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

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

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

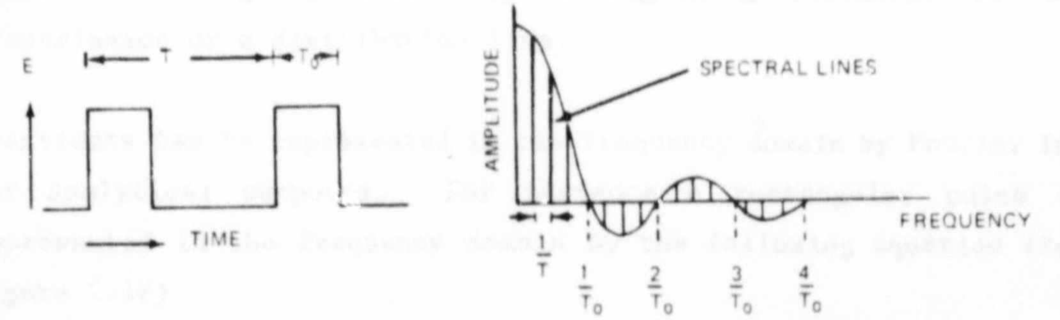


FIGURE 2.14 SPECTRUM OF RECTANGULAR PULSES (IEEE 518–1982[30])

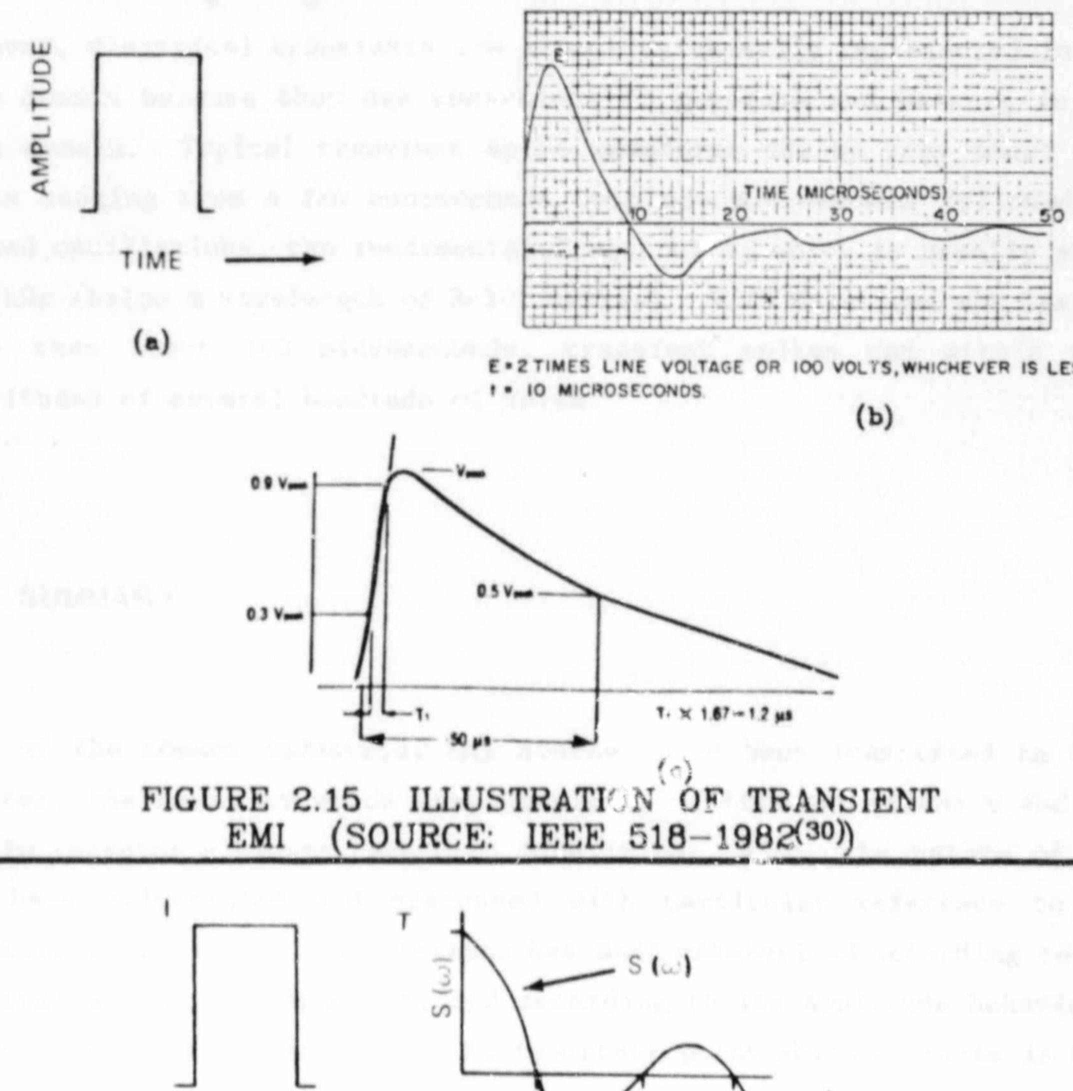


FIGURE 2.15 ILLUSTRATION OF TRANSIENT EMI (SOURCE: IEEE 518–1982[30])

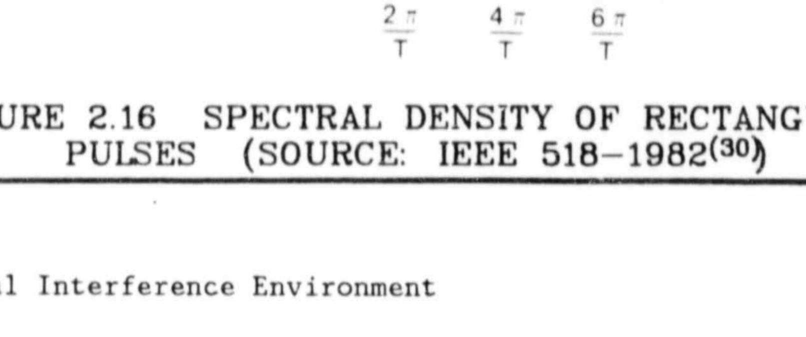


FIGURE 2.16 SPECTRAL DENSITY OF RECTANGULAR PULSES (SOURCE: IEEE 518–1982[30])

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 3×10^3 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. Int[illegible]e has been categorised according to its spectral extent, or b[illegible] according to its amplitude behaviour, be it continuous or tra[illegible]n important point which surfaces is that in any EMI control progra[illegible]e 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.

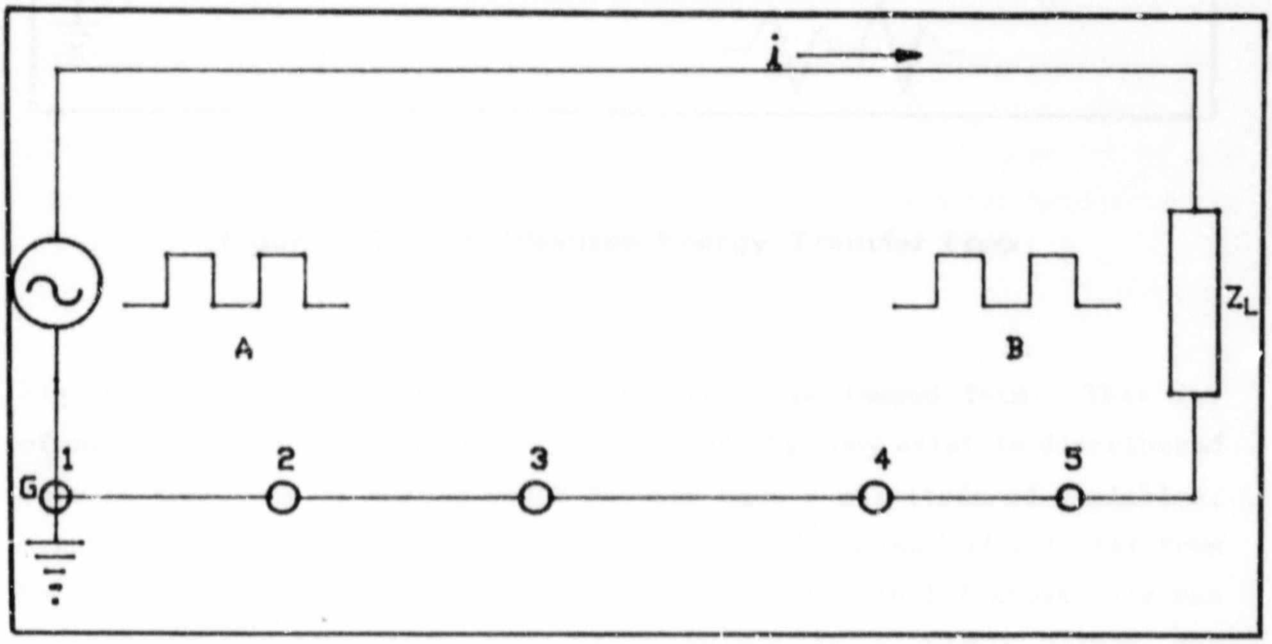


Figure 3.1 Idealised Energy Transfer Loop

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.

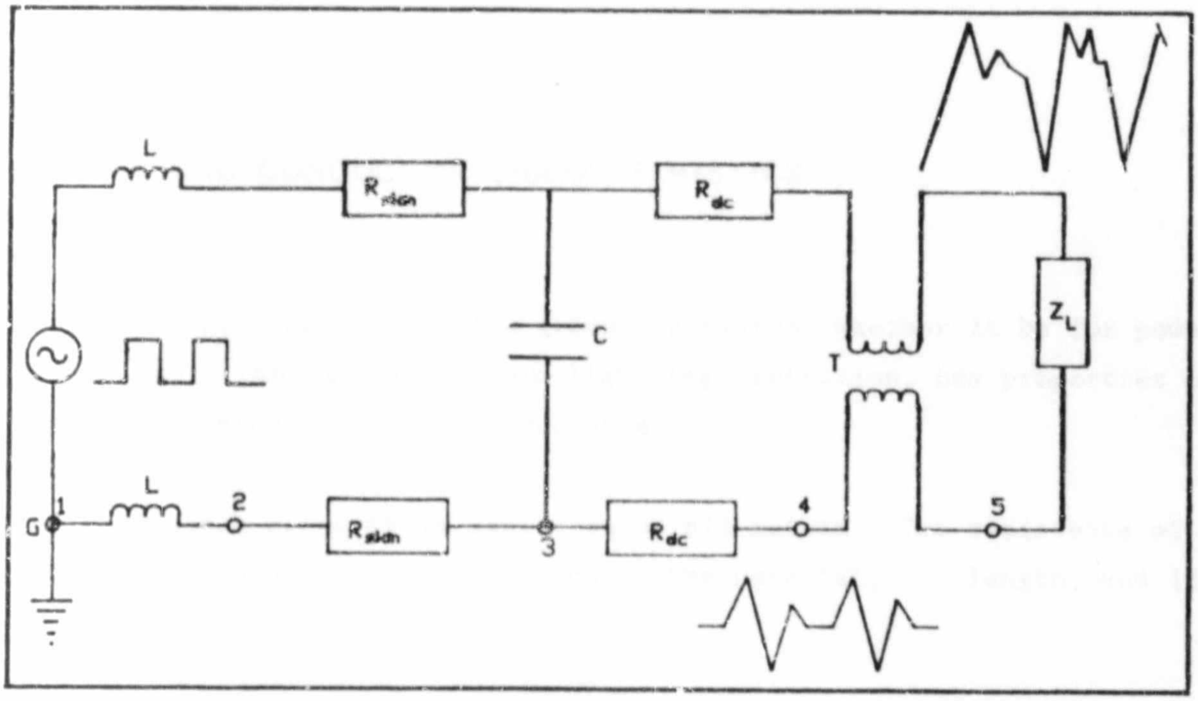


Figure 3.2 Non-Idealised Energy Transfer Loop

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 ℓ(m), cross-sectional area A(m^2) and resistivity ρ 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/ℓ, 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

α = temperature coefficient of resistivity

α_c = 0,00393 for copper

α_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

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

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

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

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

$$L = 2\times10^{-4}\ell\left[2.303\ \ell og\frac{4\ell}{d} - 0.75\right]\ \mu H \tag{3.7}$$

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 ($X_L = 2\pi f L$) and adding vectorially the resistance

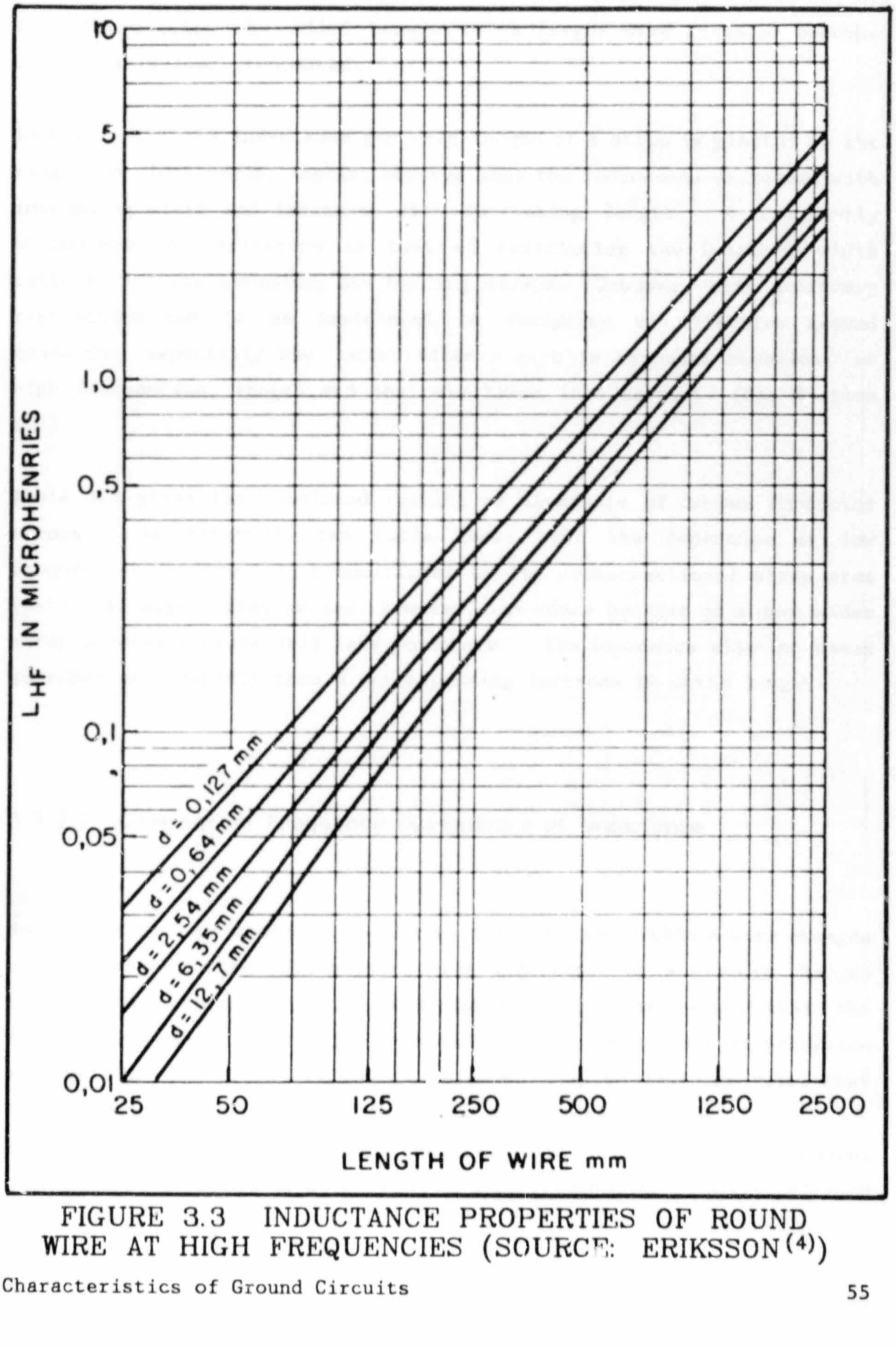


FIGURE 3.3 INDUCTANCE PROPERTIES OF ROUND WIRE AT HIGH FREQUENCIES (SOURCE: ERIKSSON[4])

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=.64mm			
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	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	

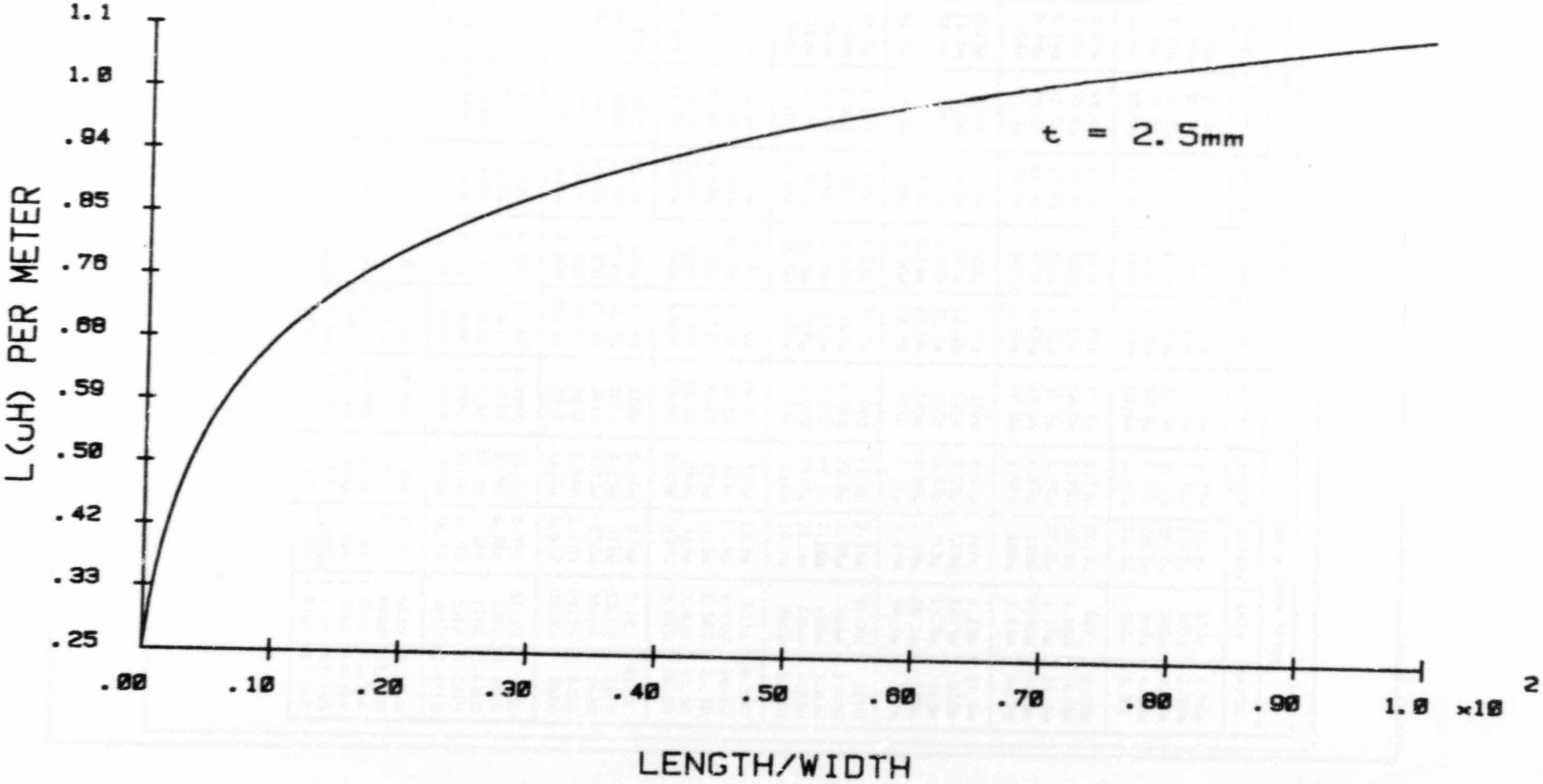
* AWG = American Wire Gage
D = wire diameter in mm
ℓ = wire length in cm or m
μ = microhms
m = milliohms
Ω = ohms

Non-Valid Region for which ℓ ≥ λ/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	120µ	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;

$$f_r = \frac{1}{2\pi\sqrt{LC}} \qquad (3.8)$$

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]:

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

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 ε 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:

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

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 ε_0 is 8.85×10^{-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

ω = 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 δ 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 μ_r = 1 = relative permeability of the conductor.

f = frequency in hertz

ρ = resistivity in ohm-cm

If

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

then the intrinsic impedance is expressed as

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

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:

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

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.

$$\text{Re } Z = R_{skin} = \frac{\rho}{\delta} \quad (3.16)$$

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

Resistance of Round Conductors

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

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

and when $\delta \ll r$

$$R_{skin} = \frac{\rho \ell}{2\pi r\delta} \qquad (3.18)$$

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.

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

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

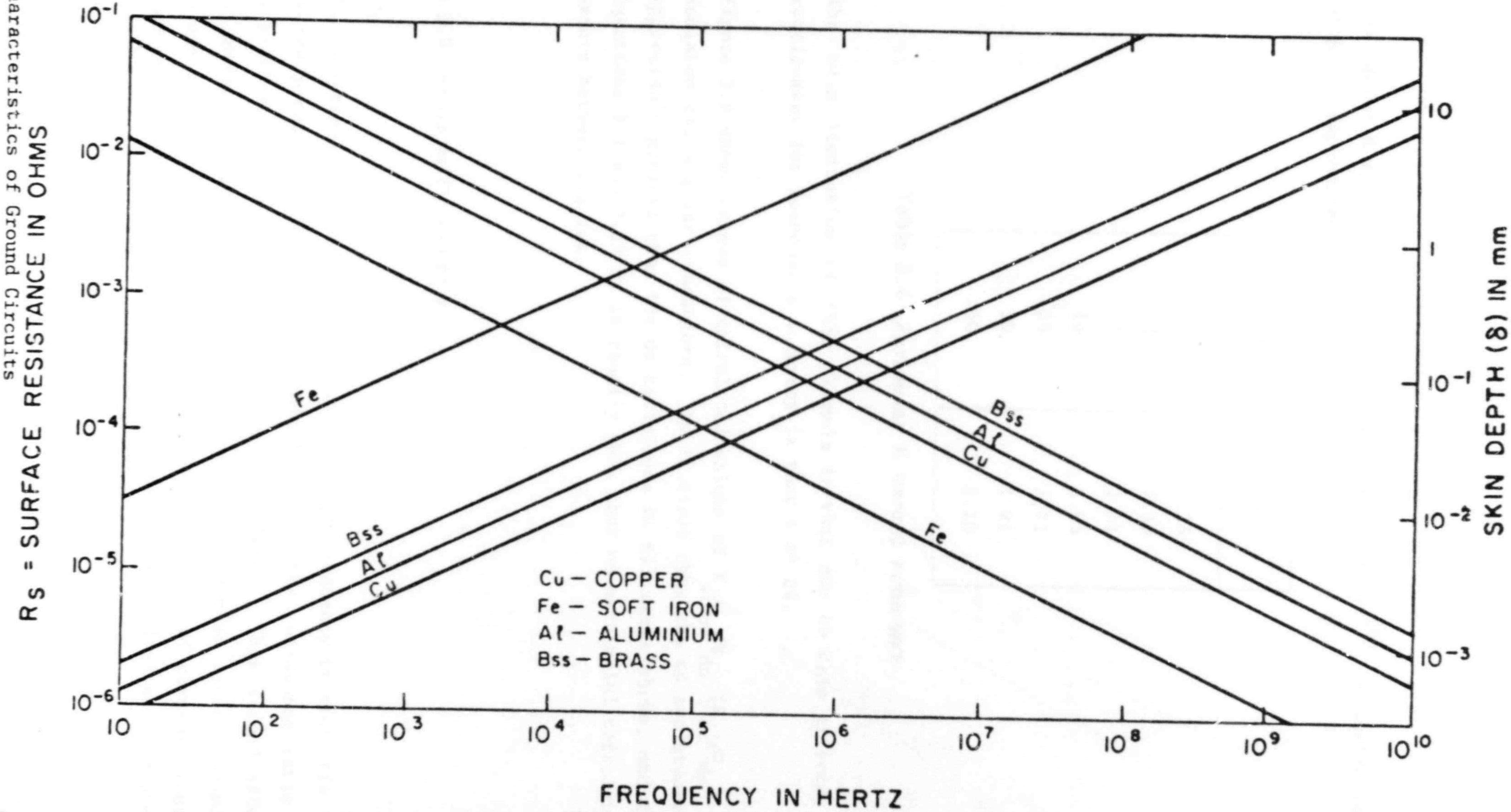


FIGURE 3.5 SURFACE RESISTANCE AND SKIN DEPTH FOR COMMON METALS (SOURCE: ERIKSSON[4])

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 $t \gg 2\delta$.

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,

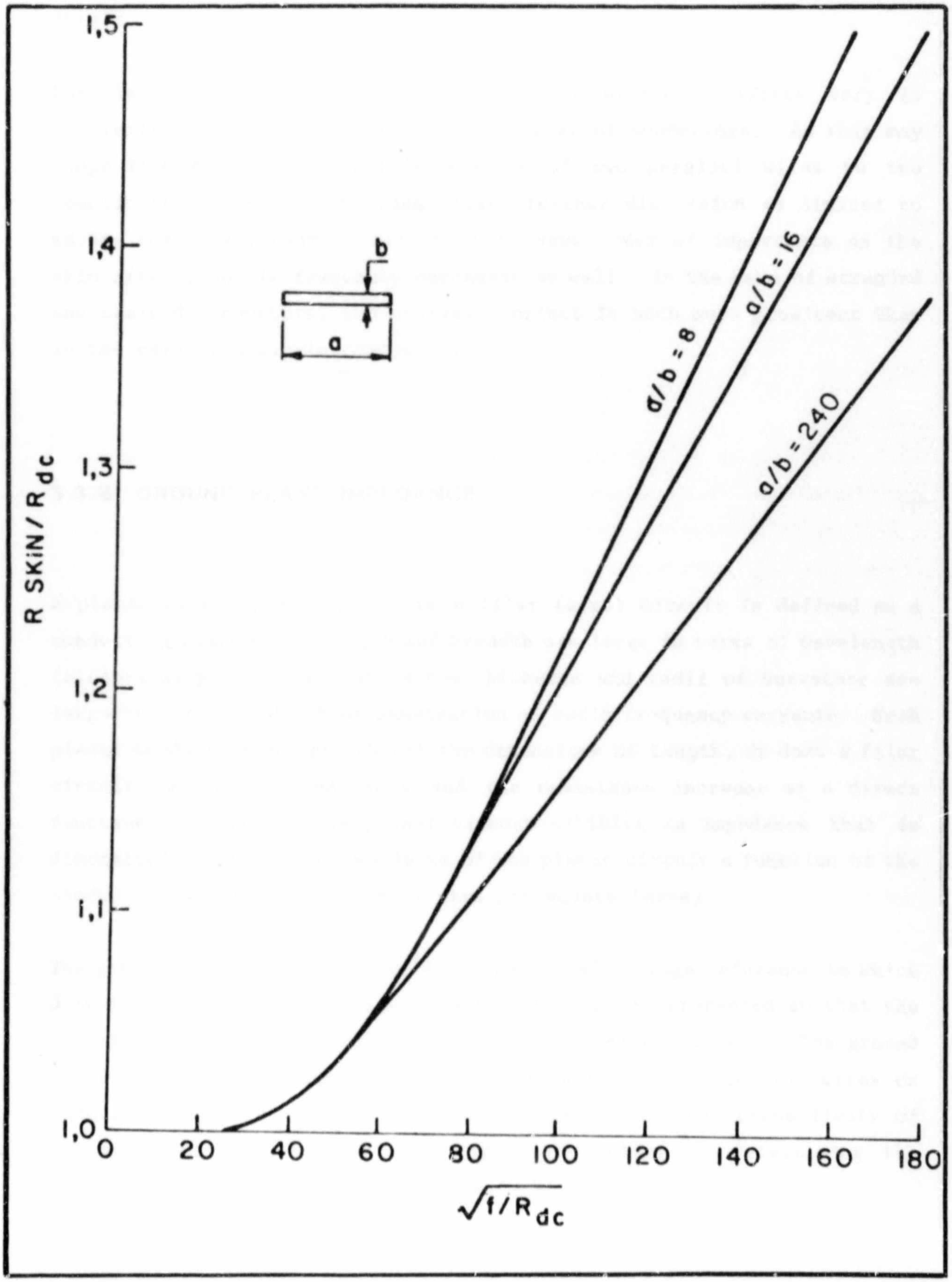


FIGURE 3.6 SKIN EFFECT IN RECTANGULAR CONDUCTORS (R_{dc} IN OHMS PER 300m) (SOURCE: ERIKSSON[4])

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]:

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

where μ_r = permeability relative to copper
= 200 for cold-rolled steel
f_{MHZ} = frequency in MHz
δ = skin-depth in mm
= $0.066\sqrt{\mu_r \sigma_r f_{MHz}}$ hd. for any metal
σ_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	3.58m	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	36.7μ	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, ℓ_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].

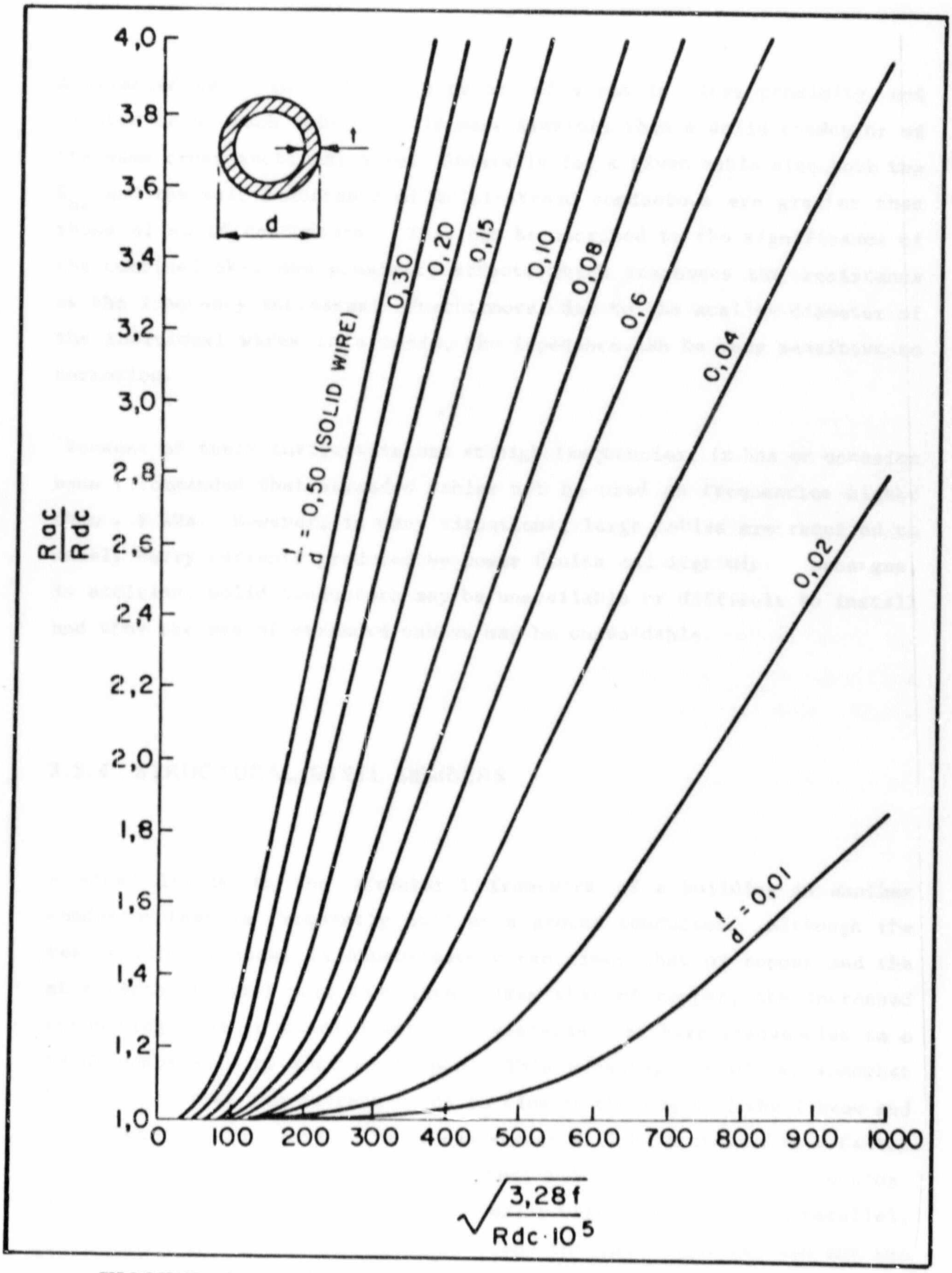


FIGURE 3.7 RESISTANCE RATIO OF NON-MAGNETIC TUBULAR CONDUCTORS (SOURCE: ERIKSSON[4])