SPECIALIZED TELEPHONE NOISE MEASUREMENTS AND INVESTIGATION

CONTENTS

1. GENERAL

1.1 This section provides REA borrowers, consulting engineers, contractors and other interested parties with technical information for use in the design and construction of REA borrowers telephone systems. It is written to provide an understanding of specialized noise measurements in the telecommunications network. Specialized noise measurements are defined as those which are observed as a continuation of an initial noise investigation undertaken by the telephone company craftspeople which has not provided a solution to the problem. As in TE&CM Section 451, the discussion will be primarily directed to interference from harmonics of 60 Hertz power lines.

1.2 Section 451 provided information on techniques for measurement, analysis, isolation and solution of noise problems in the telephone plant by telephone company craftspeople. If, after completing those techniques, it is determined that the telephone plant has high balance, shields are continuous, noise is not originating in the telephone system, etc., it can be assumed the noise probably is the result of some abnormal condition in the power system.

1.3 The investigation at this stage has turned from studying potential problem areas in the telephone system toward a search for problem areas in the power system. While the power company could be contacted at this point there are some additional measurements which can be completed by telephone company personnel. In many situations the power system problem areas can be identified and sometimes located through completion of these measurements. This information can help make the initial contact with the power company more productive.

1.4 Performance of a power system may be analyzed by studying the voltage or current waveform. Since the majority of telephone service today is provided via shielded cable only the power system current waveform will be discussed. This is due to the induced noise in cable being the result of magnetic coupling as discussed in TE&CM Section 451.

2. POWER LINE UNBALANCE CURRENT

2.1 As discussed in Paragraph 7 of TE&CM Section 451, earth return currents of power system harmonics are the source of a high percentage of noise problems in telephone systems. Odd-triple (Zero Sequence, 3rd, 9th, 15th, etc.) harmonics are of major concern since odd-triple currents in each phase conductor are in phase (at the same phase angle). Earth return current is the vector sum of the currents in the phase conductors. When currents are in phase, as with an odd-triple harmonic, the resultant contribution to earth return current is merely the arithmetic sum of the in phase currents. Unbalanced conditions will only make this condition more severe because the vector sum resolution of unequal <u>non</u> odd-triple harmonics contribute to the ground return current where on a balanced system they cancel and are not part of earth return.

2.2 Fundamental frequency phase currents may be shown by a vector (See Figure 1). The current in each phase is thus:

$$I_A\ 0^\circ = I_A\ (\cos 0^\circ + j \sin 0^\circ) = 1I_A + j\ 0I_A$$

$$I_B\ 120^\circ = I_B\ (\cos 120^\circ + j \sin 120^\circ) = -.5I_B + j.87I_B$$

$$I_C\ 240^\circ = I_C\ (\cos 240^\circ + j \sin 240^\circ) = -.5I_C - j.87I_B$$

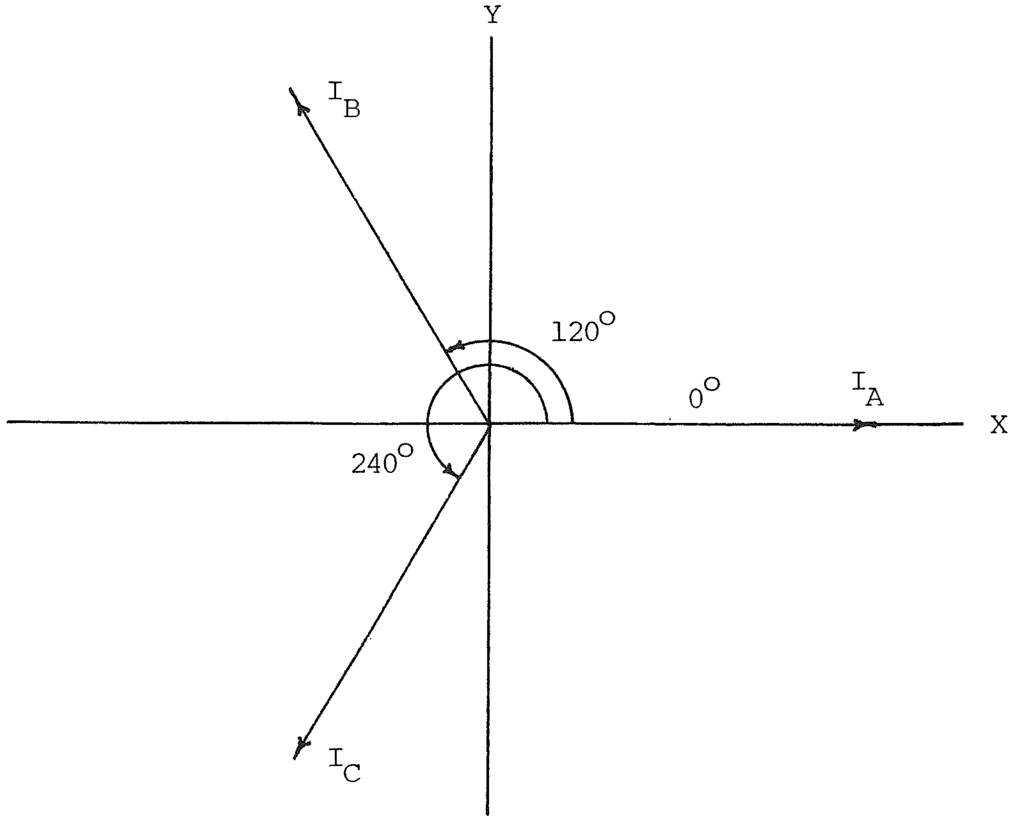


FIGURE 1: PHASE CURRENTS IN THREE-PHASE POWER SYSTEM

2.2.1 Where phase current magnitudes are the same ($I_A = I_B = I_C$) there is no unbalance current and there is no contribution to earth return current. Assuming a 40 ampere current in each phase:

$$
\begin{aligned}
1\ (40) + j\ 0(40) &= \quad 40 + j\ 0 \\
-.5\ (40) + j\ .87\ (40) &= -20 + j\ 34.8 \\
-.5\ (40) - j\ .87\ (40) &= \underline{-20 - j\ 34.8} \\
&= \quad 0 + j\ 0 \text{ Ampere Unbalance}
\end{aligned}
$$

2.2.2 When magnitudes, $I_A \neq I_B \neq I_C$, the vector sum of the currents will not be zero and there will be an unbalance current which will return via the neutral conductor and earth. Assuming $I_A = 20$, $I_B = 80$, $I_C = 40$, Amperes.

$$
\begin{aligned}
1\ (20) + j\ 0\ (20) &= \quad 20 + j\ 0 \\
-.5\ (80) + j\ .87\ (80) &= -40 + j\ 69.6 \\
-.5\ (40) - j\ .87\ (40) &= \underline{-20 - j\ 34.8} \\
& \quad -40 + j\ 34.8 \text{ Ampere Unbalance}
\end{aligned}
$$

Converting from rectangular to polar form = 53 $\underline{/139^\circ}$ Amperes Unbalance

2.2.3 The unbalance current remains the same regardless of which phase is carrying a given current. For example assume the same three phase currents shown in Paragraph 2.2.2, above but distributed among the phases thus, $I_A = 80$ $I_B = 40$ $I_C = 20$. Only the phase angle changes.

$$\begin{array}{rcl} 1\ (80) + j\ 0\ (80) & & 80 + j\ 0 \\ -.5\ (40) + j\ .87\ (40) & = & -20 + j\ 34.8 \\ -.5\ (20) + j\ .87\ (20) & = & \underline{-10 - j\ 17.4} \\ & & 50 + j\ 17.4 \text{ Ampere Unbalance} \end{array}$$

Converting from rectangular to polar form = 53 $\underline{/19^{\circ}}$ Amperes Unbalance

2.3 There is the special case where two of the phase currents are of equal magnitude. The vectors can be oriented so that the j components will cancel out and the following equation will apply:

$$.5I_e + .5I_e - I_u = I_N$$

Where: I_e = The equal phase currents
I_u = The unequal phase current
I_N = The unbalance current that would flow in the neutral and earth path.

2.3.1 This equation is easier to use than the computation of the vector sum of the phase currents. It is reasonably accurate even when the two "equal" phase currents vary from each other by as much as twenty percent provided the "unequal" phase current is large in relation to the "equal" phase currents. For example, take a case where; $I_A = 40$, $I_B = 80$, and $I_C = 48$ amperes. .5 (40 + .5 (48) = 20 + 24 - 80 = 36 amperes.

2.3.2 The vector sum computation for the phase currents shown in Paragraph 2.3.1 is:

$$\begin{array}{rcl} 1\ (40) + j\ 0\ (40) & = & 40 + j\ 0 \\ -.5\ (80) + j\ .87\ (80) & = & -40 + j\ 69.6 \\ -.5\ (48) - j\ .87\ (48) & = & \underline{-24 - j\ 41.8} \\ & & -24 + j\ 27.8 \text{ Ampere Unbalance} \end{array}$$

Converting from rectangular to polar form = 37 $\underline{/130^{\circ}}$ Amperes Unbalance

2.4 Power line currents may be measured directly at any location. Power company personnel can measure current in each phase wire and the neutral wire with a clamp-on ammeter and compute the earth return current. This method is accurate but involves a lot of time and expense. As will be discussed later there are methods of determining the magnitude of earth return currents with a reasonable accuracy which are fast, inexpensive and do not require power company assistance.

3. MUTUAL IMPEDANCE

3.1 A simple explanation of magnetic induction is given in Paragraph 4 of TE&CM Section 451. It describes how a magnetic field produced by an ac current flowing in a power conductor will induce a longitudinal voltage in a nearby telephone conductor. The magnitude of this induced voltage may be determined for an unshielded telephone conductor by calculating the mutual impedance between the two conductors and multiplying this impedance by the earth return current.

3.1.1 Mutual impedance may be defined as the ratio of the induced open circuit voltage to ground in the telephone conductor per unit length to the unbalance current (earth return current) in the power system.

3.1.2 Mutual impedance provides a valuable tool for use during noise investigations. The expected power influence in an exposed telephone circuit can be calculated for comparison with recorded measured values. Other paralleling metallic conductors, including the telephone cable shield help "shield" cable pairs and reduce induced voltages. Shielding, therefore, should be considered in any calculations. Shielding and shield factors will be presented in Paragraph 4 of this TE&CM.

3.2 J. R. Carson of Bell Laboratories developed the equation for mutual impedance in 1926. E. D. Sunde[1] presented a simplified form of Carsons equation for mutual impedance between power and telephone. For separations between the two facilities normally found during noise investigations, Sunde's simplified equation is valid to within five percent. This is an acceptable accuracy for calculations discussed in this section. Sunde's simplified equation for close separation is:

$$Z_{12} = \frac{j\,\omega\mu_o}{4\pi}\left[2\ln\left(\frac{\sqrt{2}\,\delta}{g d_{12}}\right) + 1 - \frac{j\pi}{2} + \frac{4}{3\delta}\,(1 + j)\,(h_1 + h_2)\right]$$

Where:
- Z_{12} = Complex mutual impedance per unit length (ohms/meter)
- ω = $2\pi f$ = angular frequency of inducing current (radians per second)
- μ_o = $4\pi \times 10^{-7}$ = free space permeability (henry/meter)
- g = $1.7811 = e^{\gamma}$
- d_{12} = $\sqrt{(h_1 - h_2)^2 + x^2}$ = radial distance between conductors
- X = horizontal separation between power and telephone lines
- h_1 = height of power line above ground (negative if buried cable)
- h_2 = height of telephone line above ground (negative if buried cable)
- ρ = earth resistivity in meter-ohms
- δ = skin depth in meters = $2\rho/\omega\mu_o$
- γ = .5772 = Euler's Constant
- ln = Log_e

NOTE: X, h_1 and h_2 are in meters.

3.2.1 A complex impedance is made up of a real part and an imaginary part. Thus, the complex impedance (Z_{12}) is composed of a mutual resistance (R_{12}) and a mutual reactance (X_{12}). Therefore, $Z_{12} = R_{12} + j X_{12}$.

3.2.2 The equation shown in Paragraph 3.2 can be simplified by collecting its real and imaginary parts. This simplification is valuable for engineers when performing mutual impedance calculations. The real part of the equation is:

[1] E. D. Sunde, "Earth Conduction Effects in Transmission Systems", Dover Publications, N. Y. (1968).

$$R_{12} = \frac{\omega\mu_o}{4\pi}\left[\frac{\pi}{2} - \frac{4}{3\delta}\quad(h_1 + h_2)\right]$$

and the imaginary part is:

$$X_{12} = \frac{\omega\mu_o}{4\pi}\left[2In\left(\frac{\sqrt{2}\delta}{gd_{12}}\right) + 1 + \frac{4}{3\delta}\,(h_1 + h_2)\right]$$

3.2.3 The results of computations in ohms/meter may be converted to ohms/kilofoot by multiplying by 304.8.

3.4 The equation in Paragraph 3.2.2 has been used to develop the curves in Figure 2 for determining the mutual impedance between the power and telephone system at the fundamental frequency (60 Hertz). To use the chart enter from the bottom scale following the vertical line from the separation of the conductors in feet to the point of intersection with the earth resistivity line of interest. Read the mutual impedance on the left hand scale of the chart along the horizontal line from the point of intersection.

3.4.1 Assuming there is a buried telephone cable beneath a power line and the separation between them is 44 feet in an area with 100 meter-ohms earth resistivity enter the Figure 2 at 44 foot point on the bottom scale and follow this vertical line to the point where it intersects the $\rho = 100$ line. Moving horizontally to the left scale, observe that the mutual impedance is about 0.098 ohms per kilofoot. If there is one ampere of 60 Hz earth return current in the power system there would be an open circuit 60 Hz voltage to ground of 0.098 volts per kilofoot of unshielded telephone conductcr.

3.4.2 Where the average earth resistivity of an area is known and it is not close to one shown, the chart may be entered at the point $(d)/\sqrt{\rho}$ on the bottom scale. Follow the vertical line to the intersection with the $\rho = 1$ curve and read Zm of this point on the left scale of the chart.

3.5 The curves in Figure 3 are for determining the mutual impedance between power and telephone systems at a frequency of 540 Hertz. Application is identical to that for Figure 2 discussed in Paragraph 3.4, above.

3.6 The use of Figures 2 and 3 should cover most situations where calculations of mutual impedance between power and telephone systems are desired. There will be cases where harmonics other than the ninth (540 Hertz) are predominant and mutual impedances at these harmonics are desired. Figure 4 has been developed for these cases. Figure 4 provides the mutual impedance in ohms per Hertz. The chart is entered along the bottom horizontal scale at the point $(d) \times \sqrt{f}$ (d = conductor separation in feet and f = frequency in Hertz). Follow the vertical line to the point of intersection with earth resistivity of interest and read the mutual impedance for one Hertz on the left scale of the chart. Multiply this value by f to obtain the desired mutual impedance in ohms per kilofoot.

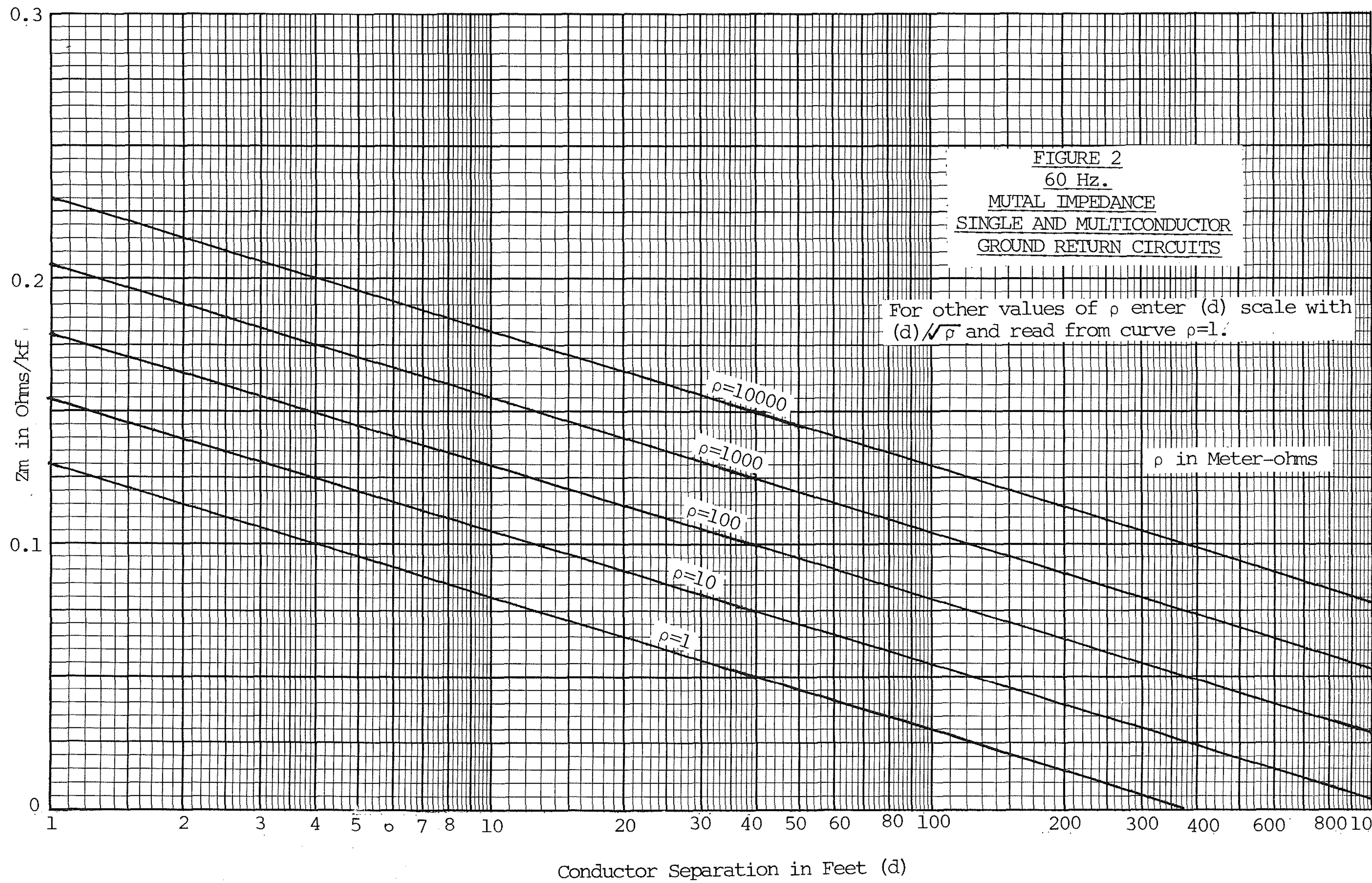


FIGURE 2
60 Hz.
MUTAL IMPEDANCE
SINGLE AND MULTICONDUCTOR
GROUND RETURN CIRCUITS
For other values of ρ enter (d) scale with (d)/√ρ and read from curve ρ=1.
ρ in Meter-ohms
ρ=10000
ρ=1000
ρ=100
ρ=10
ρ=1
Zm in Ohms/kf
0.3
0.2
0.1
0
1
2
3
4
5
6
7
8
10
20
30
40
50
60
80
100
200
300
400
600
800
1000
Conductor Separation in Feet (d)

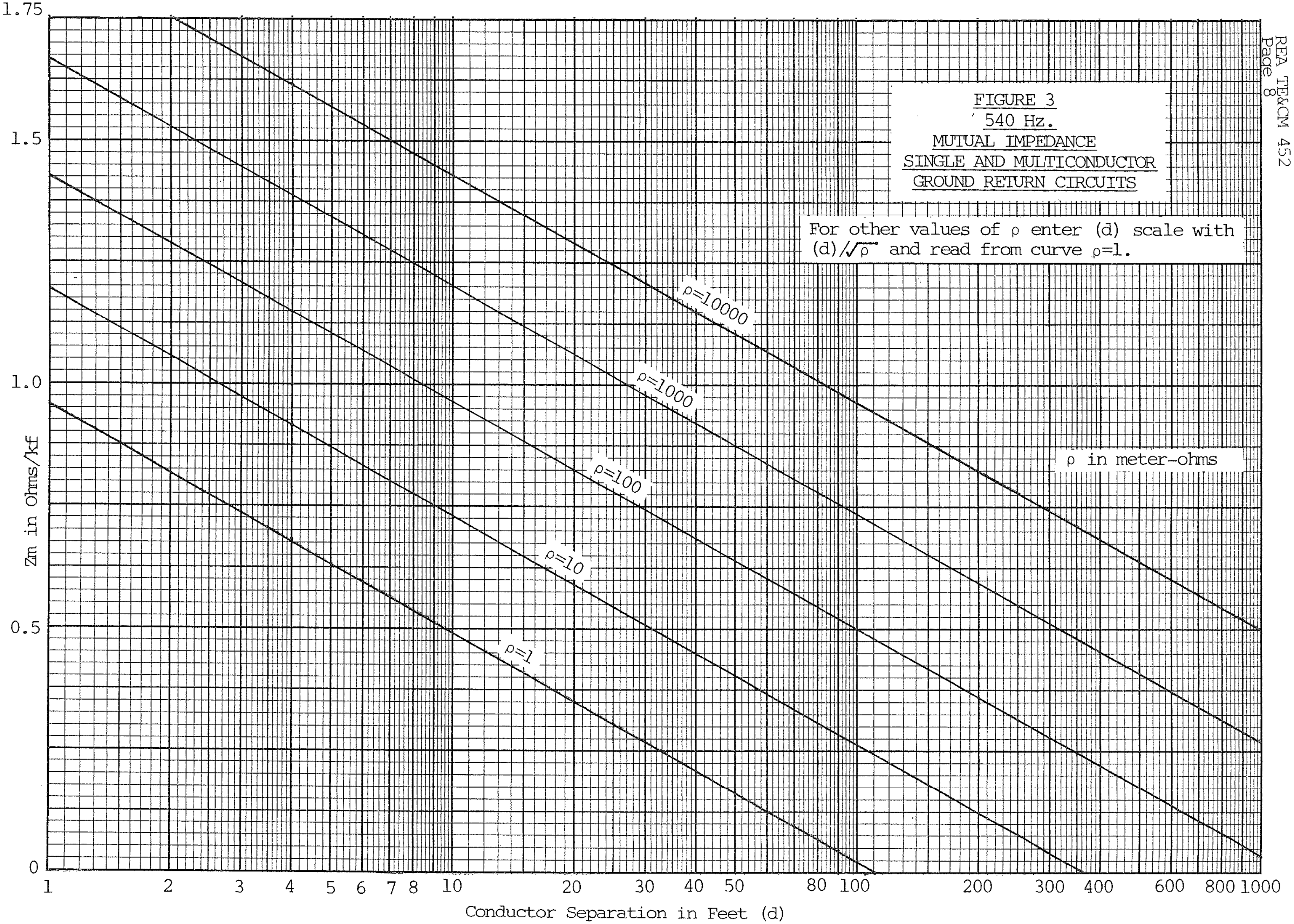


FIGURE 3
540 Hz.
MUTUAL IMPEDANCE
SINGLE AND MULTICONDUCTOR
GROUND RETURN CIRCUITS
For other values of ρ enter (d) scale with (d)/√ρ and read from curve ρ=1.
ρ in meter-ohms
ρ=10000
ρ=1000
ρ=100
ρ=10
ρ=1
1.75
1.5
1.0
0.5
0
Zm in Ohms/kf
1
2
3
4
5
6
7
8
10
20
30
40
50
80
100
200
300
400
600
800
1000
Conductor Separation in Feet (d)

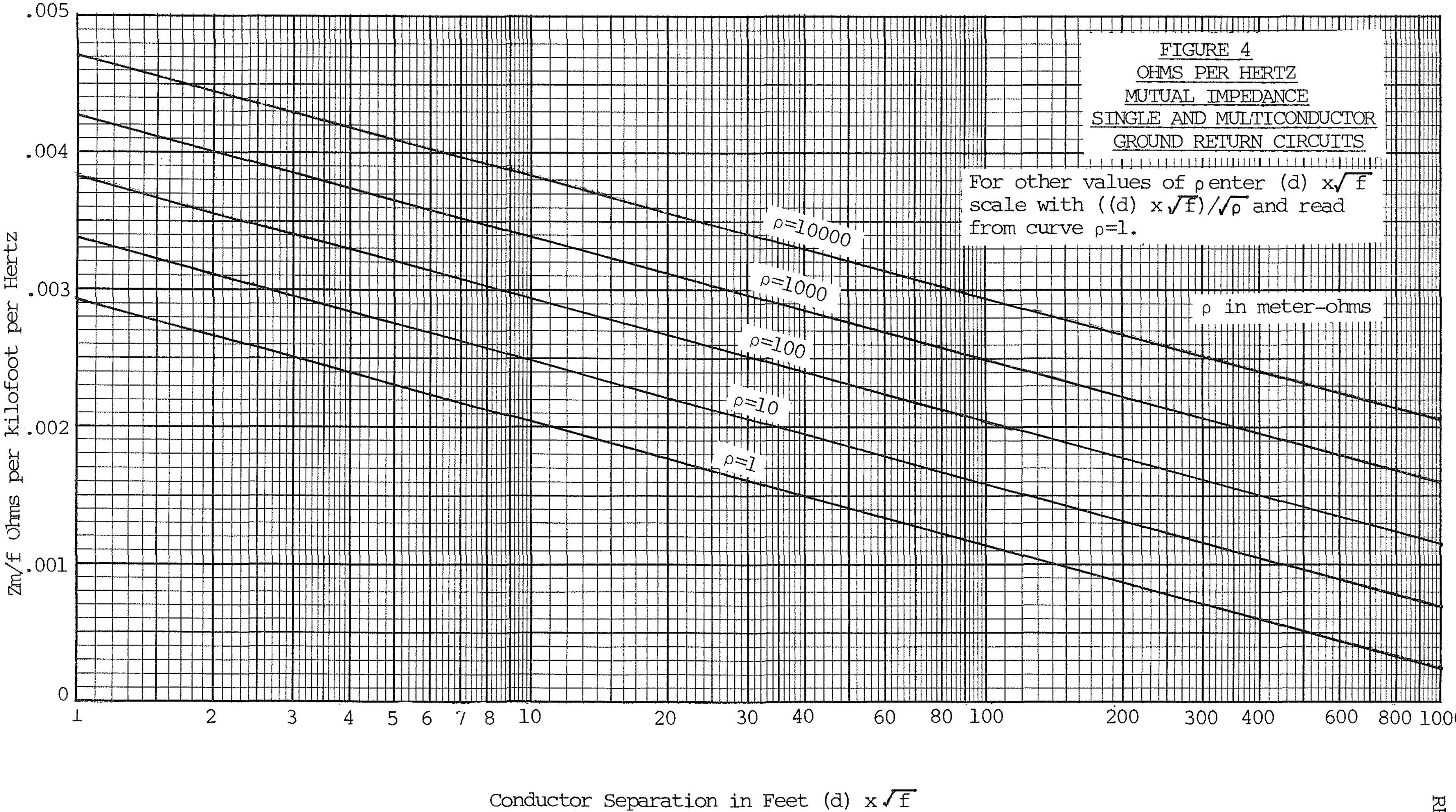


FIGURE 4
OHMS PER HERTZ
MUTUAL IMPEDANCE
SINGLE AND MULTICONDUCTOR
GROUND RETURN CIRCUITS
For other values of ρ enter (d) x√f scale with ((d) x√f)/√ρ and read from curve ρ=1.
ρ in meter-ohms
ρ=10000
ρ=1000
ρ=100
ρ=10
ρ=1
Zm/f Ohms per kilofoot per Hertz
.005
.004
.003
.002
.001
0
1
2
3
4
5
6
7
8
10
20
30
40
60
80
100
200
300
400
600
800
1000
Conductor Separation in Feet (d) x√f

3.6.1 Assume the predominant harmonic along a power line proves to be the fifteenth (900 Hertz). The separation between power and telephone conductors is 25 feet and earth resistivity is 100 meter-ohms. Since $25 \times \sqrt{900} = 750$ the chart is entered at the 750 point along the bottom scale. Moving vertically to the point of intersection with the $\rho = 100$ curve then horizontally to the left hand scale, the mutual impedance of .0013 ohms per kilofoot/Hertz is found. Multiplying this value of .0013 ohms per kilofoot/Hertz by 900 Hertz results in the 900 Hertz mutual impedance of 1.17 ohms per kilofoot. Thus where there is one ampere earth return current at 900 Hertz there would be an induced 900 Hz voltage to ground of 1.17 volts per kilofoot on unshielded telephone conductors.

3.6.2 Where the average earth resistivity of an area is not close enough to resistivity values on the curves in Figure 4 enter the chart at the point (d) $\sqrt{f}\,)/\sqrt{\rho}$ on the bottom scale (d = conductor separation in feet, f = frequency in Hertz and ρ = earth resistivity in meter-ohms). Follow the vertical line to the intersection with the $\rho = 1$ line and read Zm per Hertz of this point on the left scale of the Chart. For example had the earth resistivity for the illustration in Paragraph 3.6.1 been 500 meter-ohms the mutual impedance would have been 1.46 rather than 1.17 ohms per kilofoot.

3.7 Figure 5 has been prepared to provide a convenient means of determining $\sqrt{f}$ or $\sqrt{\rho}$ when needed. Enter the chart along the bottom horizontal scale at the value of f for ρ. Follow the vertical line to the point it intersects the curve. Read $\sqrt{f}$ or $\sqrt{\rho}$ at this point on the left scale of the chart.

4. SHIELD FACTORS (n)

4.1 An explanation of shielding is given in Paragraph 5 of TE & CM Section 451. Section 451 shows that the addition of a conductor between the power and telephone conductors through which current can flow between the power and telephone conductors will result in some reduction of the longitudinal induced voltage in the telephone conductor. Paragraph 5 of 451 also shows via shield factor discussion that there is minimal shielding at the 60 Hertz fundamental frequency and that shielding increases with frequency. Effects of shield resistance and resistance to earth of electrodes connecting shields to earth are also discussed.

4.1.1 Shield factor may be defined as the ratio of the voltage to ground in the telephone circuit (disturbed circuit) after introduction of the shielding circuit, to the nonshielded induced voltage to ground in the telephone circuit (disturbed circuit) with the current in the power circuit (disturbing circuit) remaining the same.

4.1.2 Shield factors are another valuable tool during noise investigation. Expected power influence, at any harmonic frequency, in an exposed telephone circuit can be calculated and compared to recorded measured values.

4.1.3 The magnitude of expected voltage to ground in a shielded telephone conductor may be found by multiplying the expected voltage to ground in a nonshielded conductor as found in Paragraph 3.1.3 by the shield factor.

4.2 The equation for calculating the shield factor when the shield conductor is close to the disturbed conductor and remote from the disturbing conductor is:

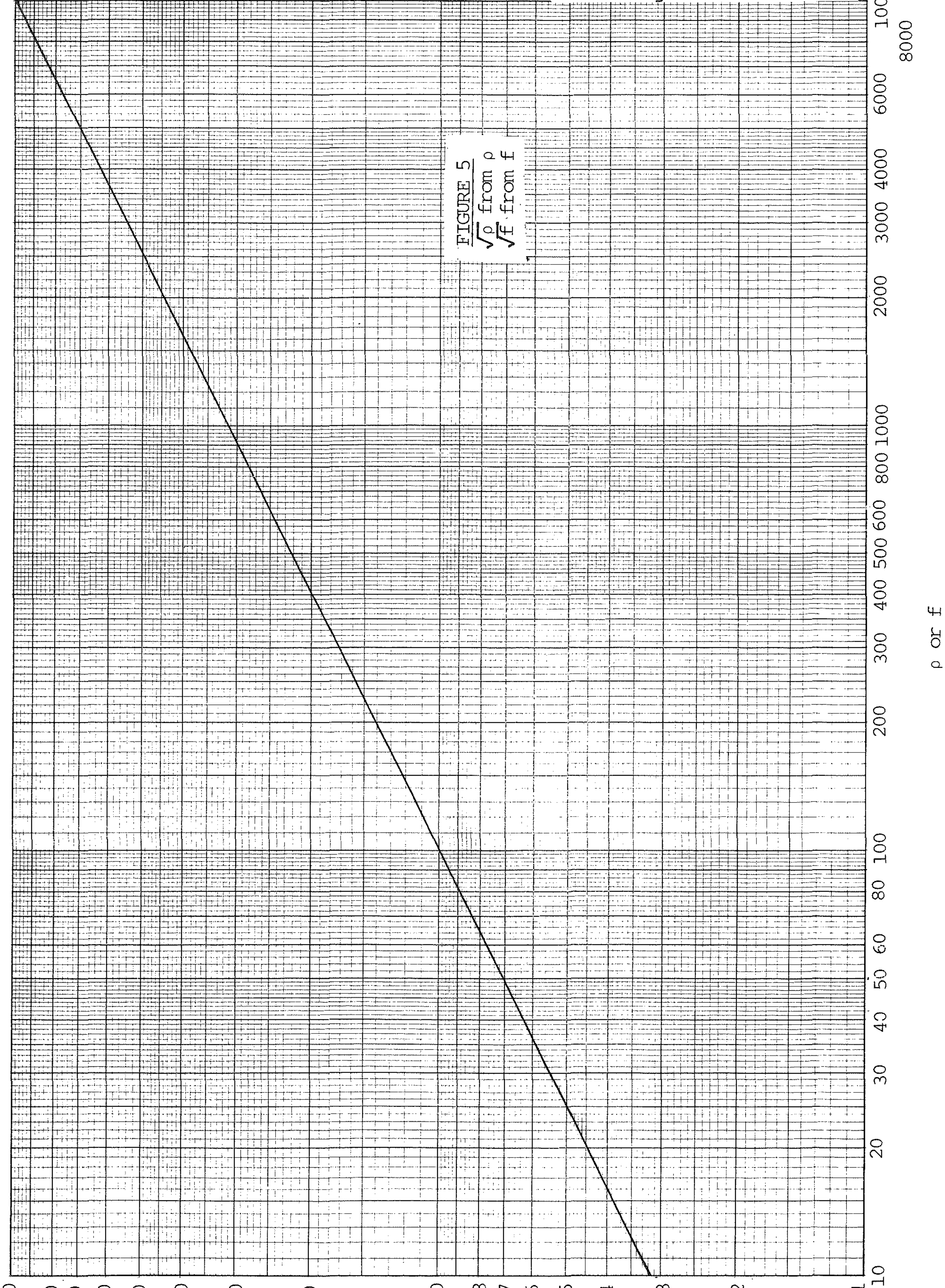


FIGURE 5
√ρ from ρ
√f from f
ρ or f
√ρ or √f
10 20 30 40 50 60 80 100 200 300 400 500 600 800 1000 2000 3000 4000 6000 8000 10000
1 2 3 4 5 6 7 8 10 20 30 40 50 60 70 80 100

$$\eta = \frac{Z_{22} - Z_{23} + \frac{R_T}{\ell}}{Z_{22} + \frac{R_T}{\ell}} = 1 - \frac{Z_{23}}{Z_{22} + \frac{R_T}{\ell}}$$

Where: η = Shield factor
Z_{22} = Ground return self impedance of the shield in ohms per kilofoot.
Z_{23} = Ground return mutual impedance between the shield and telephone conductors in ohms per kilofoot.
R_T = Total resistance to earth of earth electrodes in ohms.
ℓ = Length of cable in kilofeet

4.2.1 Since most telephone noise investigations will involve cables with nonmagnetic shields, (Aluminum, copper, etc.), the equation in Paragraph 4.2 can be simplified. For a nonmagnetic shield, the internal self reactance is negligible and the internal self resistance is the effective resistance of the cable shield. The ground return self impedance (Z_{22}) of the cable shield is thus equal to the external self impedance (Z^o_{22}) plus the effective resistance (r_{22}). The self impedance (Z_{22}) of the cable shield differs from the mutual impedance (Z_{23}) between the shield and the telephone conductors only by the effective resistance (r_{22}) of the cable shield ($Z_{22} - Z_{23} = r_{22}$).

4.2.2 Applying this to the equation in Paragraph 4.2 produces the following equation for application to cables with nonmagnetic shields:

$$\eta = \frac{r_{22} + \frac{R_T}{\ell}}{r_{22} + \frac{R_T}{\ell} + Z^o_{22}}$$

Where: η = Shield factor
r_{22} = Effective resistance of shield in ohms per kilofoot
Z^o_{22} = External self impedance of the shield circuit in ohms per kilofoot.
R_T = Total resistance to earth of earth electrodes in ohms.
ℓ = Length of cable in kilofeet

4.3 Carson's equation, discussed in Paragraph 3, can be simplified to the following form for calculation of the self and mutual impedance of earth return circuits:

$$Z_{22} = \frac{r}{n} + 0.3 \times 10^{-3} f + j\,0.882 \times 10^{-3} f \times \log_{10} \left(\frac{2280}{d \sqrt{\frac{f}{\rho}}} \right)$$

$$Z_{23} = 0.3 \times 10^{-3} f + j\,0.882 \times 10^{-3} f \times \log_{10} \left(\frac{2280}{d \sqrt{\frac{f}{\rho}}} \right)$$

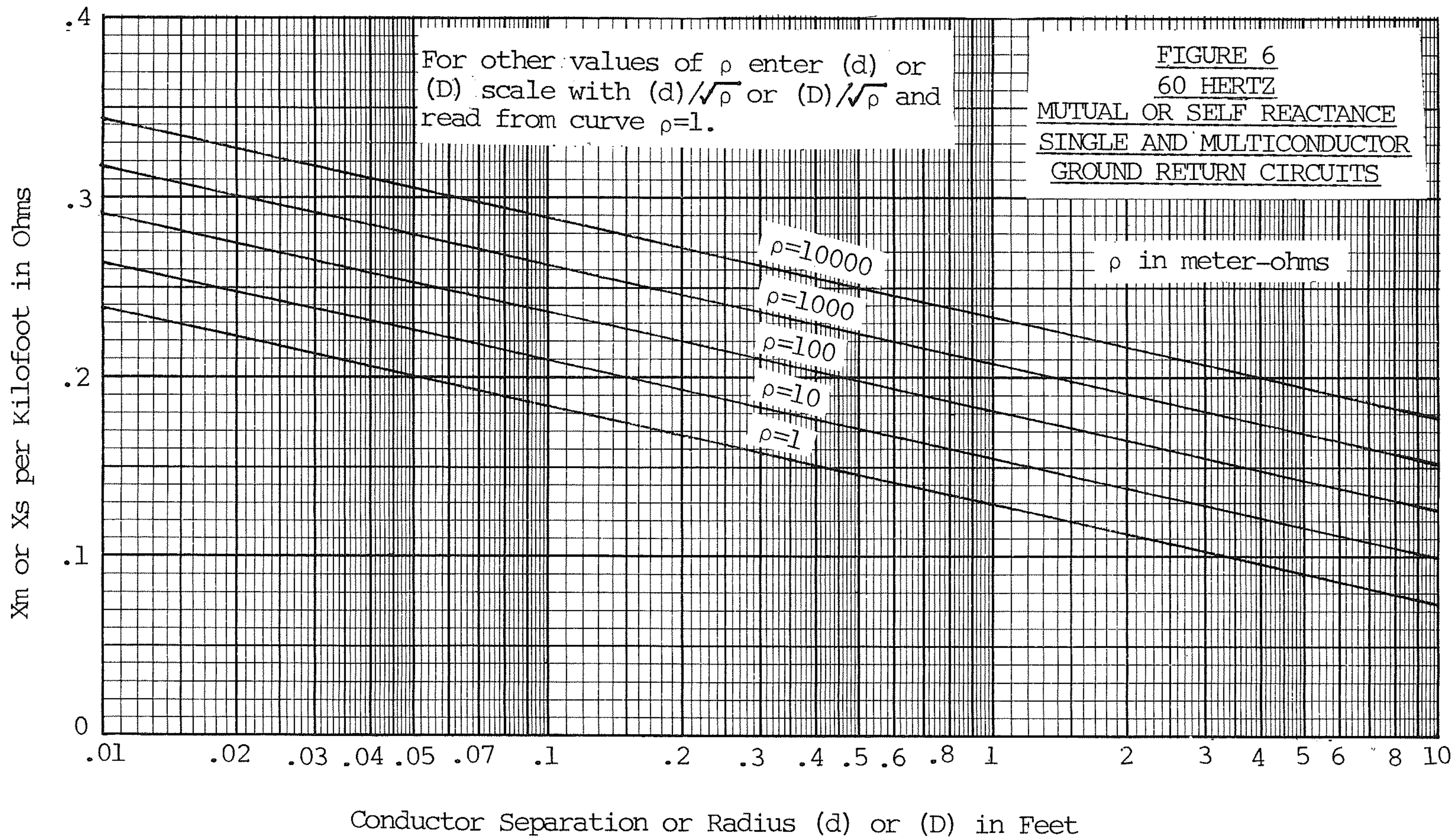


FIGURE 6
60 HERTZ
MUTUAL OR SELF REACTANCE
SINGLE AND MULTICONDUCTOR
GROUND RETURN CIRCUITS

Where: Z_{22} = Ground return self impedance of the shield in ohms per kilofoot.

Z_{23} = Ground return mutual impedance between the shield and telephone conductors in ohms per kilofoot.

$\frac{r}{n}$ = Effective resistance of shield circuit in ohms per kilofoot (where shield circuit is a single metallic shield conductor, n = 1).

f = Frequency in Hertz.

D = Radius of shield conductor in feet.

ρ = Earth resistivity in meter-ohms.

d = Radial distance between conductors.

4.3.1 As was shown in Paragraph 4.2.1 $Z_{22} = r_{22} + Z^{o}_{22}$. Z^{o}_{22} is a complex impedance and in rectangular form is equal to an external resistance term and an external reactance term, $Z^{o}_{22} = R_s + j\,x_s$.

4.3.2 The earth return mutual impedance (Z_{23}) between circuits is a complex impedance. In rectangular form it is equal to a mutual resistance term plus a mutual reactance term, $Z_{23} = R_m + X_m$.

4.3.3 These equations are approximations that are valid for the separations and frequencies most often encountered during noise investigations.

4.4 Curves in Figure 6 are for calculating 60 Hertz self or mutual reactances and are useful for finding 60 Hertz shield factors. Since these curves are intended for this single application, the (d) or (D) scale has only been plotted to 10 feet. Where mutual impedance between the power and telephone systems is desired refer to Paragraph 3.

4.4.1 Enter the bottom horizontal scale of Figure 6 at the value corresponding to the radius of the shield conductor in feet. (To find the radius of a cable shield in feet, divide the shield diameter in inches by 24). From this point, follow the vertical line to the point where it intersects the appropriate earth resistivity curve. Read the reactance on the left vertical scale.

4.4.2 Where average earth resistivity is not close to one shown in the curves, enter the scale along the bottom line at the point $(d)/\sqrt{\rho}$ or $(D)/\sqrt{\rho}$. Follow the vertical line to the intersection with the $\rho = 1$ curve and read the reactance of this point on the left vertical scale of Figure 6.

4.4.3 The external or mutual resistance term is needed to complete the external self or mutual impedance in rectangular form. This term is a direct function of frequency and is independent of separation or radius and earth resistivity. The external or mutual resistance term shown in Paragraph 4.3 is $0.3 \times 10^{-3} f$. Figure 7 provides the resistance term value for frequencies of interest for most noise investigations. Enter the Figure 7 horizontal scale at the desired frequency. Follow the vertical line to the point where it intersects and read the resistance term on the left vertical scale.

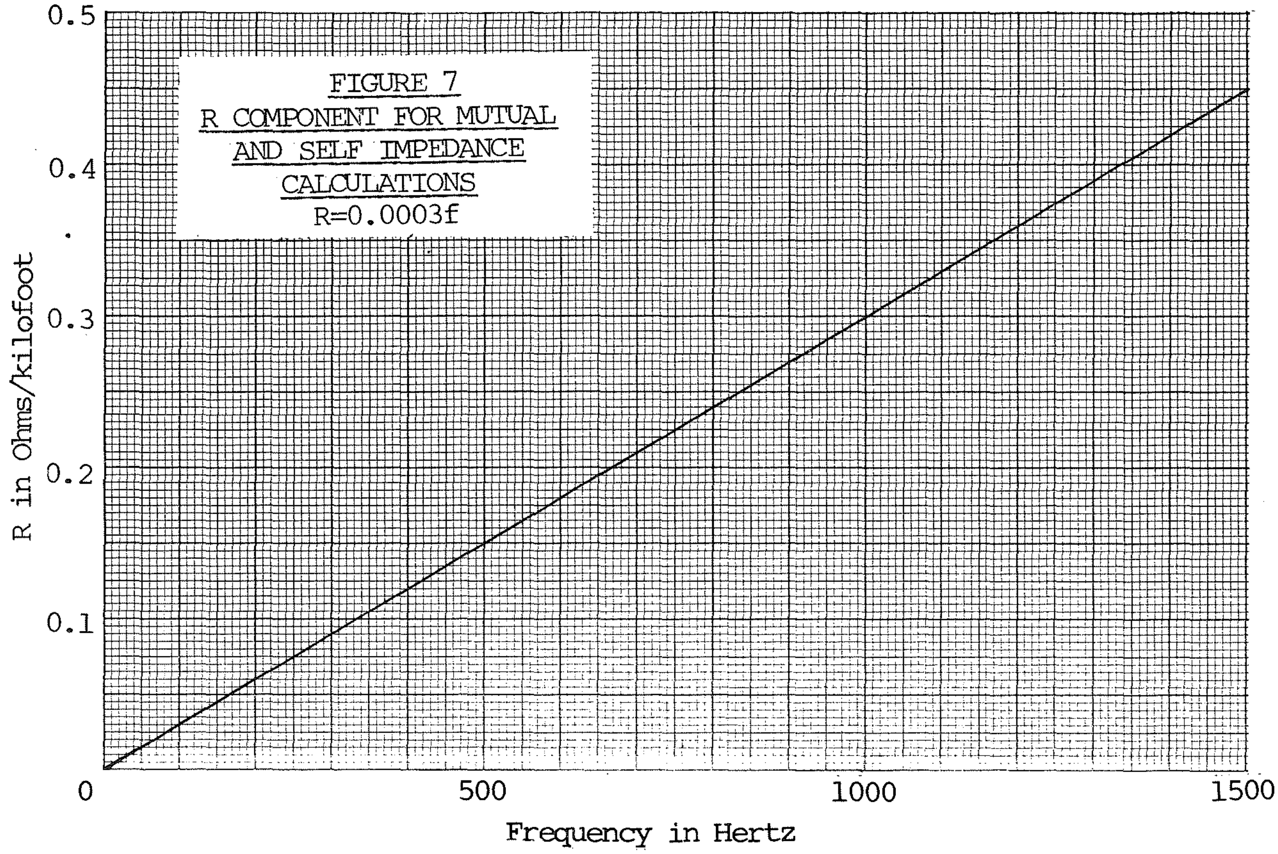


FIGURE 7
R COMPONENT FOR MUTUAL AND SELF IMPEDANCE CALCULATIONS
$R=0.0003f$

4.4.4 Assume the 60 Hertz shield factor is desired for 10 kilofeet of 25-24 filled cable with an 8 mil aluminum shield, in an area with 100 meter ohms earth resistivity. The cable diameter is found to be 0.61 inch from Table I of this TE&CM and the shield resistance is 1.1 ohms per kilofoot from Table 1 in TE&CM Section 451.

TABLE I

CABLE DIAMETERS IN INCHES FILLED CABLES

PAIRS	GAUGES 26	24	22	19
6	-	.41	.44	.51
12	-	.49	.54	.77
18	-	.53	.63	.82
25	.50	.61	.70	.92
50	.62	.76	.90	1.29
75	.70	.88	1.09	1.57
100	.77	.99	1.22	1.73
150	.93	1.19	1.48	2.09
200	1.08	1.44	1.66	2.37
300	1.26	1.62	2.01	2.79
400	1.43	1.86	2.30	-
600	1.74	2.29	2.81	-

NOTE: These diameters apply to the following shield materials; 5 mil copper, 10 mil copper, 8 mil aluminum, and 6 mil copper steel.

4.4.4.1 From Figure 7, we find the external resistance term for 60 Hertz is 0.018 ohms/kft. Dividing the cable diameter in inches (0.61) by 24 we obtain a cable radius of 0.025 feet. Figure 6 shows the external self reactance for a cable with 0.025 foot radius in an area of 100 meter-ohms earth resistivity is 0.265 ohms/kft.

4.4.4.2 Placing these values in the equation shown in Paragraph 4.2 produces:

$$\eta = \frac{r_{22} + \frac{R_T}{\ell}}{r_{22} + \frac{R_T}{\ell} + Z^o_{22}} = \frac{1.1 + \frac{10}{10}}{1.1 + \frac{10}{10} + 0.018 + j\,0.265} = \frac{2.1}{2.118 + j\,0.265}$$

4.4.4.3 The denominator (2.118 + j 0.265) is the ground return self impedance (Z_{22}) of the shield circuit in rectangular form with the added term for the resistance to earth of the end electrodes. Before the division operation can be completed the denominator must be converted from rectangular to polar form. The magnitude of the impedance (Z) = $\sqrt{R^2 + X^2}$. This gives $\frac{2.1}{2.13} = 0.99 = n$. The phase angle involved may be ignored for shield factor applications discussed here.

4.5 Curves in Figure 8 are for calculating 540 Hertz external or mutual reactances and are useful for finding 540 Hertz shield factors. Since they are intended for this single purpose the (d) or (D) scale has only been plotted to 10 feet. Refer to Paragraph 3 for mutual impedance between the power and telephone systems.

4.5.1 Enter Figure 8's bottom horizontal scale at the value corresponding to the radius of the shield conductor in feet. (To find the radius of a shield conductor in feet divide the shield diameter in inches by 24.) From this point follow the vertical line to the point where it intersects the appropriate earth resistivity curve. Read the reactance of this point on the left vertical scale.

4.5.2 Where the average earth resistivity is not close to one shown in the curves enter the scale along the bottom line at the value corresponding to $(d)/\sqrt{\rho}$ or $(D)/\sqrt{\rho}$. Follow the vertical line to the intersection with the $\rho = 1$ curve and read the reactance of this point on the left vertical scale of Figure 8.

4.5.3 The external or mutual resistance term is needed to complete the rectangular form of the external self or mutual impedance. The method for obtaining this term is discussed in detail in Paragraph 4.4.3.

4.5.4 Assume the shield factor is desired at 540 Hertz for the same cable described in Paragraph 4.4.4.

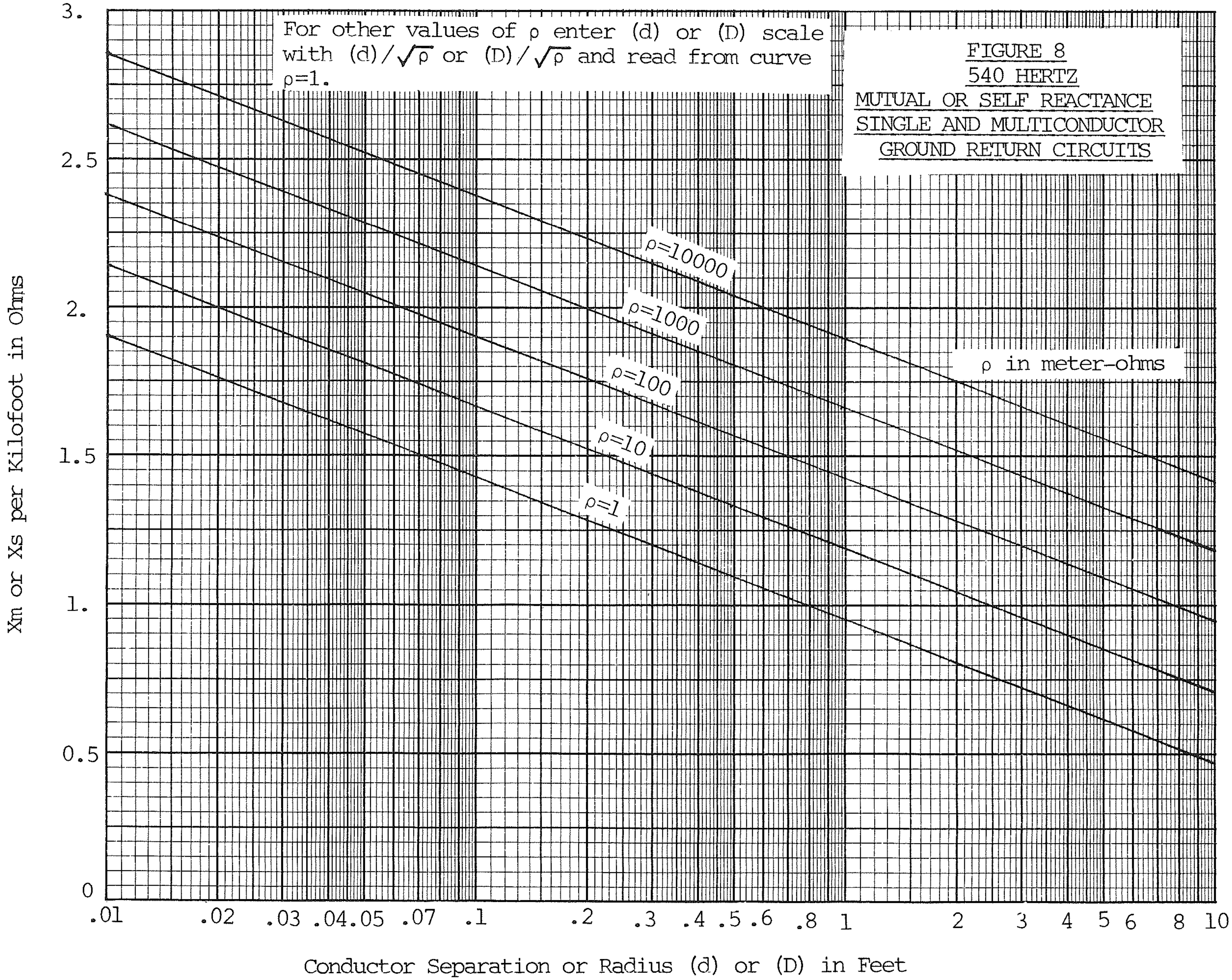
4.5.4.1 From Figure 7, the external resistance term for 540 Hertz is 0.162/kft. The external self reactance (from Figure 8) for a cable with 0.025 foot radius in an area of 100 meter-ohms earth resistivity is 2.19 ohms/kft.

4.5.4.2 Placing these values in the equation shown in Paragraph 4.2 produces:

$$\eta = \frac{r_{22} + \frac{R_T}{\ell}}{r_{22} + \frac{R_T}{\ell} + Z^o_{22}} = \frac{1.1 + \frac{10}{10}}{1.1 + \frac{10}{10} + 0.162 + j\,2.19} = \frac{2.1}{2.262 + j\,2.19} =$$

$$\frac{2.1}{3.15} = 0.67$$

Again phase angles are not necessary and are disregarded.


For other values of ρ enter (d) or (D) scale with (d)/√ρ or (D)/√ρ and read from curve ρ=1.
FIGURE 8
540 HERTZ
MUTUAL OR SELF REACTANCE
SINGLE AND MULTICONDUCTOR
GROUND RETURN CIRCUITS
ρ in meter-ohms
ρ=10000
ρ=1000
ρ=100
ρ=10
ρ=1
Xm or Xs per Kilofoot in Ohms
3.
2.5
2.
1.5
1.
0.5
0
.01
.02
.03
.04
.05
.07
.1
.2
.3
.4
.5
.6
.8
1
2
3
4
5
6
8
10
Conductor Separation or Radius (d) or (D) in Feet

4.6 The application of Figure 6 and 8 should cover most situations where calculation of the shield factor is desired. There will be cases where a harmonic other than the ninth (540 Hertz) is predominant and the shield factor at this frequency is desired. Figure 9 has been developed for these cases. It provides the external self or mutual reactance in ohms/kft per Hertz. Enter the bottom horizontal scale at the value corresponding to (d) x $\sqrt{f}$ or (D) x $\sqrt{f}$. Follow the vertical line to the point it intersects the earth resistivity of interest and read the reactance for one Hertz on the left vertical scale. Multiply this value by f to obtain the desired reactance term. The external self or mutual resistance term is obtained from Figure 7 as described in Paragraph 4.43.

4.6.1 Assume the shield factor is desired at 900 Hertz for the cable described in Paragraph 4.4. From Figure 7, the external resistance term is 0.269 ohms/kft.

4.6.1.1 To find the external self reactance, determine $\sqrt{900}$. From Figure 5, we find $\sqrt{900}$ is 30. Multiplying 30 by the cable radius in feet (0.025) produces 0.75. Entering the bottom scale of Figure 9 at this value, we find the reactance per Hertz in an area with 100 meter-ohms earth resistivity is 0.00395. Multiplying this by 900 provides the total self reactance, 3.56 ohms/kft.

4.6.1.2 Placing these values in the equation shown in Paragraph 4.2 produces:

$$\eta = \frac{r_{22} + \frac{R_T}{\ell}}{r_{22} + \frac{R_T}{\ell} + Z^o_{22}} = \frac{1.1 + \frac{10}{10}}{1.1 + \frac{10}{10} + 0.269 + j\,3.56} = \frac{2.1}{2.369 + j\,3.56} =$$

$$\frac{2.1}{4.28} = 0.49$$

5. EXPECTED VOLTAGE TO GROUND

5.1 During noise investigations it may be desirable to determine if the measured power influence in a telephone circuit is that which should be expected for the measured earth return current of the power system, either at the fundamental frequency or at a harmonic frequency. The expected voltage to ground can be calculated from the three factors discussed in Paragraph 2, 3, and 4. The resulting voltage can then be converted to power influence.

5.1.1 Calculation of expected voltage to ground is not precise. There are unpredictable variables, broad assumptions and averaging involved, all of which influence the accuracy of the results. For example, separation between power and telephone conductors is assumed constant but actually varies throughout the length of exposure. The actual value used in the calculations is an estimate of average separation.

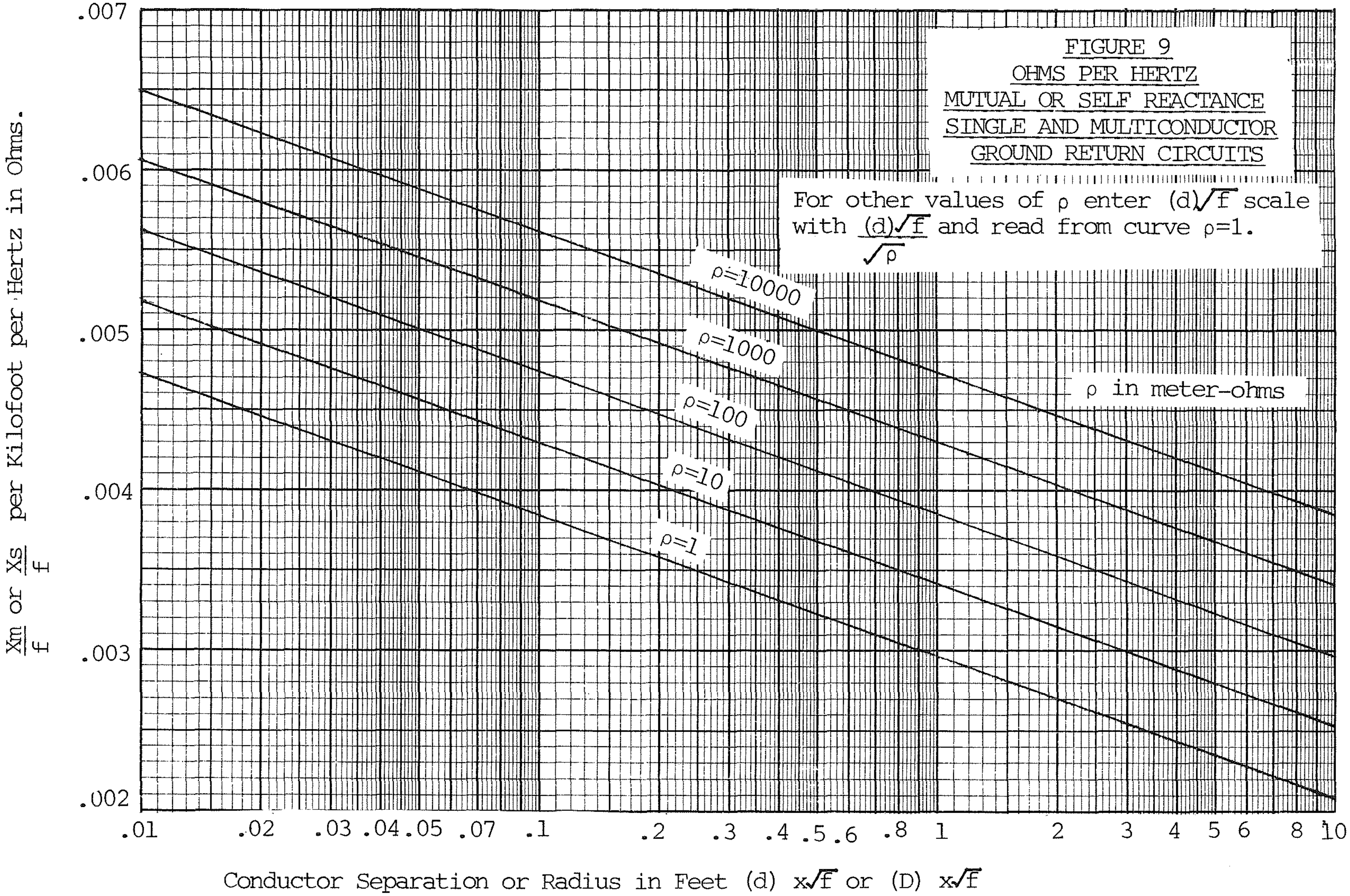


FIGURE 9
OHMS PER HERTZ
MUTUAL OR SELF REACTANCE
SINGLE AND MULTICONDUCTOR
GROUND RETURN CIRCUITS
For other values of ρ enter (d)√f scale with (d)√f / √ρ and read from curve ρ=1.
ρ in meter-ohms
ρ=10000
ρ=1000
ρ=100
ρ=10
ρ=1
.007
.006
.005
.004
.003
.002
.01
.02
.03
.04
.05
.07
.1
.2
.3
.4
.5
.6
.8
1
2
3
4
5
6
8
10
Xm/f or Xs/f per Kilofoot per Hertz in Ohms.
Conductor Separation or Radius in Feet (d) x√f or (D) x√f

5.1.2 Earth resistivity along a cable route will usually vary over a wide range. An average value based on several measured values along a route will provide an acceptable calculated power influence. It can be shown that at 60 Hertz an unshielded telephone conductor 10,000 feet long located 30 feet from a parallel power conductor with one ampere earth return current will have power influence as shown with various values of earth resistivity.

Earth Resistivity in Meter-ohms	Power Influence in dBrn
100	92.8
1000	94.6
10000	96.2

These values are within the allowable tolerance for expected voltage to ground calculations. They also indicate that calculations for areas where measured earth resistivity is unavailable may be completed using an assumed value of 1000 meter-ohms.

5.1.3 Power system earth return current will vary through the length of exposure. The value used in calculations is usually an average of two or three measurements of the earth return current along the length of exposure.

5.1.4 Calculations are usually accurate enough to determine whether measured power influence is reasonable and what is expected for the existing earth return current. When 4 dBrn or less differences are found, measured influence values are considered valid.

5.2 The total length of exposure should be surveyed, recording the lengths where separation between the power and telephone system is essentially the same. Where staking sheets are not available, lengths of exposure may be measured with an automobile odometer. Separations which vary by up to ten feet are considered to be essentially the same and the average separation for the exposure length estimated. Where greater variations are found, they should be treated as new exposure lengths.

5.2.1 The earth return current of the power system should be measured during worst case, highest expected magnitude, times at least once along each exposure length. Where a long exposure length occurs (in excess of five kilofeet), two or more measurements should be made and results averaged. This will be discussed in detail in TE&CM 452.2 and 452.3.

5.2.2 After determining: exposure lengths, separations between power and communications circuits, power system earth return current, average earth resistivity and mutual impedance between power and communications circuits as per Paragraph 3, and shield factor as per Paragraph 4, the expected open circuit voltage to ground can be calculated by the equation below.

$$E_G = Z_{12} I_{GR} \ell \eta$$

Where: E_G = Voltage to ground in volts
Z_{12} = Mutual impedance between the power and telephone circuits in ohms per kilofoot
I_{GR} = Earth return current of the power system in amperes
ℓ = Length of exposure in kilofeet
η = Shield factor for the telephone cable

5.3 Since most test equipment for measuring voltage to ground provide results in dBrn noise-to-ground (N_g) rather than volts, it is desirable to convert the expected voltage to ground (E_G) to dBrn. TE&CM Section 451 shows that the voltage reference for 0dBrn noise-to-ground is 2.45 millivolts to ground. The expected voltage to ground can be converted to noise-to-ground in dBrn with the following equation:

$$Ng \text{ dBrn} = 20 \log \frac{E_G}{2.45 \times 10^{-3}}$$

5.3.1 The noise-to-ground in dBrn provided by the equation in Paragraph 5.3 is the value which will be read on noise measuring sets capable of single frequency measurement, set for 3kHz Flat weighting. It is necessary to add 40 dBrn to obtain power influence.

5.3.2 The equation can be adjusted to provide power influence in dBrn. When the adjusted equation is used, it is necessary to add 40 dB to noise measuring set readings of noise-to-ground before comparison to the expected power influence. The adjusted equation is:

$$PI \text{ dBrn} = 20 \log \frac{E_G}{24.5 \times 10^{-6}}$$

5.3.3 The curve in Figure 10 has been prepared to provide a convenient means of converting voltage to ground to dBrn of power influence for 3 kHz Flat weighted measurements. Enter the chart along the left at the value corresponding to the voltage to ground. Follow the horizontal line to the point of intersection with the curve. Follow the vertical line from this point to the bottom scale and read the dBrn power influence.

5.3.4 When power influence at a specific frequency is desired in dBrnC, Table II (Page 30) may be used. Subtract the C-message weighting (found in Table II for the frequency of interest) from the 3kHz Flat values either calculated or found in Figure 10 for that frequency.

5.4 As an example of expected voltage to ground calculations, we can look at a 25 pair 24 gauge filled cable, with 8 mil aluminum shield, 10 kilofoot in length, with a 5 ohm ground at each end, in an area with 1000 meter ohms earth resistivity. The cable is exposed, along the entire length, to a 3-phase power line with an average separation of 40 feet. Since the ninth harmonic (540 Hertz) is a common problem harmonic, we will calculate the expected noise-to-ground at 540 Hertz. Assuming some resonance exists in the power system an average measured 540 Hz earth return current of 0.5 ampere will be used.

5.4.1 The mutual impedance between the power and telephone system is found from in Figure 3. For a 40 foot radial separation and earth resistivity of 1000 meter-ohms, Z_{23} is 0.91 ohms per kilofoot.

5.4.2 The shield factor is calculated next. Table I shows a 25 pair 24 gauge filled cable has a diameter of 0.61 inches. Table 1 in TE&CM Section 451 shows the shield resistance for this cable is 1.1 ohms per kilofoot. The external resistance term of the complex self impedance is found from Figure 7 to be 0.162 ohms per kilofoot. Cable radius in feet is found by dividing the diameter by 24, thus, 0.61/24 = 0.025 feet. Using this value in Figure 8, we find the self reactance term is 2.43 ohms.

5.4.3 Substituting these values in the equation in Paragraph 4.2 produces a shield factor of:

$$\eta = \frac{r_{22} + \frac{R_T}{\ell}}{r_{22} + \frac{R_T}{\ell} + Z^o_{22}} = \frac{1.1 + \frac{10}{10}}{1.1 + \frac{10}{10} + 0.162 + j\,2.43} = \frac{2.1}{2.262 + j\,2.43} =$$

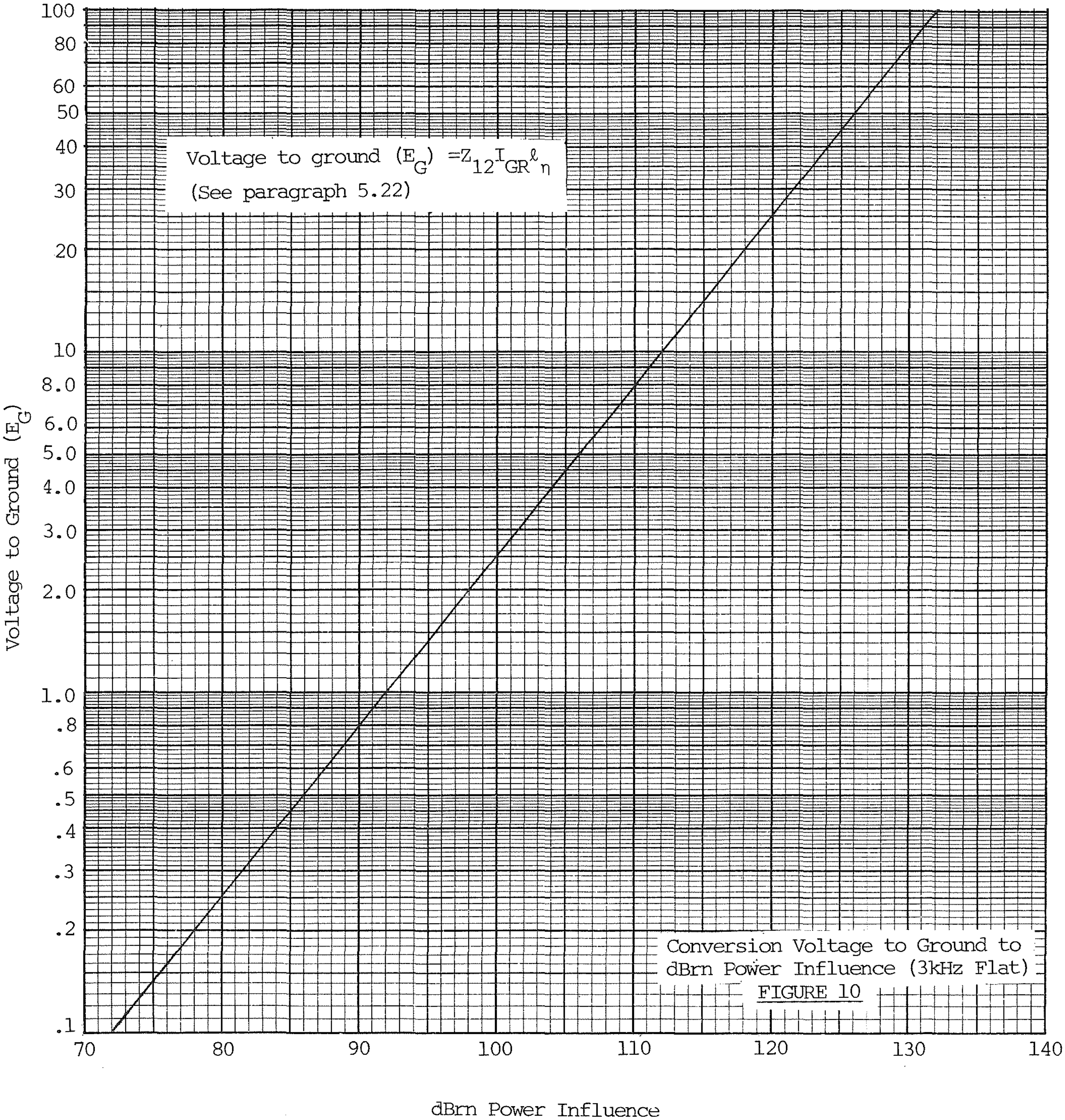
$$\frac{2.1}{3.32} = 0.63 = 540 \text{ Hz Shield Factor}$$

5.4.4 All the variables are now available for application in the equation shown in Paragraph 5.22 for calculation of expected 540 Hz voltage to ground; Z_{12} = 0.91 ohms, I_{GR} = 0.5 ampere, ℓ = 10 kilofeet, and η = 0.63. Substituting these values in the equation gives;

$$E_G = (0.91)\ (0.5)\ (10)\ (0.63) = 2.87 \text{ volts at 540 Hz.}$$

5.4.5 When desired E_G may be converted to dBrn 3kHz Flat by using Figure 10. For 2.87 volts the expected power influence is 101.2 dBrn. This can be converted to expected power influence in dBrnc by subtracting the C-message weighting factor for 540 Hz. (see Table II), resulting in 101.2 - 6.3 = 94.9 dBrnc.

5.5 The foregoing example was simple since only one cable size was involved and the separation between the power and telephone system was uniform throughout the length of exposure. Such conditions will rarely be found in the field. Cables will usually change size at one or more locations and power or telephone lines will change sides of the road. We will now consider a more typical example. Figure 11 illustrates a more typical condition which might be found in the field during a noise investigation.



Conversion Voltage to Ground to dBrn Power Influence (3kHz Flat)

FIGURE 10

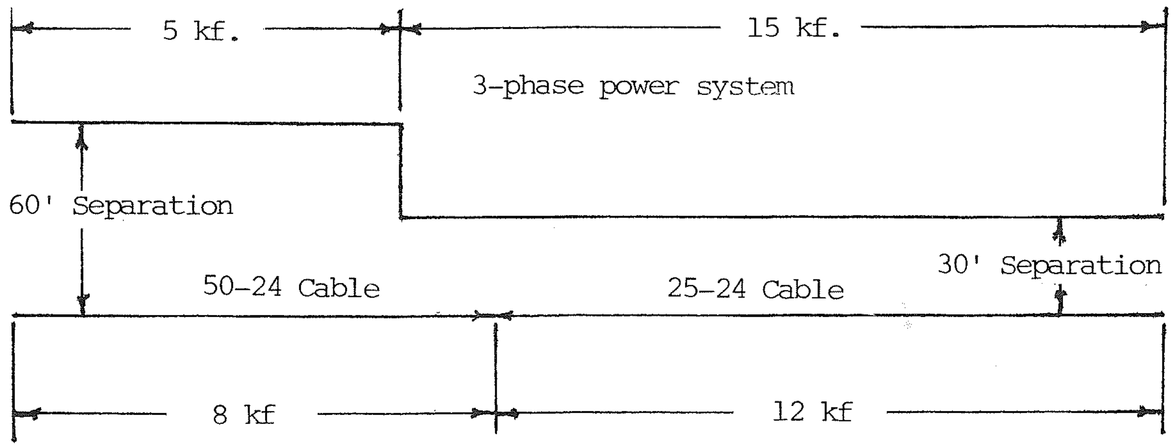


FIGURE 11: SAMPLE EXPOSURE

5.5.1 An 540 Hz earth return current of 0.5 ampere will be assumed in area of 1000 meter-ohms earth resistivity. There are two methods for calculating the expected voltage to ground along this exposure. First, the separations, cable diameters, and shield resistances can be averaged for the total length and a single calculation can be made. Second, the calculations can be made for each different exposure length, three in this example, and the results added. Calculations will be shown for both methods to illustrate that the results are the same. The resistance of the end grounds will be assumed to be zero to permit easier comparison.

5.5.2 Average the separation between the power and telephone systems to initiate the first method. (5x60) + (15x30) = 300 + 450 = 750/20 = 37.5 feet average separation. The average mutual impedance of 0.92 ohms per kilofoot is found in Figure 3 for 37.5 feet and 1000 meter-ohms earth resistivity.

5.5.3 The shield factor is calculated next. Table I shows that the diameter of a 50 pair 24 gauge filled cable with 8 mil aluminum shield is 0.76 inches and 25 pair 24 gauge filled cable diameter is 0.61 inches. These are averaged, (8x0.76) + (12x0.61) = 6.08 + 7.32 = 13.4/20 = 0.67 inches average shield diameter.

5.5.3.1 From Figure 7 the 540 Hertz external resistance term is 0.162 ohms per kilofoot. Average shield radius in feet is found by dividing the average diameter in inches by 24, thus, 0.67/24 = 0.028 feet. Using this value the self reactance of 2.4 ohms is found in Figure 8.

5.5.3.2 Table 1 in TE&CM 451 shows the shield resistance of a 50 pair 24 gauge filled cable with 8 mil aluminum shield is 0.88 ohms per kilofoot and a 25 pair 24 gauge filled cable is 1.1 ohms per kilofoot. Averaging these gives (8x0.88) + (12x1.1) = 7.04 + 13.2 = 20.24/20 = 1.01 ohms per kilofoot.

5.5.3.3 Substituting these values in the equation shown for shield factor in Paragraph 4.2 gives:

$$\eta = \frac{r22 + \frac{R_T}{\ell}}{r22 + \frac{R_T}{\ell} + Zo_{22}} = \frac{1.01 + \frac{0}{20}}{1.01 + \frac{0}{20} + 0.162 + j\,2.4} = \frac{1.01}{1.172 + j\,2.4} =$$

$$\frac{1.01}{2.67} = 0.38 = 540 \text{ Hz Shield Factor}$$

5.5.4 All the data is now available for the equation in Paragraph 5.22 for calculation of expected voltage to ground. Z_{12} = 0.92 ohms per kilofoot IGR = 0.5 ampere, ℓ = 20 kilofeet, and η = 0.38. Substituting these values in the equation gives:

E_G = (0.92) (0.5) (20) (0.38) = 3.5 volts to ground at 540 Hz.

5.5.5 From Figure 10, the 3 kHz Flat power influence is found to be 103.1 dBrn.

5.6 The expected voltage to ground can also be calculated by the second method, calculating E_G for each different exposure length and adding the results to obtain the total expected voltage. There are three different exposures in Figure 11. The 50 pair 24 gauge cable parallels the power line for a distance of 5 kilofeet with a 60 foot separation, the 50 pair 24 gauge cable parallels the power line for a distance of 3 kilofeet with a 30 foot separation, and the 25 pair 24 gauge cable parallels the power line for a distance of 12 kilofeet with a 30 foot separation.

5.6.1 Figure 3 shows the mutual impedance for the 5 kilofoot exposure length is 0.79 ohms per kilofoot. The external resistance term at 540 Hertz for a 50-24 filled cable (from Figure 7) is 0.162 ohms per kilofoot. The cable radius in feet is 0.76/24 = 0.032 feet. The external self reactance is 2.14 ohms as found in Figure 8.

5.6.1.1 Substituting values in the equation for shield factor gives:

$$\eta = \frac{0.88}{0.88 + 0.162 + j\,2.14} = \frac{0.88}{1.042 + j\,2.14} = \frac{0.88}{2.38} = 0.37 = \text{540 Hz. Shield Factor}$$

5.6.1.2 The expected voltage to ground for this exposure length is (0.79) (0.5) (5) (0.37) = 0.73 volts to ground.

5.6.2 There is only one difference between the 3 kilofoot exposure length and the 5 kilofoot discussed in Paragraph 5.61. The separation between the power line and the telephone cable is 30 feet rather than 60 feet. From Figure 3, the mutual impedance for a 30 foot separation is 0.92 ohms per kilofoot. The expected voltage to ground for this exposure is (0.92) (0.5) (3) (0.37) = 0.51 volts to ground.

5.6.3 The mutual impedance between the power line and the telephone cable for the remaining 12 kilofoot exposure length with 30 foot separation will be same as for the 3 kilofoot exposure discussed in Paragraph 5.62, 0.92 ohms per kilofoot. The external resistance term of the cable at 540 Hertz is 0.162 ohms (from Figure 7). The cable radius in feet for a 25 pair 24 gauge filled cable with an 8 mil aluminum shield is 0.61/24 = 0.025 feet. From Figure 8, the external self impedance of a cable with 0.025 foot radius is 2.42 ohms.

5.6.3.1 Substituting values in the equation for shield factor gives:

$$\eta = \frac{1.1}{1.1 + 0.162 + j\,2.42} = \frac{1.1}{1.262 + j\,2.42} = \frac{1.1}{2.73} = 0.40 = \text{540 Hz Shield Factor}$$

5.6.3.2 The expected voltage to ground for this exposure is (0.92) (0.5) (12) (0.4) = 2.2 volts to ground.

5.6.4 Adding the expected voltages to ground for the three exposure lengths gives 0.73 + 0.51 + 2.2 = 3.44 volts to ground. This is 0.6 volts less than the value obtained by averaging in Paragraph 5.54.

5.6.5 From Figure 10, the power influence for 3.44 volts to ground is 103 dBrn. This is 0.1 dBrn less than the 103.1 dBrn found by averaging.

5.7 The averaging method is recommended for calculation of expected voltages to ground. Calculation of the various exposure lengths individually works well if the ground resistances at each end are zero ohms. This condition does not occur in the field. Where there is resistance to ground at each end the problem of distributing its effects properly to the individual exposure lengths is quite complex.

5.8 There is another condition of the telephone system which has not been discussed. This is where cable shields have connections to ground electrodes at several locations along the cable route, for example, every two kilofeet. The expected voltage to ground may be calculated for such situations but the calculations are complex and will not be presented here.

5.8.1 Calculations of expected voltages to ground have been made for several exposures with distributed ground connections using the complex equations. These same calculations were then repeated assuming only a ground at each end of the cable. At 540 Hertz there was only about one dBrn difference in the power influence. This is not considered a significant difference.

5.8.2 Since the expected voltage to ground is calculated to determine if the measured voltage to ground in the telephone system is reasonable, calculations with a resistance to ground assumed at each end are accurate enough for practical comparisons.

5.8.3 The effects of distributed grounds are very important to system protection. This will be discussed in sections dealing with system protection considerations.

6. HARMONIC ANALYSIS OF POWER INFLUENCE ON TELEPHONE CABLE PAIR

6.1 One of the best means available for determining power system operating characteristics in an area is a well balanced telephone system. A telephone cable pair is equivalent to a long probe wire and measurement of the induced longitudinal voltage to ground at the power line fundamental and harmonic frequencies can provide valuable information relative to the power system operation. While the earth return currents due to unbalanced conditions in the power system cannot be calculated, specific operational problem areas can often be clearly identified.

6.2 Study of recorded results from a harmonic analysis of power influence on a telephone cable pair may provide information that will identify and locate power system problems. Even when this is not accomplished there is usually a clear indication as to where additional measurements can be made to better identify a problem.

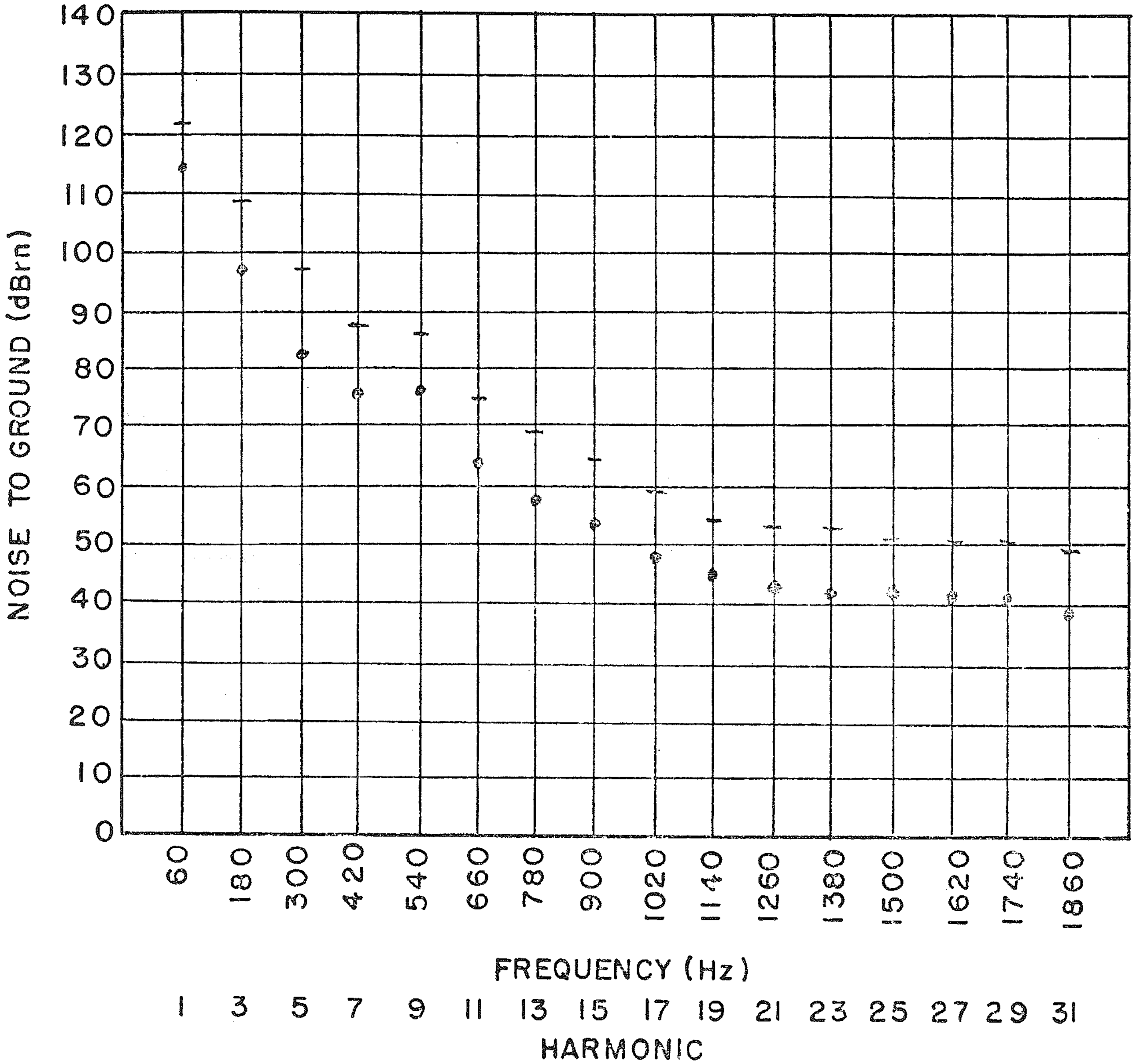
6.2.1 This procedure entails measuring power influence at fundamental and harmonic frequencies at a subscriber location. When an idle cable pair is available, it should be used for the measurement in lieu of the working one.

6.2.2 Recorded results from these measurements are then compared to the average results of a noisy loop survey /2 (Figure 12). The mean (μ) and mean plus one sigma ($\mu + \sigma$) values have been plotted for each frequency of interest. Extensive surveying has shown that these plotted values are representative of those to be expected on noisy loops in most telephone companies.

6.3 Among the power line problem areas that can be identified are:

A - Poor balance in a 3-phase power system.
B - Excessive exposure length to single-phase power system.
C - Capacitors not working at a 3-phase capacitor bank installation. (open capacitor)
D - Malfunctioning capacitor banks. (Change in capacitance value)
E - Circuit resonance.
F - Power transformer problems.
G - Harmonics from generator or motor.
H - Harmonics from SCR control devices.
I - Harmonics from Rectrifier (ac and dc side).

/2 Bell Telephone Laboratories, Inc., 1971 Noise Loop Survey



. Mean of survey (μ)
– μ + σ of survey

FIGURE 12

RESULTS OF NOISY LOOP SURVEY

6.3.1 Open shield circuits in the telephone company plant can also be detected.

6.3.2 Each of the problem areas listed has its own pattern of harmonics that will exceed the $(\mu + \sigma)$ point. Where only a single problem exists it will usually be clearly indicated. Analysis becomes more difficult where two or more problems exist along a single route. Close study will usually determine the predominant problem area and after it has been corrected a new measurement will provide data which will permit identification of the second problem area.

6.3.3 Where results of power influence measurements are equal to or less than the plotted $(\mu + \sigma)$ values and the telephone plant has good balance (60 dB or better), there is no noise problem. If C-message factors are applied to the $(\mu + \sigma)$ values and these results added on a power summation basis, resulting power influence is about 86 dBrnc. With a cable pair having 60 dB balance, resulting circuit noise will be 26 dBrnc which is acceptable on long rural subscriber loops.

6.4 A detailed discussion of how to perform harmonic frequency measurements and interpret recorded results is given in TE&CM 452.1.

7. EXPLORING COIL STUDY OF POWER LINE

7.1 An exploring coil can be a valuable tool to quickly locate some types of power line problems. A coil is used with a spectrum analyzer to monitor earth return current of a power line at any harmonic frequency, anywhere along its entire length.

7.2 This method can be utilized either as the initial step of a specialized noise investigation or as an operation subsequent to harmonic analysis of power influence on a cable pair as discussed in Paragraph 2. Experience indicates that the ninth harmonic (540 Hertz) will be predominant in the majority of noise problems. Thus when using the exploring coil technique the spectrum analyzer should usually be set to monitor 540 Hertz. Where harmonic analysis of a cable pair has identified the predominant frequency the spectrum analyzer should be set at that frequency.

7.3 Study of a power line with the exploring coil is accomplished by pointing the hand held coil toward the power line from a vehicle while traveling along the line. By monitoring the harmonic level it can be determined where capacitor banks may be providing a low impedance path to ground for harmonic currents, the location of overexcited transformers, etc. Once this information is available more precise measurements can be completed to confirm the problem location and severity.

7.4 A detailed discussion of how to perform an exploring coil study of a power line and interpretation of the findings is given in TE&CM 452.2.

8. TELEPHONE INFLUENCE FACTOR (TIF)

TABLE II

POWER HARMONIC C-MESSAGE WEIGHTING FACTORS

FREQUENCY	60-HERTZ HARMONIC	C-MESSAGE FACTOR -dB	RATIO C-M_sG Cf	FREQUENCY	60-HERTZ HARMONIC	C-MESSAGE FACTOR -dB	RATIO C-M_sG Cf
60	1	-55.7	0.0016	1380	23	-0.7	0.920
120	2	-37.8	0.013	1500	25	-1.0	0.890
180	3	-27.5	0.042	1620	27	-1.1	0.880
240	4	-21.2	0.087	1740	29	-1.2	0.870
300	5	-16.5	0.150	1800	30	-1.3	0.860
360	6	-13.1	0.222	1860	31	-1.3	0.860
420	7	-10.2	0.310	1980	33	-1.3	0.860
480	8	- 8.1	0.395	2100	35	-1.3	0.860
540	9	- 6.3	0.490	2220	37	-1.3	0.860
600	10	- 4.7	0.580	2340	39	-1.3	0.860
660	11	- 3.3	0.685	2460	41	-1.4	0.850
720	12	- 2.3	0.770	2580	43	-1.5	0.840
780	13	- 1.6	0.830	2700	45	-1.7	0.820
840	14	- 1.0	0.890	2820	47	-1.9	0.800
900	15	- 0.6	0.930	2940	49	-2.2	0.775
960	16	- 0.2	0.970	3000	50	-2.5	0.750
1020	17	- 0	1.000	3060	51	-3.0	0.700
1080	18	- 0.1	0.990	3180	53	-4.0	0.630
1140	19	- 0.1	0.990	3300	55	-5.2	0.550
1200	20	- 0.2	0.970	3480	57	-7.3	0.430
1260	21	- 0.4	0.950	3540	59	-8.2	0.390
				4500	75	-21.2	0.084

8.1 TE&CM Section 451 shows magnetic induction is an important source of power system interference on telephone lines, if currents in the various phases of power line are perfectly balanced, inductive effects should cancel out. Also when unbalance does exist, if the total unbalance current is carried in a neutral conductor located close to the other power conductors, and if the difference in spacing between the telephone line and the various power conductors can be ignored, inductive effects would again cancel out. The real concern, therefore, is with the part of the phase unbalance which does not flow in the power line neutral conductor, that is, we are concerned with the earth return current.

8.2 Often it is the TIF-weighted value of earth return current, or earth return I•T which is of greatest interest. Telephone Influence Factor or TIF is an index to the interfering effect of power system currents or voltages on nearby telephone circuits.

8.2.1 TIF weighting (W_f) is a frequency factor composed of:

a. C-Message weighting factor,
b. A frequency proportional factor (because coupling between power and telephone lines is roughly proportional to frequency), and
c. A constant factor (arbitrarily chosen to give a value of 5000 for W_f at f equals 1000 Hertz).

8.2.2 Thus:

$$W_f = 5fC_f$$

Where: C_f = The C-Message weighting factor at frequency f.

8.3 The TIF weighted amplitude of a complex waveform is the root-sum-square of the TIF weighted voltage or current amplitude of all the individual frequency components, including the fundamental. For the reasons discussed in Paragraph 1.4, only the current waveform equation will be considered here. The TIF weighted current amplitude is given by:

$$\text{TIF weighted current magnitude} = \sqrt{\Sigma\ (I_f \cdot W_f)^2}$$

8.4 TIF weighting factors for power line harmonic frequencies of interest are shown in Table III. C-Message weighting factors are shown in Table II. TIF values were derived from C-Message using the equation in Paragraph 8.2.2 and may differ from other tabulations.

9. MEASUREMENT OF EARTH RETURN CURRENT

9.1 Power system earth return currents can be determined by telephone engineers prior to contacting the power company, providing valuable information to the telephone engineer. Analysis of the power system harmonic earth return currents will often identify problems in power systems which lead

TABLE III

POWER HARMONIC TIF WEIGHTING FACTORS

FREQUENCY	60 HERTZ HARMONIC	TIF (Wf) dB	RATIO TIF Wf	FREQUENCY	60 HERTZ HARMONIC	TIF (Wf) dB	RATIO TIF Wf
60	1	-6.1	0.5	1500	25	76.5	6680
120	2	18.1	8	1620	27	77.1	7130
180	3	31.6	38	1740	29	77.6	7570
240	4	40.4	105	1800	30	77.8	7740
300	5	47.0	225	1860	31	78.1	8000
360	6	52.0	400	1980	33	78.6	8510
420	7	56.3	650	2100	35	79.1	9030
480	8	59.6	950	2220	37	79.6	9550
540	9	62.4	1320	2340	39	80.1	10060
600	10	64.8	1740	2460	41	80.4	10460
660	11	67.1	2260	2580	43	80.7	10840
720	12	68.8	2770	2700	45	80.9	11070
780	13	70.2	3240	2820	47	81.0	11280
840	14	71.5	3740	2940	49	81.1	11390
900	15	72.4	4190	3000	50	81.0	11250
960	16	73.4	4660	3060	51	80.6	10710
1020	17	74.2	5100	3180	53	80.0	10020
1080	18	74.6	5350	3300	55	79.2	9080
1140	19	75.0	5640	3480	57	77.5	7480
1200	20	75.3	5820	3540	59	76.8	6900
1260	21	75.5	5990	4500	75	65.5	1890
1380	23	76.1	6350				

to economic penalties to a power company. Also those problem areas which result in excessive noise to parallel telephone facilities can often be found. This information will generally facilitate more successful inductive coordination action with power people.

9.1.1 There are two methods whereby telephone employees can measure power line earth return currents without having to enlist power company assistance. Both methods will be discussed with the relative advantages and disadvantages of each.

9.1.2 One method involves use of an exploring coil (cited in Paragraph 7) and other method involves use of a 100 foot probe wire.

9.1.2.1 The exploring coil method has the advantage of not requiring a conductive path to earth as does the probe wire method; so less time is required to set up and complete measurements at a given location. Since the probe coil has no conductive connection to earth it is less subject to error than a probe wire from ground voltages resulting from other sources at the fundamental and lower harmonic frequencies.

9.1.2.2 The exploring coil sensitivity is approximately the same as that of measurements made with a ten foot probe wire, resulting in adequate accuracy for noise investigations.

9.1.3 Earth return current can also be measured with a probe wire. This method involves measurement of the open circuit voltage induced in a wire placed parallel to and directly under a power line, with a conductive path to earth at the far end. The length most frequently used is one hundred feet although probe wires as long as five hundred feet are sometimes used to measure the effects (<u>not</u> ground return current) of High Voltage Direct Current transmission lines.

9.1.3.1 Probe wire sensitivity is better than that of an exploring coil. This added sensitivity does not contribute much to a noise investigation, when the time required to set up and complete measurements at a given location is considered. The one hundred foot, or longer, wire must be laid on the ground parallel to the power line and a ground rod must be driven at each end. Probe wire measurements are subject to serious error at the fundamental and lower harmonic frequencies due to the presence of ground voltages from other nearby sources.

9.1.3.2 Conversion factors for use with a 100 foot probe wire in Table VI will differ from other published values. The correct probe wire equation used for calculating mutual inductance (M) is $M=14 \text{ Log } (400 + H)/H$ For years $M=14 \log ((400-H)/H)$ has been used. The minus sign appears to be in error.

9.2 Exploring coil measurement of power system earth return current will be best understood if individual frequency components of a complex power system waveform are considered. Exploring coil testing involves measurement of the induced voltage across the coil terminals with a spectrum analyzer having a high impedance input (100,000 ohms).

9.2.1 The coil voltage at any single frequency at a relative short distance from a long power line having an earth return current is given by:

$$(V_f) = \frac{4\pi \times 10^{-7} \text{ NAf } (I_f) \times 0.3048}{D}$$

Where: (V_f) = Volts across the terminals of the coil at frequency f
N = Number of turns on coil
A = Area of coil in square feet (Air core coil)
f = Frequency in Hertz
(I_f) = Earth return current of power system at frequency f in amperes.
D = Distance from geometric mean of power conductors to center of coil in feet
0.3048 = Conversion factor for feet to meters.

9.2.2 For an example we shall consider an exploring coil with 850 turns and an area of 0.7969 square feet similar to one now available. Calculations for coils of different physical dimensions would be completed in the same manner. Substituting values into the equation of Paragraph 9.2.1 gives:

$$(V_f) = \frac{4\pi \times 10^{-7} (850)\ (0.7969)\ (0.3048)\ f\ (I_f) = 2.5945 \times 10^{-4} f\ (I_f)}{D}$$

9.2.2.1 Then, at any single frequency the earth return current is given as:

$$(I_f) = \frac{(V_f)\ D}{2.5945 \times 10^{-4}\ f}$$

9.2.2.2 Some spectrum analyzers provide readings of the voltage magnitude in dBrn and a conversion to volts is necessary. The reference voltage for 0dBrn is 24.5×10^{-6} volts; so:

$$(V_f) = \left(\log^{-1} \frac{(V_f) \text{ dBrn}}{20}\right) 24.5 \times 10^{-6}$$

9.2.2.3 Substituting for (V_f) in the equation of Paragraph 9.2.2.1 gives:

$$(If) = \frac{(\log^{-1} ((V_f) \text{dBrn}/20))\ 24.5 \times 10^{-6} D}{2.5945 \times 10^{-4}\ f} = \frac{(\log^{-1}((V_f) \text{ dBrn}/20))D}{10.5898f}$$

9.2.2.4 If results in (I_f) dBA (decibel Amperes) are desired the equation of Paragraph 9.2.2.3 may be re-written accounting for the 20 log f values from Figure 13 and 20 log D correction factor from Figure 14, as follows:

$$(I_f) \text{ dBA} = (V_f) \text{ dBrn} -20.5 + 20 \log D -20 \log f$$

9.2.2.5 And to find the earth return current in amperes at any single frequency:

$$(I_f) = \log^{-1} ((I_f)\ dBA/20)$$

9.2.2.6 The magnitude of power system earth return current at any single harmonic frequency may be calculated by substituting exploring coil measurement data into the equation in Paragraph 9.2.2.3. The nomograph shown in Figure 15 has been developed based on this equation for determination of single frequency earth return currents.

9.2.3 The equation of Paragraph 9.2.2.3 cannot be used for calculation of the <u>total</u> earth return current from the recorded results of a single broad band measurement. There is a frequency term in the equation which must be eliminated before a broad band calculation can be made.

9.2.3.1 One way of eliminating the frequency term is by use of 20/f weighting. 20/f weighting is given by:

$$(V_f)\ dBrn\ 20/f = (V_f)\ dBrn + 20 \log (20/f)$$

9.2.3.2 Substituting this in the equation of 9.2.2.4 gives:

$$(I_f)\ dBA = (V_f)\ dBrn_{20/f} - 20.5 - 20 \log (20/f) - 20 \log f + 20 \log D$$
$$= (V_f)\ dBrn_{20/f} - 20.5 - 20 \log 20 + 20 \log D$$

9.2.3.3 Since 20 log 20 = 26 the equation of Paragraph 9.3.2 becomes:

$$(I_f)\ dBA = (V_f)\ dBrn_{20/f} - 46.5 + 20 \log D$$
$$(I_f)\ dBA = (V_f)\ dBrn_{20/f} - 40 + (20 \log D - 6.5)$$

9.2.3.4 This equation contains no frequency term. Use of the 20/f weighting has cancelled it out. Since the correction factor, 20 log D -46.5, applies equally to all harmonics, it must also apply to the root-sum-square total. Therefore, the equation in Paragraph 9.2.3.3 can be re-written without the frequency subscripts:

$$I_{dBA} = VdBrn_{20/f} - 40 + (20 \log D - 6.5)$$

9.2.3.5 With this equation a spectrum analyzer equipped with a 20/f weighted filter can be used for single frequency measurements and for a single broadband measurement of the total (unweighted) earth return current. The correction factor (20 log D -6.5) may be obtained from either Figure 16 or Table IV.

9.2.3.6 When a spectrum analyzer without a 20/f filter is used the (V_f) dBrn 20/f value for each frequency can be calculated by the equation in Paragraph 9.2.3.1. The 20/f weighting factors are given in Table V. The equation in Paragraph 9.2.3.4 now becomes:

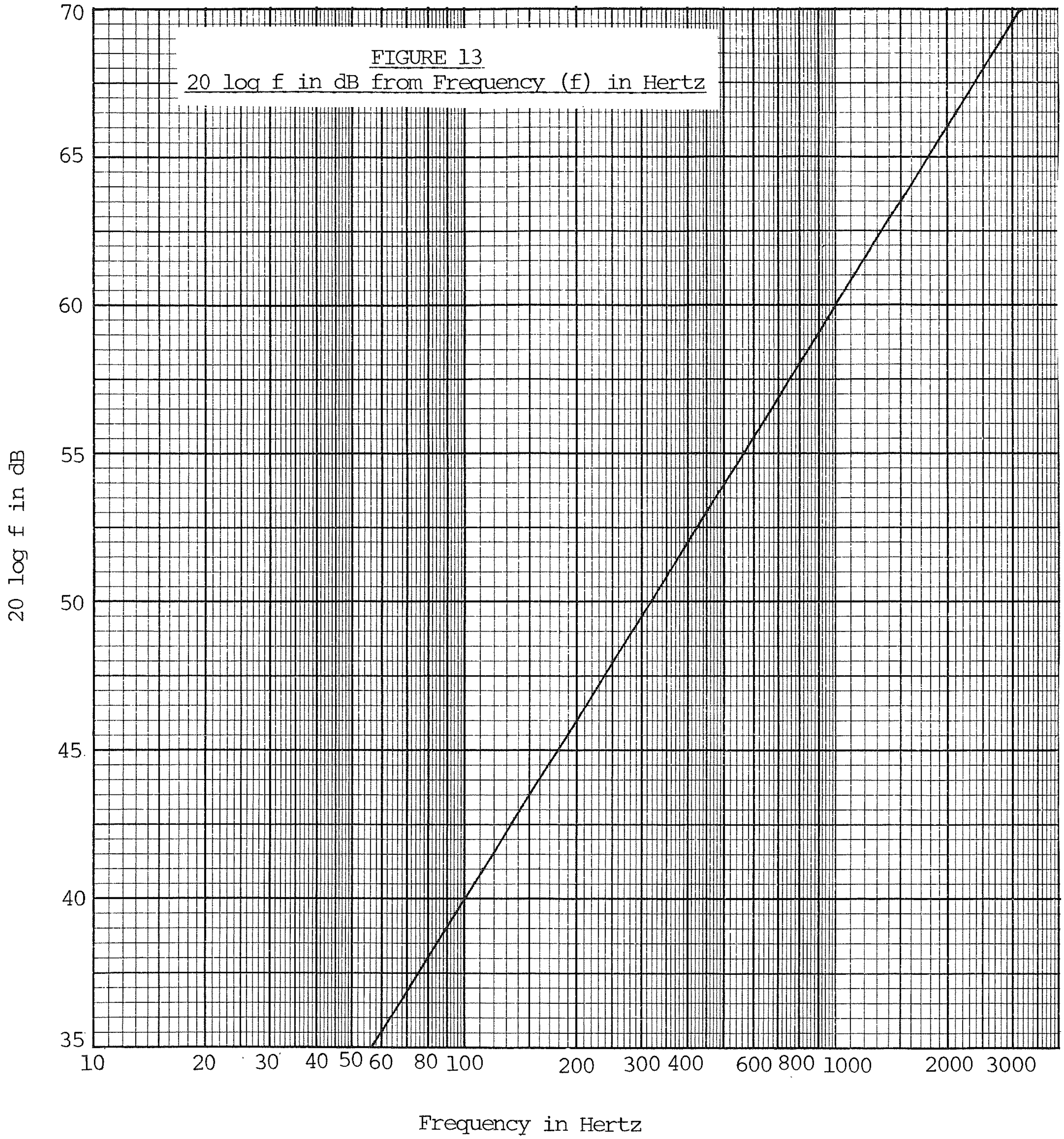
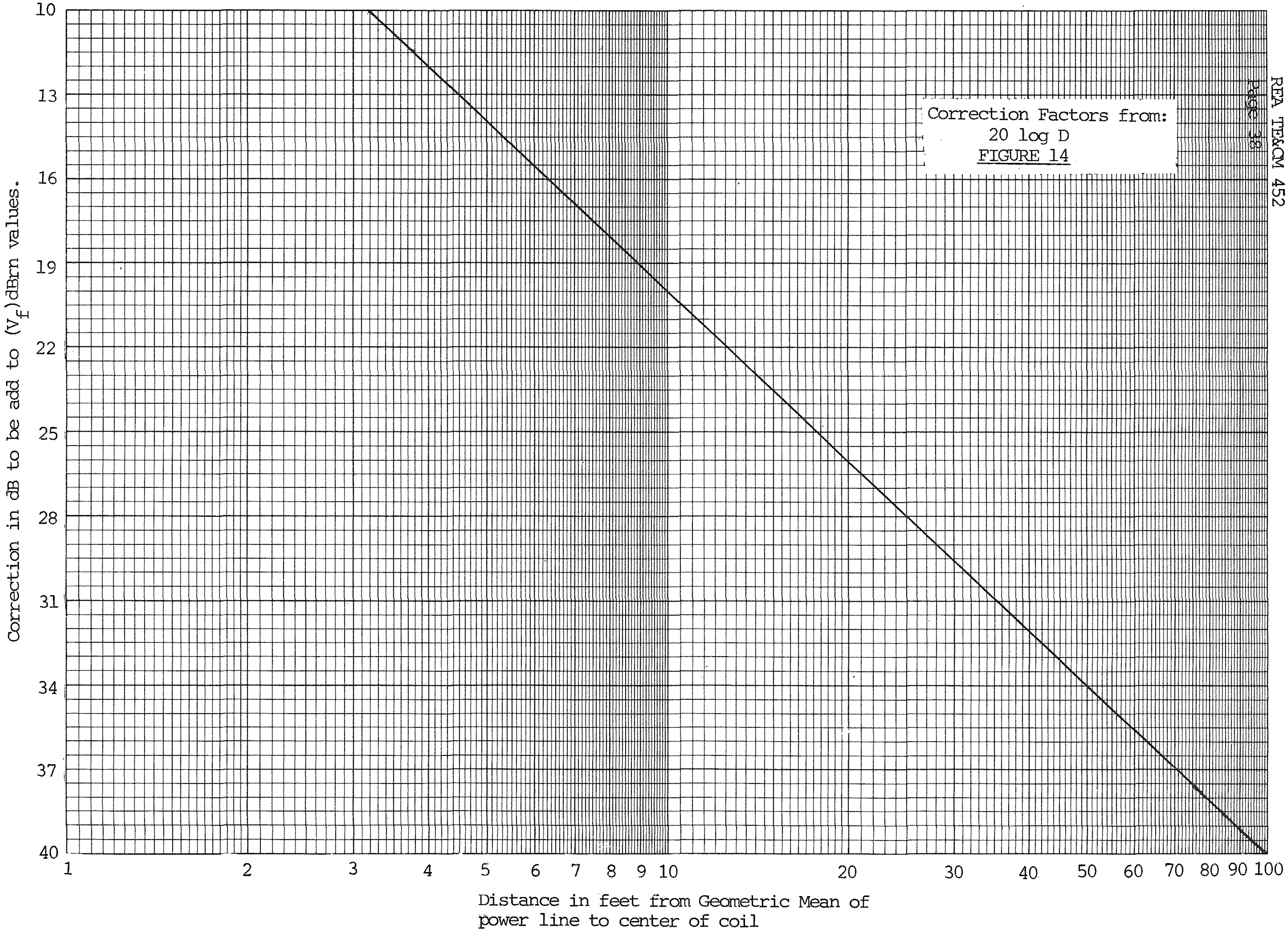
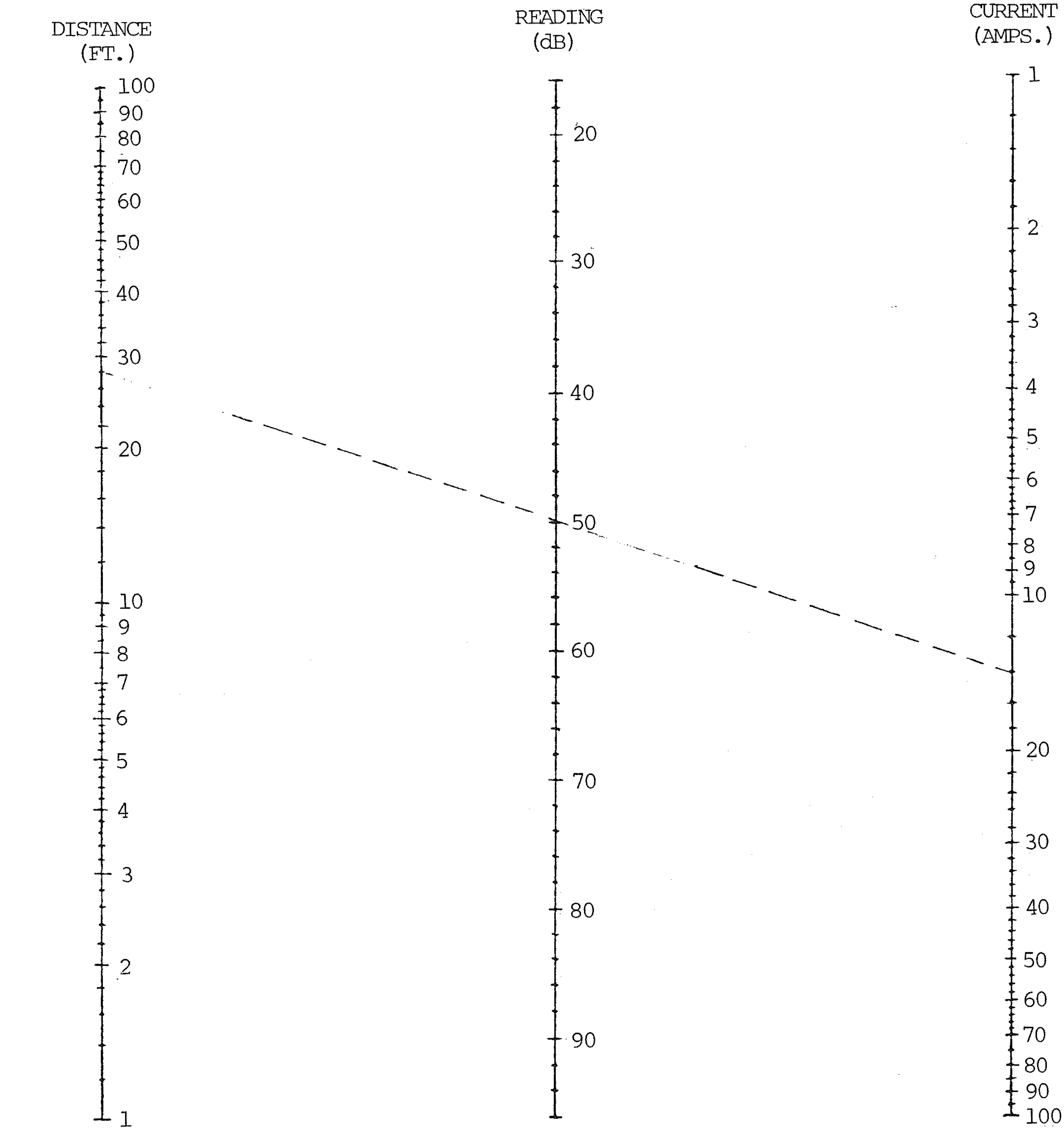


FIGURE 13
20 log f in dB from Frequency (f) in Hertz
20 log f in dB
70
65
60
55
50
45
40
35
10
20
30
40
50
60
80
100
200
300
400
600
800
1000
2000
3000
Frequency in Hertz


Correction Factors from:
20 log D
FIGURE 14
10
13
16
19
22
25
28
31
34
37
40
Correction in dB to be add to (V_f) dBrn values.
1
2
3
4
5
6
7
8
9
10
20
30
40
50
60
70
80
90
100
Distance in feet from Geometric Mean of power line to center of coil



Example: Distance between center of probe coil and geometric center of power phasewire-neutralwire configuration = 28 ft. Meter reading = 50 dB. Ground return current = 14 amperes.

Note: Divide ground return current by order of harmonic for other than 60 Hz.

Set function switch to BRDG 600

Courtesy of Wilcom Products, Inc.

FIGURE 15
SINGLE FREQUENCY EARTH RETURN CURRENT

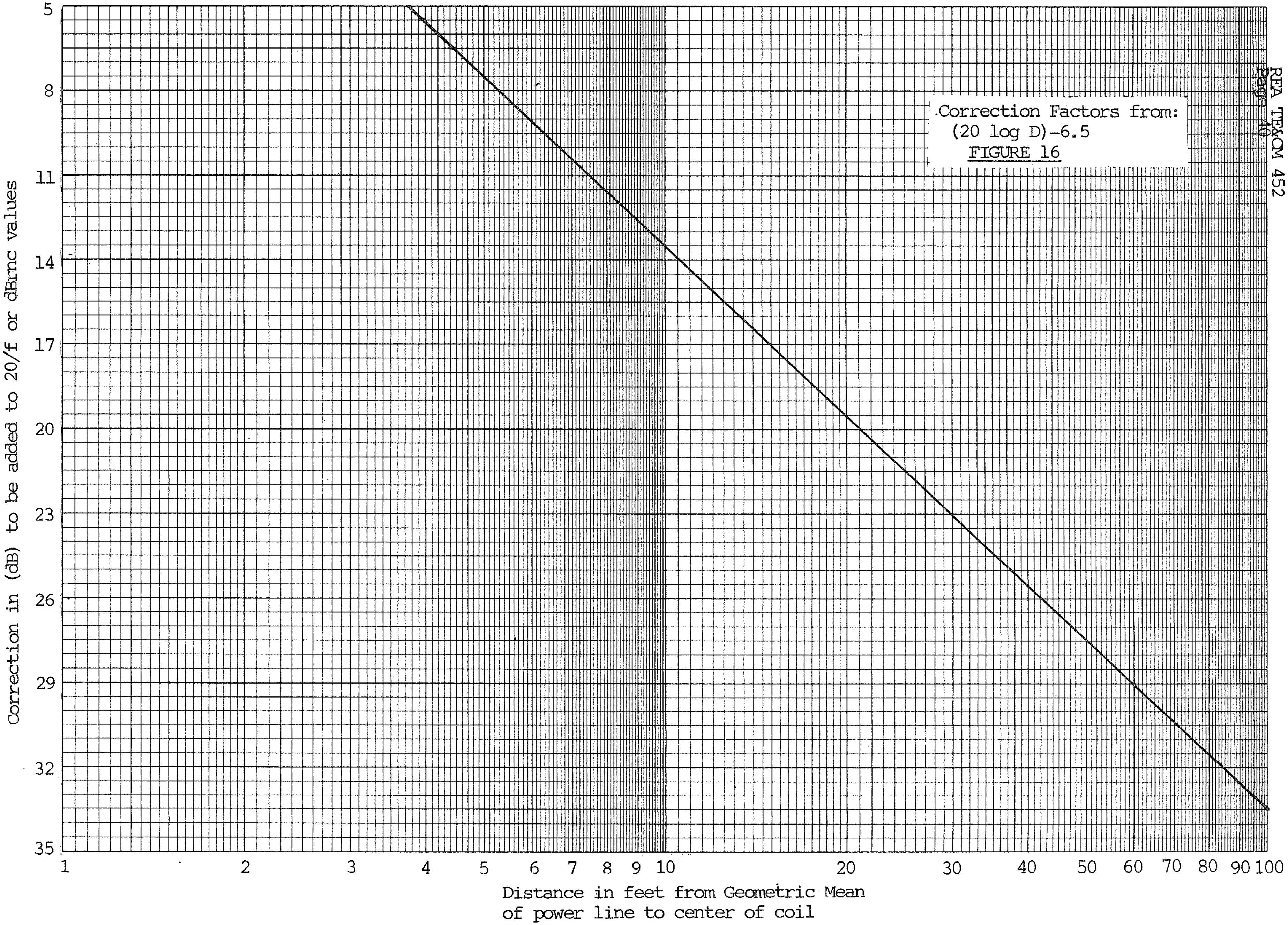

Correction Factors from:
(20 log D)-6.5
FIGURE 16
Correction in (dB) to be added to 20/f or dBrnc values
5
8
11
14
17
20
23
26
29
32
35
1
2
3
4
5
6
7
8
9
10
20
30
40
50
60
70
80
90
100
Distance in feet from Geometric Mean
of power line to center of coil

TABLE V

POWER HARMONIC 20/f WEIGHTING FACTORS

FREQUENCY	60 HERTZ HARMONIC	RATIO 20/f	20/f FACTOR dB	FREQUENCY	50 HERTZ HARMONIC	RATIO 20/f	20/f FACTOR dB
60	1	0.3330	- 9.5	1500	25	0.0133	-37.5
120	2	0.1670	-15.6	1620	27	0.0123	-38.2
180	3	0.1110	-19.1	1740	29	0.0115	-38.8
240	4	0.0833	-21.6	1800	30	0.0111	-39.1
300	5	0.0667	-23.5	1860	31	0.0108	-39.4
360	6	0.0556	-25.1	1980	33	0.0101	-40.0
420	7	0.0476	-26.4	2100	35	0.00952	-40.4
480	8	0.0417	-27.6	2220	37	0.00901	-40.9
540	9	0.0370	-28.6	2340	39	0.00855	-41.4
600	10	0.0333	-29.5	2460	41	0.00813	-41.8
660	11	0.0303	-30.4	2580	43	0.00775	-42.2
720	12	0.0278	-31.1	2700	45	0.00741	-42.6
780	13	0.0256	-31.8	2820	47	0.00709	-43.0
840	14	0.0238	-32.5	2940	49	0.00680	-43.3
900	15	0.0222	-33.1	3000	50	0.00667	-43.5
960	16	0.0208	-33.6	3060	51	0.00654	-43.7
1020	17	0.0196	-34.2	3180	53	0.00629	-44.0
1080	18	0.0185	-34.6	3300	55	0.00606	-44.3
1140	19	0.0175	-35.1	3480	57	0.00575	-44.8
1200	20	0.0167	-35.6	3540	59	0.00565	-45.0
1260	21	0.0159	-36.0	4500	75	0.00444	-47.0
1380	23	0.0145	-36.8				

20/f dB = 20 log 20/f

$$dBA = 10 \log \left[\Sigma \left(\log^{-1} \frac{(Vf)\, dBrn\ 20/f}{10} \right) \right] -40 + (20 \log D - 6.5)$$

9.2.3.7 Amperes earth return current is given by:

$$I = \log^{-1} (I_{dBA}/20)$$

9.2.4 A detailed discussion of how to perform exploring coil measurements of power system earth return currents and the analysis of recorded results is presented in TE&CM Section 452.2.

GEOMETRIC MEAN HEIGHT OF POWER LINE ABOVE CENTER OF COIL

20'	25'	30'	35'	40'	45'	50'	55'	60'
19.5	21.5	23.0	24.4	25.5	26.6	27.5	28.3	29.1

CORRECTION FACTOR = (20 log -6.5)

CORRECTION FACTORS - TABLE IV

9.2.5 I·T can be calculated at each individual frequency by multiplying the current for the frequency from the equation in Paragraph 8.2.3.7 by the TIF factor from Table III. There is an easier way of determining the I·T value using the C-message weighting setting of the spectrum analyzer. With C-message weighting the reading is given by:

$$(V_f)\ dBrnc = (V_f)\ dBrn + 20 \log C_f$$

9.2.5.1 Substituting this in the equation of Paragraph 9.2.2.4 gives:

$$(I_f)\ dBA = (V_f)\ dBrnc - 20.5 - 20 \log C_f - 20 \log f + 20 \log D$$

9.2.5.2 TIF weighted value is obtained by multiplying both sides of the equation by W_f:

$$(I_f \cdot W_f)\ dBA = (V_f)\ dBrnc - 20.5 - 20 \log C_f + 20 \log W_f - 20 \log f + 20 \log D$$

9.2.5.3 From Paragraph 8:

$$W_f = 5f\, C_f$$

9.2.5.4 Substituting this in the equation of Paragraph 9.2.5.2 gives:

$$(I_f \cdot W_f) \text{ dBA} = (V_f) \text{ dBrnc} -20.5 -20 \log Cf + 20 \log 5fC_f -20 \log f + 20 \log D$$

$$= (V_f) \text{ dBrnc} -20.5 + 20 \log 5 + 20 \log D$$

9.2.5.5 Since 20 log 5 = 14 the equation of Paragraph 9.2.5.4 becomes:

$$(I_f \cdot W_f) \text{ dBA} = \text{dBrnc} + (20 \log D -6.5)$$

9.2.5.6 Like the equation in Paragraph 9.2.3.3 this equation contains no frequency term. This time a combination has been used of C-message weighting and frequency-proportional coupling in Paragraph 9.2.2.4 to obtain TIF weighting, with a correction factor which applies equally well to all TIF weighted harmonics and, therefore, to the root-sum-square total as well. Therefore, the equation in Paragraph 9.2.5.5 can be rewritten without the frequency subscripts:

$$(I \cdot T) \text{ dBA} = \text{VdBrnc} + (20 \log D -6.5)$$

9.2.5.7 With this equation a spectrum analyzer equipped with a C-message filter can be used for single frequency measurements and for a single broadband measurement of the total I·T. The correction factor (20 log D -6.5) may be obtained from either Figure 16 or Table IV.

9.2.5.8 When a spectrum analyzer without a C-message filter is used the (V_f) dBrnc value for each frequency can be calculated by the equation in Paragraph 9.2.5. C-message factors (C_f) are given in Table II. The equation in Paragraph 9.2.5.6 now becomes:

$$(I \cdot T) \text{ dBA} = 10 \log \left[\Sigma \left(\log^{-1} \frac{(V_f \text{ dBrnc})}{10} \right) \right] + (20 \log D -6.5)$$

9.2.5.9 I·T is given by:

$$I \cdot T = \log^{-1} (I \cdot T) \text{ dBA}/20)$$

9.2.6 A detailed discussion of how to perform exploring coil measurements of power system I·T and the analysis of recorded results is presented in TE&CM Section 452.2.

9.2.7 Since TIF is the ratio of the RSS weighted amplitudes to the RMS current amplitudes (unweighted), from the equation in Paragraphs 9.2.3.4 and 9.2.5.6, we have:

$$T = \log^{-1} ((\text{VdBrnc} - \text{VdBrn } 20/f + 40)/20)$$

9.3 Probe wire measurements of power system earth return current will be best understood if the individual frequency components of a complex power system waveform are considered. The use of a spectrum analyzer having a high impedance input (> 100,000 ohms) is assumed. Thus, the input impedance is high compared to the likely ground resistance between the two electrodes and the induced voltage may be read directly.

9.3.1 The voltage at any single frequency induced in a probe wire at a relative short distance from a long power line having an earth return current is given by:

$$(V_f) = 2\pi\ f\ M\ (I_f)$$

Where: (V_f) = Volts induced in probe wire at frequency f
f = Frequency in Hertz
(I_f) = Earth return current of power system at frequency f
M = Mutual inductance between the probe wire and average of all power-line conductors, given by:

$$M = 0.14 \times 10^{-6} \ell \log \left(\frac{400 + D}{D}\right) \text{ Henries}$$

ℓ = Length of probe wire in feet
D = Distance from geometric mean of power conductors to probe wire

9.3.2 At any single frequency the earth return current is given as:

$$(I_f) = (V_f)\ /\ 2\pi f M$$

9.3.2.1 By expressing the current and voltage in dB relative to one ampere and one volt, respectively, the equation can be written:

$$(I_f)\ \text{dBA} = (V_f)\ \text{dBV} - 20 \log 2\ \pi\ f - 20 \log M$$

9.3.2.2 Since most spectrum analyzers provide levels in dBrn, a conversion to dBV is necessary. The zero dBrn reference level is 24.5 microvolts, giving:

$$V_{dBV} = V_{dBrn} + 20 \log (24.5 \times 10^{-6})$$
$$= V dBrn - 92.2$$

9.3.2.3 Combining the equation in Paragraph 9.3.2.1 with the one in Paragraph 9.3.2.2 gives:

$$(I_f)\ \text{dBA} = (V_f)\ \text{dBrn} - 92.2 - 20 \log 2\ \pi\ f - 20 \log M$$

9.3.2.4 And to find the amperes earth return current at any single frequency:

$$(I_f) = \log^{-1} ((I_f)\ \text{dBA}/20)$$

9.3.3 The magnitude of power system earth return currents at any harmonic frequency may be calculated by the equation in Paragraph 9.3.2.3, substituting results of probe wire measurements. It cannot be used for calculation of total earth return current from results of a single broadband measurement. The frequency term in the equation must be eliminated before a broadband calculation can be made.

9.3.3.1 A method of eliminating the frequency term is by use of 20/f weighting. 20/f weighting is given by:

$$(V_f) \text{ dBrn } 20/f = (V_f) \text{ dBrn} + 20 \log (20/f)$$

9.3.3.2 Combining the equation in Paragraph 9.3.2.3 and the one in Paragraph 9.3.3.1 gives:

$$(I_f) \text{ dBA} = (V_f) \text{ dBrn}_{20/f} -20 \log (20/f) -92.2 -20 \log 2\pi f -20 \log M$$

$$= (V_f) \text{ dBrn}_{20/f} -20 \log 40\pi -92.2 -20 \log M$$

9.3.3.3 Since 20 log 40π = 42 the equation of Paragraph 9.3.3.2 becomes:

$$(I_f) \text{ dBA} = (V_f) \text{ dBrn } 20/f -134.2 -20 \log M$$

or more conveniently:

$$(I_f) \text{ dBA} = (V_f) \text{ dBrn } 20/f -40 -(20 \log M + 94.2)$$

9.3.3.4 With this equation a spectrum analyzer equipped with a 20/f weighted filter can be used to determine the power line earth return current component at any single frequency in dB above one ampere. Values of the correction factor (20 log M + 94.2) for a 100-foot probe wire at various power line heights are shown in Table VI.

9.3.3.5 The equation in Paragraph 9.3.3.3 contains no frequency term. Use of the 20/f weighting has cancelled it out. Since the correction factor (20 log M + 134.2), applies equally to all harmonics, it must also apply to the root-sum-square total. The equation can, therefore, be written without the frequency subscripts:

$$I_{dBA} = V_{dBrn}\ 20_f -40 -(20 \log M + 94.2)$$

9.3.3.6 Thus a spectrum analyzer, with 20/f weighting, may be used for a single broadband measurement of the total (unweighted) earth return current as well as that for single frequencies. The Correction Factors may be obtained from Table IV.

9.3.3.7 When a spectrum analyzer without a 20/f filter is used, the (VF) dBrn 20/f values for each frequency can be calculated by the equation in Paragraph 9.3.3.1. The 20/f weighting factors are given in Table V. The equation in Paragraph 9.3.3.5 now becomes:

$$I_{dBA} = 10 \log \left[\Sigma \left(\log^{-1} \frac{(V_f) \text{ dBrn } 20/f}{10} \right) \right] -40 -(20 \log M + 94.2)$$

TABLE VI

CORRECTION FACTORS (20 LOG M + 94.2) FOR 100 FOOT PROBE WIRE

D*	FACTOR dB	D*	FACTOR dB	D*	FACTOR dB
11	1.05	28	-1.41	45	-2.92
12	0.85	29	-1.51	46	-2.99
13	0.66	30	-1.62	47	-3.07
14	0.47	31	-1.72	48	-3.14
15	0.30	32	-1.81	49	-3.21
16	0.14	33	-1.91	50	-3.28
17	-0.02	34	-2.00	51	-3.35
18	-0.17	35	-2.09	52	-3.42
19	-0.31	36	-2.18	53	-3.49
20	-0.45	37	-2.27	54	-3.56
21	-0.58	38	-2.36	55	-3.62
22	-0.71	39	-2.44	56	-3.69
23	-0.84	40	-2.53	57	-3.75
24	-0.96	41	-2.61	58	-3.82
25	-1.08	42	-2.68	59	-3.88
26	-1.19	43	-2.77	60	-3.94
27	-1.30	44	-2.84		

D = Height of power line above probe wire in feet.

9.3.3.8 Amperes earth return current is given by:

$$I = \log^{-1} (I_{dBA}/20)$$

9.3.4 I·T can be calculated at each individual frequency by multiplying the current for the frequency from the equation in Paragraph 9.3.3.5 by the TIF factor from Table III. There is an easier way of determining the I·T value using the C-message weighting setting of the spectrum analyzer. With C-message weighting the reading is given by:

$$(V_f)\ dBrnc = (V_f)\ dBrn + 20 \log C_f$$

9.3.4.1 Substituting this in the equation of Paragraph 9.3.2.9 gives:

$$(I_f)\ dBA = (V_f)\ dBrnc - 20 \log C_f - 92.2 - 20 \log 2\pi f - 20 \log M$$

9.3.4.2 The TIF weighted value is obtained by multiplying both sides by W_f:

$$(I_f \cdot W_f)\ dBA = (V_f)\ dBrnc - 92.2 - 20 \log C_f + 20 \log W_f - 20 \log 2\pi f - 20 \log M$$

9.3.4.3 Substituting the value for W_f from Paragraph 9.2.5.3 gives:

$$(I_f \cdot W_f)\ dBA = (V_f)\ dBnc - 92.2 - 20 \log C_f + 20 \log 5fC_f - 20 \log 2\pi f - 20 \log M = (V_f)\ dBrnc - 92.2 + 20 \log 5/2\pi - 20 \log M$$

9.3.4.4 Since $20 \log 5/2\pi = 2.0$ the equation in Paragraph 9.3.4.3 becomes:

$$(I_f \cdot W_f)\ dBA = (V_f)\ dBrnc - (20 \log M + 94.2)$$

9.3.4.5 With this equation, a spectrum analyzer with C-message weighting can be used to determine the earth return I·T contribution of each harmonic frequency in dB above one weighted ampere. Values of the correction factor (20 log M + 94.2) for a 100 foot probe wire at various power line heights are shown in Table VI.

9.3.4.6 The equation in Paragraph 9.3.4.4 contains no frequency term. This time a combination has been used of C-message weighting and frequency proportional coupling in Paragraph 9.3.1 to obtain TIF weighting with a correction factor which applies equally well to all TIF weighted harmonics and, therefore, to the root-sum-square total as well. The equation can, therefore, be written without the frequency subscripts:

$$(I \cdot T)\ dBA = VdBrnc - (20 \log M + 94.2)$$

9.3.4.7 Again, the spectrum analyzer can be used, this time with C-message weighting, for a single broadband measurement of the earth return I·T as well as for single frequencies. The correction factors may be obtained from Table VI.

9.3.4.8 When a spectrum analyzer without a C-message filter is used the (V_f) dBrnc value for each frequency can be calculated by the equation in Paragraph 9.3.4 C-message factors (C_f) are given in Table II. The equation in Paragraph 9.3.4.6 now becomes:

$$(I \cdot T)\ dBA = 10 \log \left[\Sigma \left(\log^{-1} \frac{(V_f)\ dBrnc}{10} \right) \right] - (20 \log M + 94.2)$$

9.3.4.9 Numerical I·T is given by:

$$I \cdot T = \log^{-1} ((I \cdot T)\ dBA/20)$$

9.3.5 A detailed discussion of how to perform probe wire measurements of power system earth return I and I·T with analysis of recorded results is presented in TE&CM Section 452.3.

9.3.6 Since TIF is the ratio of weighted to unweighted amplitudes, from the equations in Paragraphs 9.3.3.5 and 9.3.4.6, we have:

$$T = \log^{-1} ((VdBrnc - VdBrn\ 20/f + 40)/20)$$

☆ U.S. GOVERNMENT PRINTING OFFICE : 1980—340-938/REA-4266