Ω | 387Ω |
| 5MHz | 87.1m | 2.13Ω | 35.6Ω | 500Ω | 133m | 2.70Ω | 41.4Ω | 558Ω | 214m | 3.57Ω | 50.1Ω | 646Ω |
| 7MHz | 122m | 2.98Ω | 49.8Ω | 700Ω | 186m | 3.78Ω | 58.0Ω | 782Ω | 300m | 5.00Ω | 70.2Ω | 904Ω |
| 10MHz | 174m | 4.26Ω | 71.2Ω | 1.00kΩ | 266m | 5.40Ω | 82.8Ω | 1.11kΩ | 428m | 7.14Ω | 100Ω | 1.29kΩ |
| 20MHz | 348m | 8.53Ω | 142Ω | 2.00kΩ | 532m | 10.8Ω | 165Ω | 2.23kΩ | 857m | 14.2Ω | 200Ω | 2.58kΩ |
| 30MHz | 523m | 12.8Ω | 213Ω | 3.00kΩ | 798m | 16.2Ω | 248Ω | 3.35kΩ | 1.28Ω | 21.4Ω | 301Ω | 3.87kΩ |
| 50MHz | 871m | 21.3Ω | 356Ω | 5.00kΩ | 1.33Ω | 27.0Ω | 414Ω | 5.58kΩ | 2.14Ω | 35.7Ω | 501Ω | 6.46kΩ |
| 70MHz | 1.22Ω | 29.8Ω | 498Ω | 7.00kΩ | 1.86Ω | 37.8Ω | 580Ω | 7.82kΩ | 3.00Ω | 50.0Ω | 702Ω | 9.04kΩ |
| 100MHz | 1.74Ω | 42.6Ω | 712Ω | 10.0kΩ | 2.66Ω | 54.0Ω | 828Ω | 11.1kΩ | 4.28Ω | 71.4Ω | 1.00kΩ | 12.9kΩ |
| 200MHz | 3.48Ω | 85.3Ω | 1.42kΩ | 20.0kΩ | 5.32Ω | 108Ω | 1.65kΩ | 22.3kΩ | 8.57Ω | 142Ω | 2.00kΩ | 25.8kΩ |
| 300MHz | 5.23Ω | 128Ω | 2.13kΩ | 30.0kΩ | 7.98Ω | 162Ω | 2.48kΩ | 33.5kΩ | 12.8Ω | 214Ω | 3.01kΩ | 38.7kΩ |
| 500MHz | 8.71Ω | 213Ω | 3.56kΩ | 50.0kΩ | 13.3Ω | 270Ω | 4.14kΩ | 55.8kΩ | 21.4Ω | 357Ω | 5.01kΩ | 64.6kΩ |
| 700MHz | 12.2Ω | 298Ω | 4.98kΩ | 70.0kΩ | 18.6Ω | 378Ω | 5.80kΩ | 78.2kΩ | 30.0Ω | 500Ω | 7.02kΩ | 90.4kΩ |
| 1GHz | 17.4Ω | 426Ω | 7.12kΩ | | 26.6Ω | 540Ω | 8.28kΩ | | 42.8Ω | 714Ω | 10.0kΩ | |

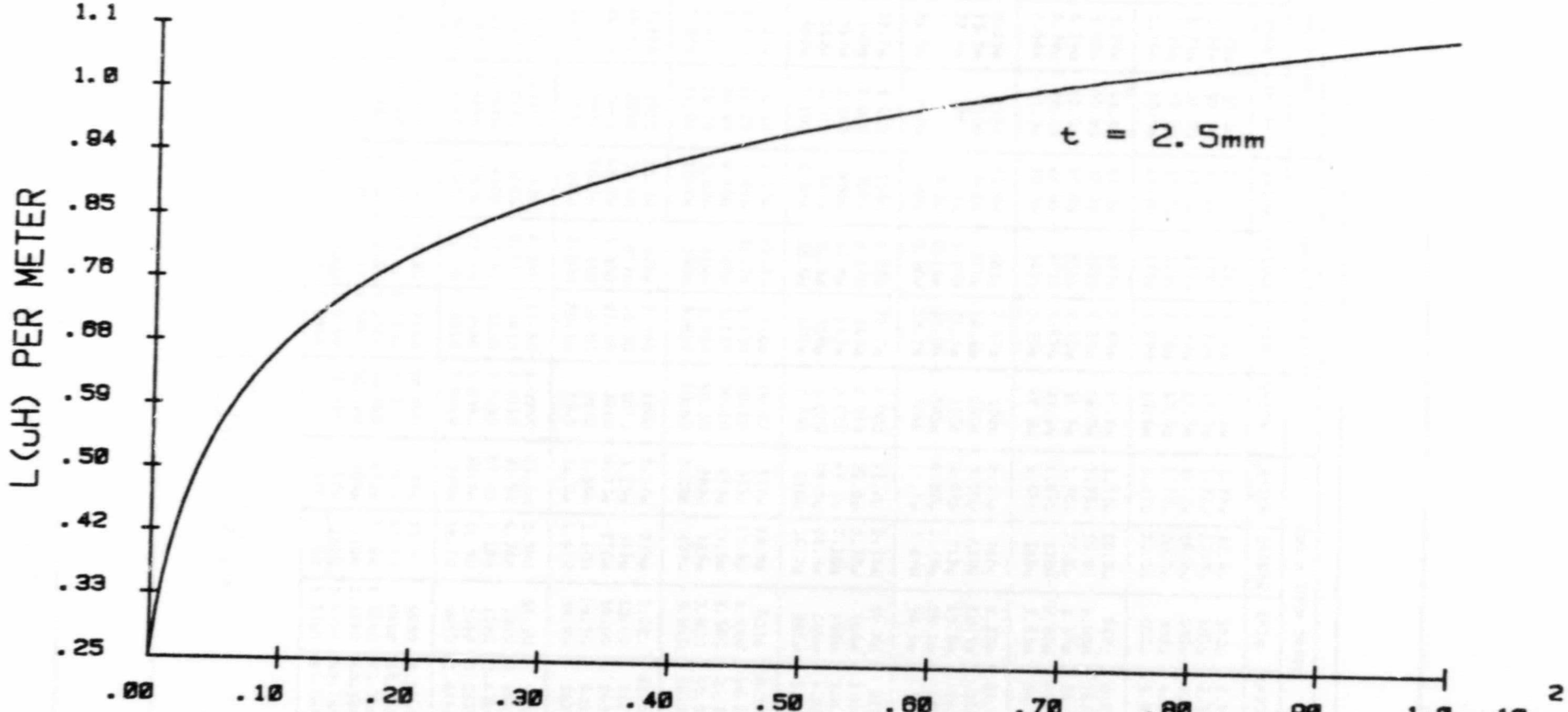
* AWG = American Wire Gage
D = wire diameter in mm
t = wire length in cm or m
μ = microhms
m = milliohms
Ω = ohms

Non-Valid Region for which $t \geq \lambda/4$

**Values derived from free space inductance, when the conductor is far from its return circuit or plane.

TABLE 3.2 IMPEDANCE OF STRAIGHT CIRCULAR COPPER WIRE (SOURCE: WHITE[5])

FIG 3.4 - INDUCTANCE OF STRAPS L vs L/W RATIO



| | .3mm x 10mm Strap | | | | 1mm x 10mm Strap | | | | 2mm x 50mm Strap | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FREQ. | ℓ=1cm | ℓ=10cm | ℓ=1m | ℓ=10m | ℓ=1cm | ℓ=10cm | ℓ=1m | ℓ=10m | ℓ=1cm | ℓ=10cm | ℓ=1m | ℓ=10m |
| 10Hz | 57.4μ | 574μ | 5.74m | 57.4m | 17.2μ | 172μ | 1.72m | 17.2m | 1.72μ | 17.4μ | 180μ | 1.90m |
| 20Hz | 57.4μ | 574μ | 5.74m | 57.5m | 17.2μ | 172μ | 1.73m | 17.3m | 1.72μ | 17.8μ | 201μ | 2.36m |
| 30Hz | 57.4μ | 574μ | 5.75m | 57.5m | 17.2μ | 172μ | 1.73m | 17.5m | 1.72μ | 18.6μ | 232μ | 2.98m |
| 50Hz | 57.4μ | 575μ | 5.75m | 57.6m | 17.2μ | 173μ | 1.76m | 17.9m | 1.72μ | 20.9μ | 312μ | 4.40m |
| 70Hz | 57.4μ | 575μ | 5.76m | 57.9m | 17.2μ | 175μ | 1.79m | 18.6m | 1.72μ | 24.0μ | 404μ | 5.93m |
| 100Hz | 57.4μ | 576μ | 5.79m | 58.3m | 17.3μ | 177μ | 1.86m | 19.9m | 1.73μ | 29.5μ | 549μ | 8.29m |
| 200Hz | 57.5μ | 581μ | 5.92m | 60.9m | 17.5μ | 192μ | 2.24m | 26.4m | 1.75μ | 50.8μ | 1.05m | 16.3m |
| 300Hz | 57.6μ | 589μ | 6.14m | 65.0m | 17.8μ | 215μ | 2.75m | 34.7m | 1.78μ | 73.8μ | 1.57m | 24.3m |
| 500Hz | 58.0μ | 614μ | 6.79m | 76.6m | 18.8μ | 275μ | 3.97m | 53.1m | 1.89μ | 126μ | 2.61m | 40.5m |
| 700Hz | 58.5μ | 615μ | 7.66m | 91.3m | 20.3μ | 346μ | 5.30m | 72.5m | 2.04μ | 168μ | 3.65m | 56.7m |
| 1kHz | 59.6μ | 721μ | 9.25m | 116m | 23.0μ | 462μ | 7.37m | 102m | 2.33μ | 240μ | 5.22m | 81.1m |
| 2kHz | 65.8μ | 1.04m | 15.5m | 210m | 35.1μ | 874μ | 14.4m | 201m | 3.59μ | 479μ | 10.4m | 162m |
| 3kHz | 5.0μ | 1.43m | 22.4m | 309m | 49.1μ | 1.29m | 21.5m | 302m | 5.03μ | 718μ | 15.6m | 243m |
| 5kHz | 98.7μ | 2.25m | 36.7m | 510m | 78.6μ | 2.15m | 35.8m | 503m | 8.07μ | 1.19m | 26.1m | 405m |
| 7kHz | 126μ | 3.11m | 51.0m | 712m | 108μ | 3.00m | 50.2m | 704m | 11.1μ | 1.67m | 36.5m | 567m |
| 10kHz | 170μ | 4.40m | 72.7m | 1.01Ω | 154μ | 4.29m | 71.7m | 1.00Ω | 15.8μ | 2.39m | 52.2m | 810m |
| 20kHz | 326μ | 8.75m | 145m | 2.02Ω | 307μ | 8.57m | 143m | 2.01Ω | 31.6μ | 4.78m | 104m | 1.62Ω |
| 30kHz | 485μ | 13.1m | 217m | 3.04Ω | 460μ | 12.8m | 215m | 3.01Ω | 47.3μ | 7.18m | 156m | 2.43Ω |
| 50kHz | 805μ | 21.8m | 362m | 5.07Ω | 767μ | 21.4m | 358m | 5.03Ω | 78.9μ | 11.9m | 261m | 4.05Ω |
| 70kHz | 1.12m | 30.5m | 507m | 7.10Ω | 1.07m | 30.0m | 501m | 7.04Ω | 110μ | 16.7m | 365m | 5.67Ω |
| 100kHz | 1.60m | 43.7m | 725m | 10.1Ω | 1.53m | 42.8m | 716m | 10.0Ω | 157μ | 23.9m | 522m | 8.10Ω |
| 200kHz | 3.21m | 87.4m | 1.45Ω | 20.2Ω | 3.06m | 85.7m | 1.43Ω | 20.1Ω | 315μ | 47.8m | 1.04Ω | 16.2Ω |
| 300kHz | 4.82m | 131m | 2.17Ω | 30.4Ω | 4.60m | 128m | 2.15Ω | 30.1Ω | 473μ | 71.8m | 1.56Ω | 24.3Ω |
| 500kHz | 8.03m | 218m | 3.62Ω | 50.7Ω | 7.67m | 214m | 3.58Ω | 50.3Ω | 789μ | 119m | 2.61Ω | 40.5Ω |
| 700kHz | 11.2m | 305m | 5.07Ω | 71.0Ω | 10.7m | 300m | 5.01Ω | 70.4Ω | 1.10m | 167m | 3.65Ω | 56.7Ω |
| 1MHz | 16.0m | 437m | 7.25Ω | 101Ω | 15.3m | 428m | 7.16Ω | 100Ω | 1.57m | 239m | 5.22Ω | 81.0Ω |
| 2MHz | 32.1m | 874m | 14.5Ω | 202Ω | 30.6m | 857m | 14.3Ω | 201Ω | 3.15m | 478m | 10.4Ω | 162Ω |
| 3MHz | 48.2m | 1.31Ω | 21.7Ω | 304Ω | 46.0m | 1.28Ω | 21.5Ω | 301Ω | 4.73m | 718m | 15.6Ω | 243Ω |
| 5MHz | 80.3m | 2.18Ω | 36.2Ω | 507Ω | 76.7m | 2.14Ω | 35.8Ω | 503Ω | 7.89m | 1.19Ω | 26.1Ω | 405Ω |
| 7MHz | 112m | 3.05Ω | 50.7Ω | 710Ω | 107m | 3.00Ω | 50.1Ω | 704Ω | 11.0m | 1.67Ω | 36.5Ω | 567Ω |
| 10MHz | 160m | 4.37Ω | 72.5Ω | 1.01kΩ | 153m | 4.28Ω | 71.6Ω | 1.00kΩ | 15.7m | 2.39Ω | 52.2Ω | 810Ω |
| 20MHz | 321m | 8.74Ω | 145Ω | 2.02kΩ | 306m | 8.57Ω | 143Ω | 2.01kΩ | 31.5m | 4.78Ω | 104Ω | 1.62kΩ |
| 30MHz | 482m | 13.1Ω | 217Ω | 3.04kΩ | 460m | 12.8Ω | 215Ω | 3.01kΩ | 47.3m | 7.18Ω | 156Ω | 2.43kΩ |
| 50MHz | 803m | 21.8Ω | 362Ω | 5.07kΩ | 767m | 21.4Ω | 358Ω | 5.03kΩ | 78.9m | 11.9Ω | 261Ω | 4.05kΩ |
| 70MHz | 1.12Ω | 30.5Ω | 507Ω | 7.10kΩ | 1.07Ω | 30.0Ω | 501Ω | 7.04kΩ | 110m | 16.7Ω | 365Ω | 5.67kΩ |
| 100MHz | 1.60Ω | 43.7Ω | 725Ω | 10.1kΩ | 1.53Ω | 42.8Ω | 716Ω | 10.0kΩ | 157m | 23.9Ω | 522Ω | 8.10kΩ |
| 200MHz | 3.21Ω | 87.4Ω | 1.45kΩ | 20.2kΩ | 3.06Ω | 85.7Ω | 1.43kΩ | 20.1kΩ | 316m | 47.8Ω | 1.04kΩ | 16.2kΩ |
| 300MHz | 4.82Ω | 131Ω | 2.17kΩ | 30.4kΩ | 4.60Ω | 128Ω | 2.15kΩ | 30.1kΩ | 473m | 71.8Ω | 1.56kΩ | 24.3kΩ |
| 500MHz | 8.03Ω | 218Ω | 3.62kΩ | 50.7kΩ | 7.67Ω | 214Ω | 3.58kΩ | 50.3kΩ | 789m | 119Ω | 2.61kΩ | 40.5kΩ |
| 700MHz | 11.2Ω | 305Ω | 5.07kΩ | 71.0kΩ | 10.7Ω | 300Ω | 5.01kΩ | 70.4kΩ | 1.10Ω | 167Ω | 3.65kΩ | 56.7kΩ |
| 1GHz | 16.0Ω | 437Ω | 7.25kΩ | | 15.3Ω | 428Ω | 7.16kΩ | | 1.57Ω | 239Ω | 5.22kΩ | 81.0kΩ |

* Strap dimensions are thickness x width in mm

ℓ = strap length in cm or m
μ = microhms
m = milliohms
Ω = ohms

Non-Valid Region for which $\ell \geq \lambda/4$

TABLE 3.3 IMPEDANCE OF COPPER STRAPS (SOURCE: WHITE[5])

a character as to reduce the flux linkages. The difference between the low-frequency and high-frequency inductance is comparatively small. At very high frequencies the inductance deceases from about 6 per cent for short wires to about 2 per cent for long wires[6].

### 3.3.3 CAPACITANCE

In addition to resistance and inductance, solid conductors also possess stray capacitance to adjacent conductive surfaces, as shown in Figure 3.2. The capacitance associated with cables whose height varies from a conductive plane or earth ground can become very complex and difficult to evaluate. However, as long as capacitive reactance is much less than the inductive reactance and the frequency of interest is much less than the resonant frequency given by;

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{3.8}$$

then the capacitive reactance can be neglected and rigorous calculations of the capacitance will not be necessary.

However, equations are provided below which apply to two specialised situations. One such case is that of two parallel plates. The general equation for calculating the capacitance of a parallel plate capacitor, neglecting fringe effects, is given by[7]:

$$C = \frac{0.0885\varepsilon\{(N-1)A\}}{t} \tag{3.9}$$

where C is in picofarads, N is the number of plates, A is the area of one side of the plate in square centimetres, t is the thickness of the dielectric in centimetres and $\varepsilon$ is the dielectric constant relative to air.

In the case of two parallel circular plates of equal radius a, and thickness b expressed in metres, the capacitance in farad is given by:

$$C = \frac{\varepsilon_0 A}{d} + \varepsilon_0 a\left[\log \frac{16\pi(d+b)a}{d^2} + \frac{b}{d} \log \frac{d+b}{b} - 1\right] \qquad (3.10)$$

where A is the area of one side of a plate in square meters, d is the separation of the two plates in meters, and $\varepsilon_0$ is $8.85\times10^{-12}$ farads per meter. Since the variety of situations vary widely and the effort involved too great, a approximate value of $10^{-12}$ F can be assumed.

### 3.3.4 RESISTANCE COMPONENT AT HIGH FREQUENCIES (SKIN EFFECT)

In addition to the R-L-C considerations, there is another factor which tends to increase the impedance of conductors. When alternating or time varying currents flow through conductors, an internal magnetic flux, caused by the current flow, induces an equal and opposite current in the centre of the conductor. As the frequency of the passing current increases the cross sectional area of the cable in which the induced current tends to flow decreases, restricting the intended current to the outer edges of the conductor this phenomenon is referred to as the SKIN EFFECT.

When the skin effect is pronounced, the conductance is no longer proportional to the cross-sectional area of the conductor, but instead is proportional to the circumference, or more precisely, to the surface area of the conductor. The impedance of the conductor can then be given in terms of surface area and is referred to as a surface or intrinsic impedance.

Just as there is a wave impedance associated with air given by:

$$\frac{E}{H} = \left(\frac{\mu_0}{\varepsilon_0}\right)^{\frac{1}{2}} = 377\ \Omega$$

there is also a wave impedance associated with metals given by:

$$Z = \frac{E}{H} = \frac{\omega\mu}{k} \tag{3.11}$$

where $E$ = electric field component

$H$ = magnetic field component.

$k$ = wave number

$\omega$ = angular frequency = $2\pi f$

$\mu = \mu_r\mu_0$ = permeability of conductor.

The wave number k is a complex function equal to:

$$k = \frac{1 - j}{\delta} \tag{3.12}$$

where the skin depth $\delta$ is given by:

$$\delta = \left(\frac{2\rho}{\omega\mu}\right)^{\frac{1}{2}}$$

$$= 5033 \left(\frac{\rho}{\mu_r f}\right)^{\frac{1}{2}} \text{ mm} \tag{3.13}$$

The skin depth for different metals are given below:

| | |
|---|---|
| silver | $\delta = 6.41/\sqrt{f}$ cm |
| copper | $\delta = 6.62/\sqrt{f}$ cm |
| aluminium | $\delta = 8.25/\sqrt{f}$ cm |
| brass | $\delta = 12.70/\sqrt{f}$ cm |
| solder | $\delta = 18.96/\sqrt{f}$ cm |

where $\mu_r = 1$ = relative permeability of the conductor.

$f$ = frequency in hertz

$\rho$ = resistivity in ohm-cm

If

$$\frac{1 + j}{\sqrt{2}} = 1 \angle 45^\circ$$

then the intrinsic impedance is expressed as

$$Z = (\rho\mu\omega)^{\frac{1}{2}} \angle 45^\circ \tag{3.14}$$

Note, from Equation 3.14, the intrinsic impedance of a conductor is a complex quantity. This is analogous to the situation in a circuit having resistance and inductance in series where the current lags the applied voltage. Thus the conducting metal behaves like an inductive impedance at high frequencies. This is an important result to be remembered when designing grounding systems.

The influence of skin effect on the resistance component can be calculated by assuming the current to flow on the outside and to be evenly distributed in a tube with a sectional area described by the external dimensions of the conductor and the skin depth. Note that the skin depth is the distance where-in the field is reduced in magnitude by 1/e, where e = 2.718. For copper at 20°C the skin depth is $6.62/\sqrt{f}$ in cm, and $f$ is in hertz. Combining Equations 3.12 and 3.13 the intrinsic impedance is given by:

$$Z = \frac{\rho}{\delta}(1 + j) \tag{3.15}$$

which is the surface impedance per square of surface area. Since the resistance to the conduction current is of interest, the real part of Equation 3.14 is taken.

$$\text{Re } Z = R_{skin} = \frac{\rho}{\delta} \tag{3.16}$$

Equation 3.16 indicates that the equivalent impedance of a solid conductor is equal to the dc impedance of a shell whose thickness is $\delta$.

## Resistance of Round Conductors

For a solid round conductor of radius r and length $\ell$ the equivalent impedance $R_{skin}$ is given by

$$R_{skin} = \frac{\rho \ell}{\pi \delta (2r - \delta)} \tag{3.17}$$

and when $\delta << r$

$$R_{skin} = \frac{\rho \ell}{2\pi r \delta} \tag{3.18}$$

Figure 3.5 shows curves of calculated values of the skin depth, as well as the surface resistance of various metals.

## Resistance of Rectangular Conductors

In the case of a rectangular conductor of width w and thickness t, the radius of curvature varies so rapidly at the corners such that Equation 3.18 must be modified as follows.

$$R_{skin} = K \frac{\rho \ell}{2(w+t)\delta} \tag{3.19}$$

where K is a function of the ratio w/t.

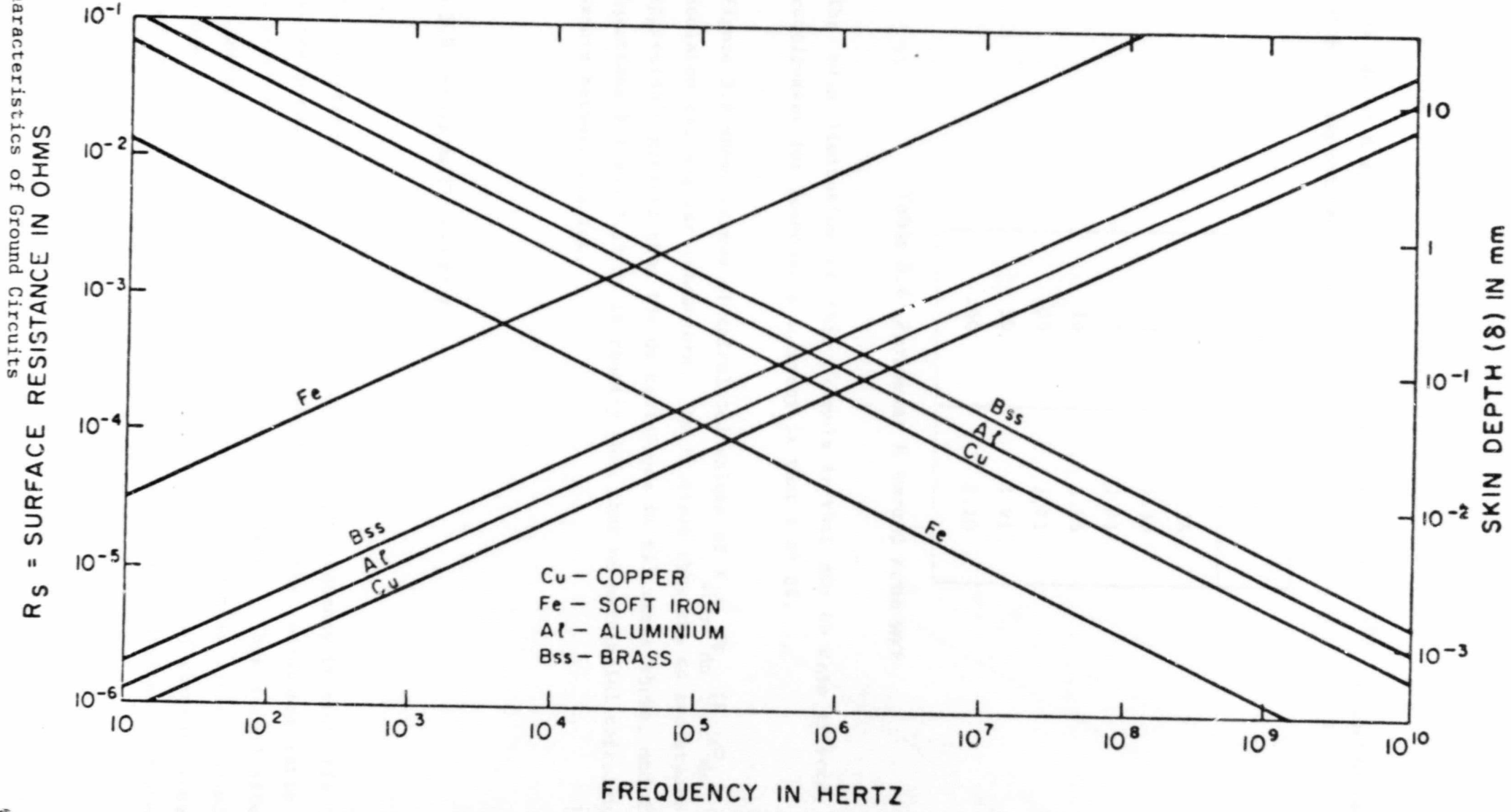



FIGURE 3.5 SURFACE RESISTANCE AND SKIN DEPTH FOR COMMON METALS (SOURCE: ERIKSSON[4])

The factor K appears as a curve on page 36 of Terman[6]. Selected values of K are reproduced below as Table 3.4.

| w/t | K |
|---|---|
| 1 | 1.35 |
| 2 | 1.30 |
| 5 | 1.41 |
| 10 | 1.56 |
| 20 | 1.71 |
| 50 | 1.91 |
| 100 | 2.10 |

**Table 3.4 Parameter K versus ratio w/t**

The main limitation of this formula is that due to skin effects. A requirement for reasonable accuracy is that $t >> 2\delta$.

Figure 3.6 shows curves of calculated values of $R_{skin}/R_{dc}$ ($R_{ac}/R_{dc}$) for isolated rectangular conductors. It is clear that the ac resistance is appreciably greater than the dc resistance in all cases shown, and from Equations 3.1 and 3.19 it is readily seen that no meaningful correlation exists between the two.

### 3.3.5 PROXIMITY EFFECT

The resistance component of a conductor at high frequency is also affected by the proximity effect, and ordinarily causes the resistance ratio to be greater than in the case of simple skin effect. This second effect is encountered when current-carrying conductors are in close proximity to one another. This is a result of a redistribution of current along a conductor due to the magnetic flux produced by the adjacent conductor,

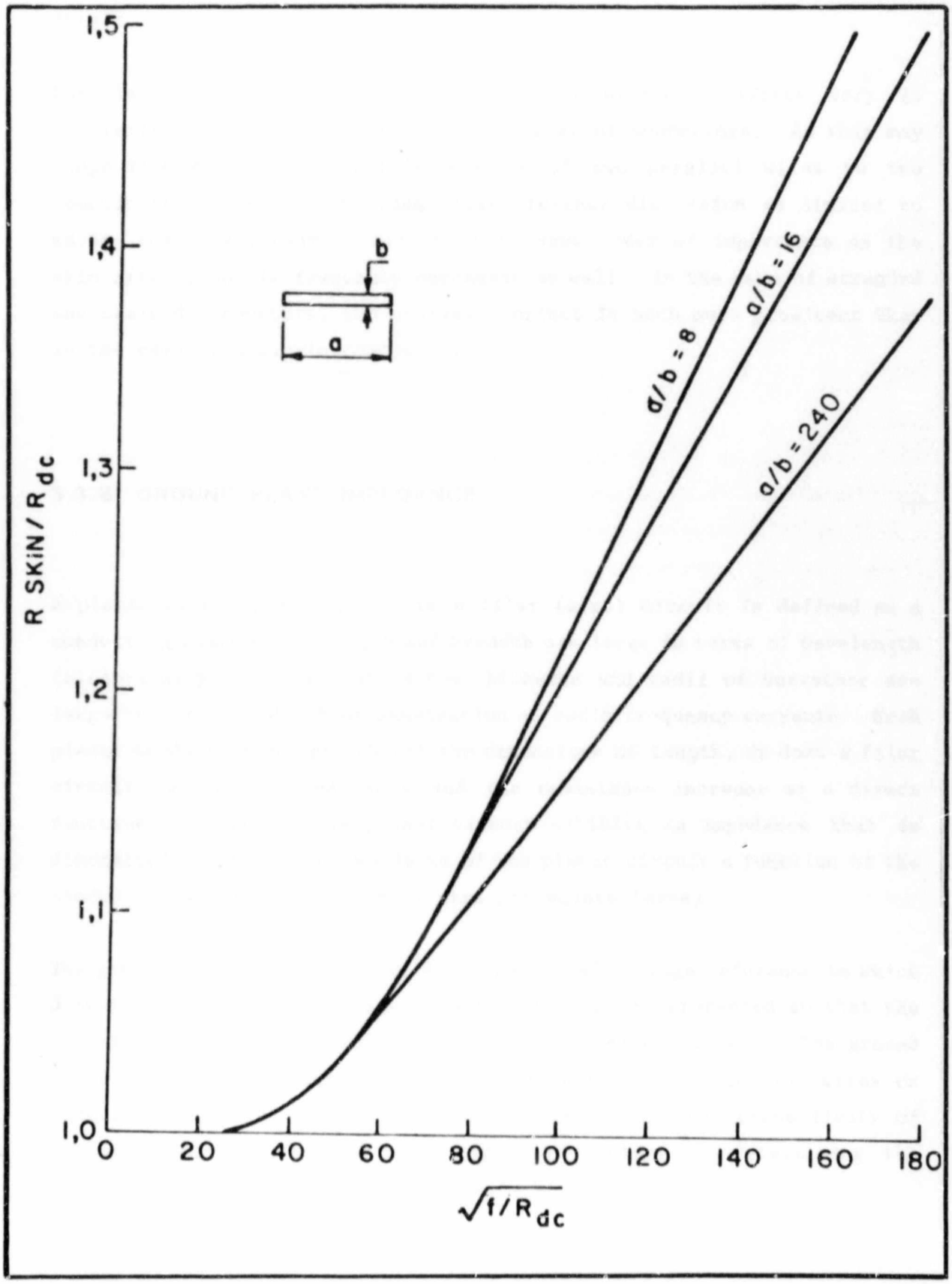



FIGURE 3.6 SKIN EFFECT IN RECTANGULAR CONDUCTORS ($R_{dc}$ IN OHMS PER 300m) (SOURCE: ERIKSSON[4])

as well as the magnetic flux produced by the current in the conductor itself.

Formulae for incorporating the theory of proximity effect vary in complexity, and are dependent on the number of conductors. As this may range from a relatively simple example of two parallel wires to the complicated case of a braided strap, further discussion is limited to saying that the proximity effect is of same order of importance as the skin effect, and is frequency dependent as well. In the case of stranded and braided conductors, the proximity effect is much more prominent than in the case of a single conductor.

### 3.3.6 GROUND PLANE IMPEDANCE

A planar circuit, as opposed to a filar (wire) circuit is defined as a conducting plane whose length and breadth are large in terms of wavelength (electrically infinite), and whose thickness and radii of curvature are large in terms of depth of penetration of radio frequency currents. Such planar conductors do not exhibit the dimensions of length, as does a filar circuit, where the reactance and the resistance increase as a direct function of length. The planar circuit exhibits an impedance that is dimensionless, with the impedance of the planar circuit a function of the conductive material in terms of ohms per square (area).

The ground plane serves well as a equipotential voltage reference to which a number of electrical or electronic units can be referenced so that the potential between interconnected units is a minimum or zero. The ground plane is usually a flat conductive area, with interconnecting wires or tubular conductors. Its physical configuration and the conductivity of its material are the two most important factors in determining the inherent impedance of a ground plane.

The following formula gives the high-frequency impedance of a metal ground plane[2]:

$$Z_{skin} = \frac{369\sqrt{\mu_r f_{MHz}/\sigma_r}}{1 - e^{-t/\delta}} \quad \mu\Omega/sq \tag{3.20}$$

where $\mu_r$ = permeability relative to copper
= 200 for cold-rolled steel
$f_{MHZ}$ = frequency in MHz
$\delta$ = skin-depth in mm
$= 0.066\sqrt{\mu_r \sigma_r f_{MHz}}$ hd. for any metal
$\sigma_r$ = conductivity relative to copper
= 0.17 for cold-rolled steel

Impedance values of typical ground plane sizes are given in Table 3.5. Observe, that even large sheet ground planes do not offer zero impedances although they will offer three to four orders of magnitude of impedance less than a single small wire. Thus their use as a ground reference point is superior to wires.

For design purposes, the impedance of any metal may be determined with the use of Table 3.5 provided that its relative conductivity and permeability are known. The dc and high-frequency impedances are:

$$R_{dc} = \text{from Table 3.5 (for copper)} \times \rho_r \tag{3.21}$$

$$Z_{skin} = \text{from Table 3.5 (for copper)} \times \sqrt{\mu_r \rho_r} \tag{3.22}$$

and for aluminium $\rho_r = 1/0.6$ and $\mu_r = 1$

## 3.4 COMMENTS ON PREVIOUS SECTIONS

From the preceding sections, one concludes that a ground conductor can no longer be regarded as exhibiting a pure dc resistance but has also a frequency dependent ac resistance $R_{skin}$, inductance L, and capacitance C. In addition there is the influence of proximity effect, which is significant over and above skin effect. Although skin effect exists at

| | COPPER, COND-1, PERM-1 | | | | | | STEEL, COND-17, PERM-200 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Freq. | t=.03 | t=.1 | t=.3 | t=1 | t=3 | t=10 | t=.03 | t=.1 | t=.3 | t=1 | t=3 | t=10 |
| 10Hz | 574μ | 172μ | 57.4μ | 17.2μ | 5.74μ | 1.75μ | 3.38m | 1.01m | 338μ | 101μ | 38.5μ | 40.3μ |
| 20Hz | 574μ | 172μ | 57.4μ | 17.2μ | 5.75μ | 1.83μ | 3.38m | 1.01m | 338μ | 102μ | 49.5μ | 56.6μ |
| 30Hz | 574μ | 172μ | 57.4μ | 17.2μ | 5.75μ | 1.95μ | 3.38m | 1.01m | 338μ | 103μ | 62.3μ | 69.3μ |
| 50Hz | 574μ | 172μ | 57.4μ | 17.2μ | 5.76μ | 2.30μ | 3.38m | 1.01m | 338μ | 106μ | 86.2μ | 89.6μ |
| 70Hz | 574μ | 172μ | 57.4μ | 17.2μ | 5.78μ | 2.71μ | 3.38m | 1.01m | 338μ | 110μ | 105μ | 106μ |
| 100Hz | 574μ | 172μ | 57.4μ | 17.2μ | 5.82μ | 3.35μ | 3.38m | 1.01m | 338μ | 118μ | 127μ | 126μ |
| 200Hz | 574μ | 172μ | 57.4μ | 17.2μ | 6.04μ | 5.16μ | 3.38m | 1.01m | 340μ | 157μ | 179μ | 179μ |
| 300Hz | 574μ | 172μ | 57.4μ | 17.2μ | 6.38μ | 6.43μ | 3.38m | 1.01m | 342μ | 199μ | 219μ | 219μ |
| 500Hz | 574μ | 172μ | 57.4μ | 17.3μ | 7.36μ | 8.27μ | 3.38m | 1.01m | 350μ | 275μ | 283μ | 283μ |
| 700Hz | 574μ | 172μ | 57.4μ | 17.3μ | 8.55μ | 9.77μ | 3.38m | 1.01m | 362μ | 335μ | 335μ | 335μ |
| 1kHz | 574μ | 172μ | 57.4μ | 17.5μ | 10.4μ | 11.6μ | 3.38m | 1.01m | 385μ | 403μ | 400μ | 400μ |
| 2kHz | 574μ | 172μ | 57.5μ | 18.3μ | 16.1μ | 16.5μ | 3.38m | 1.02m | 495μ | 566μ | 566μ | 566μ |
| 3kHz | 574μ | 172μ | 57.5μ | 19.5μ | 20.3μ | 20.2μ | 3.38m | 1.03m | 623μ | 693μ | 694μ | 694μ |
| 5kHz | 574μ | 172μ | 57.6μ | 23.0μ | 26.2μ | 26.1μ | 3.38m | 1.06m | 862μ | 896μ | 896μ | 896μ |
| 7kHz | 574μ | 172μ | 57.8μ | 27.1μ | 30.9μ | 30.9μ | 3.38m | 1.10m | 1.05m | 1.06m | 1.06m | 1.06m |
| 10kHz | 574μ | 172μ | 58.2μ | 33.5μ | 36.9μ | 36.9μ | 3.38m | 1.18m | 1.27m | 1.26m | 1.26m | 1.26m |
| 20kHz | 574μ | 172μ | 60.4μ | 51.6μ | 52.2μ | 52.2μ | 3.40m | 1.57m | 1.79m | 1.79m | 1.79m | 1.79m |
| 30kHz | 574μ | 172μ | 63.8μ | 64.3μ | 63.9μ | 63.9μ | 3.42m | 1.99m | 2.19m | 2.19m | 2.19m | 2.19m |
| 50kHz | 574μ | 173μ | 73.6μ | 82.7μ | 82.6μ | 82.6μ | 3.50m | 2.75m | 2.83m | 2.83m | 2.83m | 2.83m |
| 70kHz | 574μ | 173μ | 85.5μ | 97.7μ | 97.7μ | 97.7μ | 3.62m | 3.35m | 3.35m | 3.35m | 3.35m | 3.35m |
| 100kHz | 574μ | 175μ | 104μ | 116μ | 116μ | 116μ | 3.85m | 4.03m | 4.00m | 4.00m | 4.00m | 4.00m |
| 200kHz | 575μ | 183μ | 161μ | 165μ | 165μ | 165μ | 4.95m | 5.66m | 5.66m | 5.66m | 5.66m | 5.66m |
| 300kHz | 575μ | 195μ | 203μ | 202μ | 202μ | 202μ | 6.23m | 6.93m | 6.94m | 6.94m | 6.94m | 6.94m |
| 500kHz | 576μ | 230μ | 262μ | 261μ | 261μ | 261μ | 8.62m | 8.96m | 8.96m | 8.96m | 8.96m | 8.96m |
| 700kHz | 578μ | 271μ | 309μ | 309μ | 309μ | 309μ | 10.5m | 10.6m | 10.6m | 10.6m | 10.6m | 10.6m |
| 1MHz | 582μ | 335μ | 369μ | 369μ | 369μ | 369μ | 12.7m | 12.6m | 12.6m | 12.6m | 12.6m | 12.6m |
| 2MHz | 604μ | 516μ | 522μ | 522μ | 522μ | 522μ | 17.9m | 17.9m | 17.9m | 17.9m | 17.9m | 17.9m |
| 3MHz | 638μ | 643μ | 639μ | 639μ | 639μ | 639μ | 21.9m | 21.9m | 21.9m | 21.9m | 21.9m | 21.9m |
| 5MHz | 736μ | 827μ | 826μ | 826μ | 826μ | 826μ | 28.3m | 28.3m | 28.3m | 28.3m | 28.3m | 28.3m |
| 7MHz | 855μ | 977μ | 977μ | 977μ | 977μ | 977μ | 33.5m | 33.5m | 33.5m | 33.5m | 33.5m | 33.5m |
| 10MHz | 1.04m | 1.16m | 1.16m | 1.16m | 1.16m | 1.16m | 40.0m | 40.0m | 40.0m | 40.0m | 40.0m | 40.0m |
| 20MHz | 1.61m | 1.65m | 1.65m | 1.65m | 1.65m | 1.65m | 56.6m | 56.6m | 56.6m | 56.6m | 56.6m | 56.6m |
| 30MHz | 2.03m | 2.02m | 2.02m | 2.02m | 2.02m | 2.02m | 69.4m | 69.4m | 69.4m | 69.4m | 69.4m | 69.4m |
| 50MHz | 2.62m | 2.61m | 2.61m | 2.61m | 2.61m | 2.61m | 89.6m | 89.6m | 89.6m | 89.6m | 89.6m | 89.6m |
| 70MHz | 3.09m | 3.09m | 3.09m | 3.09m | 3.09m | 3.09m | 106m | 106m | 106m | 106m | 106m | 106m |
| 100MHz | 3.69m | 3.69m | 3.69m | 3.69m | 3.69m | 3.69m | 126m | 126m | 126m | 126m | 126m | 126m |
| 200MHz | 5.22m | 5.22m | 5.22m | 5.22m | 5.22m | 5.22m | 179m | 179m | 179m | 179m | 179m | 179m |
| 300MHz | 6.39m | 6.39m | 6.39m | 6.39m | 6.39m | 6.39m | 219m | 219m | 219m | 219m | 219m | 219m |
| 500MHz | 8.26m | 8.26m | 8.26m | 8.26m | 8.26m | 8.26m | 283m | 283m | 283m | 283m | 283m | 283m |
| 700MHz | 9.77m | 9.77m | 9.77m | 9.77m | 9.77m | 9.77m | 335m | 335m | 335m | 335m | 335m | 335m |
| 1GHz | 11.6m | 11.6m | 11.6m | 11.6m | 11.6m | 11.6m | 400m | 400m | 400m | 400m | 400m | 400m |
| 2GHz | 16.5m | 16.5m | 16.5m | 16.5m | 16.5m | 16.5m | 566m | 566m | 566m | 566m | 566m | 566m |
| 3GHz | 20.2m | 20.2m | 20.2m | 20.2m | 20.2m | 20.2m | 694m | 694m | 694m | 694m | 694m | 694m |
| 5GHz | 26.1m | 26.1m | 26.1m | 26.1m | 26.1m | 26.1m | 896m | 896m | 896m | 896m | 896m | 896m |
| 7GHz | 30.9m | 30.9m | 30.9m | 30.9m | 30.9m | 30.9m | 1.06Ω | 1.06Ω | 1.06Ω | 1.06Ω | 1.06Ω | 1.06Ω |
| 10GHz | 36.9m | 36.9m | 36.9m | 36.9m | 36.9m | 36.9m | 1.26Ω | 1.26Ω | 1.26Ω | 1.26Ω | 1.26Ω | 1.26Ω |

* t is in units of mm
μ = microhms
m = milliohms
Ω = ohms

NOTE: Do not use table at frequencies in MHz above $5/\ell_m$ since the separation distance in meters, $\ell_m$, of two grounded equipments will exceed 0.05λ where error becomes significant.

TABLE 3.5 METAL GROUND PLANE IMPEDANCE IN OHMS/SQUARE (SOURCE: WHITE[5])

all frequencies, it becomes more significant as the frequency increases and could increase as high as 25 times the dc resistance over a 10MHz frequency range. From Tables 3.2 and 3.3 one observes that the reactance of a conductor also increases with frequency to further increase the conductor impedance above its dc value. Thus, t design an effective ground system one must consider the relative effects of the dc resistance, the ac resistance, and the inductance L upon the total impedance of the ground conductor. As shown below, these are not the only effects to consider when designing ground conductors.

## 3.5 THE EFFECT OF GEOMETRY

The discussion in preceding sections has concentrated on describing the impedance characteristics of two common types of ground conductors, i.e. wires and solid rectangular straps. It is important to note that the design of ground conductors is not only influenced by the impedance requirements but also by such considerations as flexibility, available space, weight and cost, and is also related to the geometry of the conductor. Furthermore, the impedance characteristics varies with conductor geometry and, of course, frequency. The following sections consider the effect of geometry on conductor impedance[4].

### 3.5.1 RECTANGULAR CONDUCTORS

With regard to geometry it is clear from Figure 3.4 and Table 3.3 that the impedance is affected by the width, thickness, length and frequency. At low frequencies the impedance is lowest for short, thick and wide conductors. At high frequencies the impedance is lowest for thin, wide conductors due to the influence of skin effect. At higher frequencies,

however, the added benefit of a much wider strap becomes considerably less pronounced. The impedance also increases somewhat more rapidly for a corresponding increase in strap length.

Flat ground straps are often required for RF ground paths because of their lower impedance compared to wires at the frequencies of concern. Furthermore, they are easy to install from a mechanical point of view. The major electrical drawbacks of flat straps are the unknown effects of voltage fringing, the unknown contact impedance of the mating surfaces, the probability of corrosion at points of contact, and the difficulty in determining the characteristic impedance of the straps. Another problem is that of the radiation capability of the strap. At very high frequencies the effect causes the current to concentrate along the sharp edges of the conductor which in turn causes the conductor to radiate efficiently. A possible remedy is to round the edges of the conductor.

### 3.5.2 TUBULAR CONDUCTORS

Tubular conductors provide the best compromise between factors such as availability, cost, weight, cross sectional area, skin effect, resistance ratio and reactance. By using the actual cross-sectional area of the conductive material, the dc resistance of tubular conductors can be determined from Equation 3.1.

Both the dc and ac resistances of a tubular conductor are greater than those of a solid conductor with the same outside diameter. However, the ac resistance does not increase as much as the dc resistance, and therefore the resistance ratio of a tubular conductor is always less than that of a solid conductor. Figure 3.7 shows that the $R_{ac}/R_{dc}$ ratio for a cable is less than that of a solid wire. Furthermore the self-inductance of the conductor is reduced by the absence of conducting medium in the centre[3].

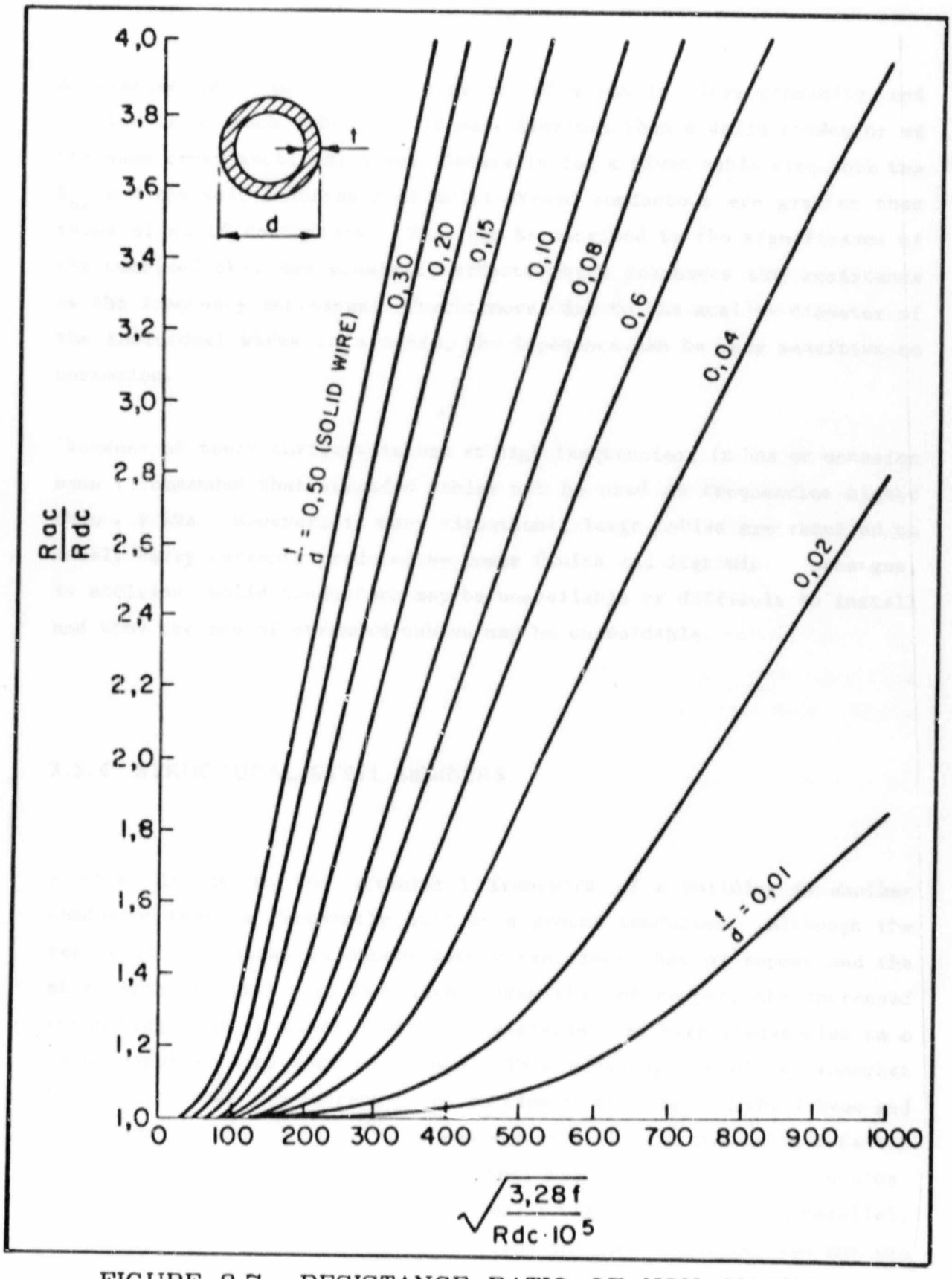



FIGURE 3.7 RESISTANCE RATIO OF NON--MAGNETIC TUBULAR CONDUCTORS (SOURCE: ERIKSSON[4])

**Author** Ambelal Dependra
**Name of thesis** Earthing And Grounding For The Control Of Emi In Industrial Instrumentation And Control Systems. 1986

***PUBLISHER:***
**University of the Witwatersrand, Johannesburg**
**©2013**

***LEGAL NOTICES:***

**Copyright Notice:** All materials on the University of the Witwatersrand, Johannesburg Library website are protected by South African copyright law and may not be distributed, transmitted, displayed, or otherwise published in any format, without the prior written permission of the copyright owner.

**Disclaimer and Terms of Use:** Provided that you maintain all copyright and other notices contained therein, you may download material (one machine readable copy and one print copy per page) for your personal and/or educational non-commercial use only.

The University of the Witwatersrand, Johannesburg, is not responsible for any errors or omissions and excludes any and all liability for any errors in or omissions from the information on the Library website.