ANEXO 12

PROCEDIMIENTO DE CÁLCULO DEL FACTOR DE DIVISIÓN DE CORRIENTE

Annex C

(informative)

Graphical and approximate analysis of current division

C.1 Introduction

A graphical method for determining the maximum grid current, based on results obtained using a computer program of EPRI TR-100622 [B63] has been developed. This method attempts to correlate the substation zero sequence fault obtained from a standard short circuit study to the actual current flowing between the grounding system and surrounding earth. The original presentation of this concept was published in Garret, Myers, and Patel [B73]. That paper describes the parametric analysis performed and the resulting basis for the assumptions used to develop the curves. Additional curves have since been developed to address other system configurations. The following is an explanation of the use of the graphs shown in Figure C.1 through Figure C.22.

The graphs are divided into the following four categories:

- Category A: 100% remote and 0% local fault current contribution, representing typical distribution substations with delta-wye transformer, with X transmission lines and Y feeders (Figure C.1 through Figure C.16)
- Category B: 75% remote and 25% local ground fault current contribution (Figure C.17 and Figure C.18)
- Category C: 50% remote and 50% local ground fault current contribution (Figure C.19 and Figure C.20)
- Category D: 25% remote and 75% local ground fault current contribution (Figure C.21 and Figure C.22)

Categories B–D represent typical transmission substations or generating plants with X transmission lines (feeders are considered to be transmission lines in these cases), and with local sources of zero sequence current, such as auto transformers, three winding transformers, generators (grounded-wye GSUs), etc. Category A works well for practical cases. Categories B–D are rough approximations, and the accuracy depends on several system parameters (particularly the source of the local ground fault current).

The following assumptions were used to obtain the graphs:

a) Transmission line length of 23.5 mi (37.82 km) and a distance between grounds of 500 ft (152 m).
b) Transmission tower footing resistance of 15 or 100 Ω.
c) Transmission line structure single pole with 1–7#10 alumoweld shield wire and 336.4 kcmil, 26/7 ACSR conductor.
d) Distribution line length of 2.5 mi (4 km) and a distance between grounds of 400 ft (122 m).
e) Distribution pole footing resistance of 25 Ω or 200 Ω.
f) Distribution pole three-phase triangular layout, with one 336.4 kcmil, 26/7 ACSR phase and 1/0 ACSR neutral conductor.
g) Soil resistivity of 100 Ω·m.
h) Substation grounding system resistances of 0.1 Ω, 0.5 Ω, 1.0 Ω, 5.0 Ω,10.0 Ω, and 25.0 Ω.
i) Number of transmission lines varied from 0, 1, 2, 4, 8, 12, and 16.

j) Number of distribution lines varied from 0, 1, 2, 4, 8, 12, and 16.

k) One remote source for each two transmission lines.

C.2 How to use the graphs and equivalent impedance table

Referring to Figure C.1 through Figure C.22, a family of curves is plotted, with each curve representing a different number of transmission lines or distribution feeders. The abscissa is a range of grounding system resistances from 0.1 Ω to 25.0 Ω. The ordinate is the percent of the total zero sequence substation bus ground fault current which flows between the grounding system and surrounding earth (i.e., the grid current I_g).

When using Category A curves and Table C.1, only the delta-connected bus fault current should be used as the multiplier of the split factor, because this fault current is the one that is from remote sources and is the basis of these curves. When using Category B–D curves, the fault current and contributions should be determined for all transmission voltage levels and the case resulting in the highest grid current should be used.

Table C.1 shows the equivalent transmission and distribution ground system impedance at 1 Ω for 100% remote contribution with X transmission lines and Y distribution feeders. The first column of impedances is for transmission line ground electrode resistance R_{tg} of 15 Ω and distribution feeder ground electrode resistance R_{dg} of 25 Ω. The second column of impedances is for R_{tg} of 100 Ω and R_{dg} of 200 Ω. To determine the GPR with current splits, parallel the grid resistance with the appropriate impedance from the table and multiply this value by the total fault current. For example, a substation with one transmission line and two distribution feeders has a ground grid resistance of 5 Ω, a total fault current of 1600 A, R_{tg} of 15 Ω, and R_{dg} of 25 *W*. From Table C.1, the equivalent impedance of the transmission and distribution ground system is 0.54 +*j*0.33 Ω. The magnitude of the equivalent total ground impedance is

$$|Z_g| = \left|\frac{(5.0)(0.54 + j0.33)}{5.0 + 0.54 + j0.33}\right| = 0.57\Omega$$

and the GPR is

$$GPR = (0.57)(1600) = 912 \text{ V}$$

To calculate the grid current, divide the GPR by the ground grid resistance.

$$I_g = \frac{912}{5} = 182 \text{ A}$$

The grid current may also be computed directly by current division.

$$|I_g| = 1600 \cdot \left|\frac{(0.54 + j0.33)}{5.0 + 0.54 + j0.33}\right| = 182 \text{ A}$$

C.3 Examples

To illustrate the use of the graphical analysis, consider a substation with two transmission lines and three distribution feeders, and a ground grid resistance of 1 Ω, as shown in Figure C.23. Using EPRI TR-100622 [B63], the maximum grid current is 2354.6 A, with the total bus ground fault is 9148.7 A. The system in question has two transmission lines with R_{tg} of 15 Ω and R_{dg} of 25 Ω. Figure C.3 shows curves for two lines/

two feeders and two lines/four feeders. Thus, interpolation is necessary for this example. From Figure C.3, we see that the approximate split factor S_f is (32+23)/2 or 27.5%. The maximum grid current is

$$I_g = (9148.7)(0.275) = 2516 \text{ A}$$

Using Table C.1, the equivalent impedance of the transmission and distribution ground system for two lines and two distribution feeders is 0.455 + j0.241 W, and for two lines and four distribution feeders is 0.27 + j0.165 Ω. The average of the split factors for these two cases will be used.

$$S_f = \left|\frac{0.455 + j0.241}{1.0 + 0.455 + j0.241}\right| = 0.349$$

$$S_f = \left|\frac{0.27 + j0.165)}{1.0 + 0.27 + j0.165}\right| = 0.247$$

Thus, S_f = (0.349 +0.247)/2 = 0.298 or 29.8%

The resulting grid current using this method is

$$I_g = (9148.7)(0.298) = 2726$$

Both methods compare favorably with the value of 2354.6 A or 26% of $3I_0$ from the computer program, though the equivalent impedance method is generally more conservative.

Next consider the more complex system shown in Figure C.24. This example is similar to the first, except that the distribution substation is replaced with a local source of generation, such as a cogeneration plant. For this example, there is both local and remote sources of ground fault current, so the percent of local vs. remote ground fault current contribution must be computed. The computer program of EPRI TR-100622 [B63] computed a total fault current of 19 269.6 A at the 115kV bus, with 48.7% contributed by the local source and 51.3% contributed by the remote sources. The closest curves are for 50/50 split (Figure C.19). For a grid resistance of 0.9 Ω, the split factor is determined from the curve for two lines and no feeders –S_f = 29%. The maximum grid current is

$$I_g = (19\,269.6)(0.29) = 5588 \text{ A}$$

For this case, the computer program results in a value of 4034.8 A, or 21% of $3I_0$. This does not compare as well as the case with 100% remote contribution, but is still closer than using the total fault current, or even the remote or local contribution. The equivalent impedance method (Table C.1) does not work as well for cases other than 100% remote contribution, and is not included in Table C.1.

C.4 Equations for computing line impedances

The following equations are found in the ABB T&D Reference Book, Fourth Edition [B1]. The definitions of the terms used in the equations are

GMD	is the geometric mean distance between the phase conductors in ft
GMR	is the geometric mean radius of the conductor in ft
d_{ab}	is the distance between conductors a and b in ft
r_a	is the ac resistance of the conductor at frequency f
x_a	is the inductive reactance of the conductor to one foot spacing at frequency f

f is the frequency in Hz
D_e is the equivalent depth of earth return in ft
r is the soil resistivity in Ω·m

The positive sequence impedance, Z_1, of a transmission line (with earth return), ignoring the effects of overhead shield wires, is

$$Z_1 = r_a + jx_a + jx_d \;\; \Omega/\text{mi} \tag{C.1}$$

where

$$x_a = 0.2794 \cdot \log_{10}\frac{1}{GMR}$$

and

$$GMD = 0.2794 \cdot \frac{f}{60} \cdot \log_{10}\sqrt[3]{d_{ab} \cdot d_{bc} \cdot d_{ca}}$$

The zero sequence self impedance, $Z_{0(a)}$, of the transmission line (with earth return), with no overhead shield wires is

$$Z_{0(a)} = r_a + r_e + jx_a + jx_e - 2 \cdot x_d \;\; \Omega/\text{mi} \tag{C.2}$$

where

$$r_e = 0.00477 \cdot f$$

and

$$x_e = 0.006985 \cdot f \cdot \log_{10}\left(4.6655 \cdot 10^6 \cdot \frac{\rho}{f}\right)$$

and r_a, x_a, and x_d are as defined above using characteristics of the phase conductors.

The zero sequence self impedance, $Z_{0(g)}$, of one overhead shield wire (with earth return) is

$$Z_{0(g)} = 3 \cdot r_a + r_e + j3 \cdot x_a + jx_e \;\; \Omega/\text{mi} \tag{C.3}$$

where r_a and x_a are as defined above using characteristics of the overhead shield wire, and r_e and x_e are as defined above.

The zero sequence self impedance, $Z_{0(g)}$, of two overhead shield wires (with earth return) is

$$Z_{0(g)} = \frac{3}{2} \cdot r_a + r_e + j\frac{3}{2} \cdot x_a + jx_e - j\frac{3}{2} \cdot x_d \;\; \Omega/\text{mi} \tag{C.4}$$

where

$$x_d = 0.2794 \cdot \frac{f}{60} \cdot \log_{10} d_{xy}$$

d_{xy} is the distance between the two overhead shield wires, r_a and x_a are as defined above using characteristics of the overhead shield wire, and r_e and x_e are as defined above.

The zero sequence mutual impedance, $Z_{0(ag)}$ between one circuit and n shield wires (with earth return) is

$$Z_{0(ag)} = r_e + jx_e - j3 \cdot x_d \ \ \Omega/\text{mi} \tag{C.5}$$

where

$$x_d = 0.2794 \cdot \frac{f}{60} \cdot \log_{10}(3 - \sqrt[n]{d_{ag1} \cdot d_{bg1} \cdot d_{cg1} \ldots d_{agn} \cdot d_{bgn} \cdot d_{cgn}})$$

d_{ag1} is the distance between phase a and the first overhead shield wire, etc., and r_e and x_e are as defined above.

Then, the zero sequence impedance of one circuit with n shield wires (and earth return) is

$$Z_0 = Z_{0(a)} - \frac{Z_{0(ag)}^2}{Z_{0(g)}} \Omega/\text{mi} \tag{C.6}$$

These equations for Z_1 and Z_0 are used, along with appropriate impedances for transformers, generators, etc., to compute the equivalent fault impedance.

To compute the impedance of an overhead shield wire or feeder neutral for use in Endrenyi's formula, the simple self impedance (with earth return) of the conductor is used.

$$Z_s = r_c + \frac{r_e}{3} + jx_a + j\frac{x_e}{3} \ \ \Omega/\text{mi} \tag{C.7}$$

where

r_a and x_a are as defined above using characteristics of the overhead shield wire or feeder neutral, and r_e and x_e are as defined above.

Table C.1—Approximate equivalent impedances of transmission line overhead shield wires and distribution feeder neutrals

Number of transmission lines	Number of distribution neutrals	$R_{tg} = 15$; $R_{dg} = 25$; $R + jx$ (Ω)	$R_{tg} = 15$; $R_{dg} = 25$; $R + jx$ (Ω)
1	1	0.91 + j.485	3.27 + j.652
1	2	0.54 + j0.33	2.18 + j.412
1	4	0.295 + j0.20	1.32 + j.244
1	8	0.15 + j0.11	0.732 + j.133
1	12	0.10 + j.076	0.507 + j.091
1	16	0.079 + j.057	0.387 + j.069
2	1	0.685 + j.302	2.18 + j.442
2	2	0.455 + j.241	1.63 + j.324
2	4	0.27 + j.165	1.09 + j.208
2	8	0.15 + j0.10	0.685 + j.122
2	12	0.10 + j0.07	0.47 + j.087
2	16	0.08 + j.055	0.366 + j.067
4	1	0.45 + j0.16	1.30 + j.273
4	2	0.34 + j0.15	1.09 + j0.22
4	4	0.23 + j0.12	0.817 + j0.16
4	8	0.134 + j.083	0.546 + j.103
4	12	0.095 + j.061	0.41 + j.077
4	16	0.073 + j0.05	0.329 + j0.06
8	1	0.27 + j0.08	0.72 + j.152
8	2	0.23 + j0.08	0.65 + j.134
8	4	0.17 + j.076	0.543 + j0.11
8	8	0.114 + j.061	0.408 + j.079
8	12	0.085 + j.049	0.327 + j.064
8	16	0.067 + j.041	0.273 + j.052
12	1	0.191 + j.054	0.498 + j.106

Table C.1—Approximate equivalent impedances of transmission line overhead shield wires and distribution feeder neutrals (continued)

Number of transmission lines	Number of distribution neutrals	$R_{tg} = 15$; $R_{dg} = 25$; $R + jx$ (Ω)	$R_{tg} = 15$; $R_{dg} = 25$; $R + jx$ (Ω)
12	2	$0.17 + j.055$	$0.462 + j.097$
12	4	$0.14 + j.053$	$0.406 + j.083$
12	8	$0.098 + j.047$	$0.326 + j.066$
12	12	$0.077 + j.041$	$0.272 + j.053$
12	16	$0.062 + j.035$	$0.234 + j.046$
16	1	$0.148 + j0.04$	$0.380 + j.082$
16	2	$0.135 + j.041$	$0.360 + j.076$
16	4	$0.113 + j.041$	$0.325 + j.067$
16	8	$0.086 + j.038$	$0.272 + j.055$
16	12	$0.068 + j.034$	$0.233 + j.047$
16	16	$0.057 + j0.03$	$0.203 + j.040$
1	0	$2.64 + j0.60$	$6.44 + j1.37$
2	0	$1.30 + j0.29$	$3.23 + j0.70$
4	0	$0.65 + j.15$	$1.61 + j.348$
8	0	$0.327 + j.074$	$0.808 + j.175$
12	0	$0.22 + j.049$	$0.539 + j.117$
16	0	$0.163 + j.037$	$0.403 + j.087$
0	1	$1.29 + j.967$	$6.57 + j1.17$
0	2	$0.643 + j.484$	$3.29 + j0.58$
0	4	$0.322 + j.242$	$1.65 + j.291$
0	8	$0.161 + j.121$	$0.826 + j.148$
0	12	$0.108 + j.081$	$0.549 + j.099$
0	16	$0.080 + j.061$	$0.412 + j.074$

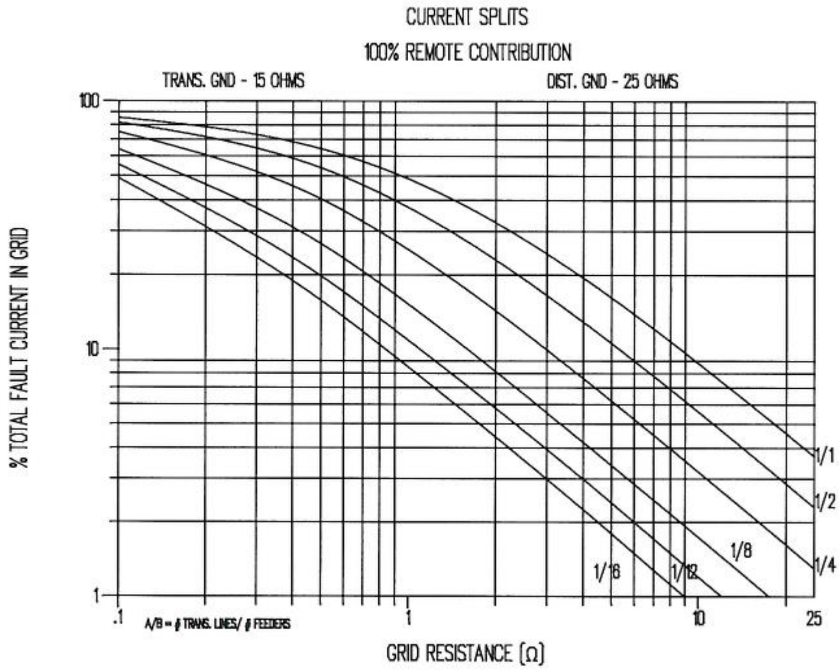

Figure C.1—Curves to approximate split factor S_f

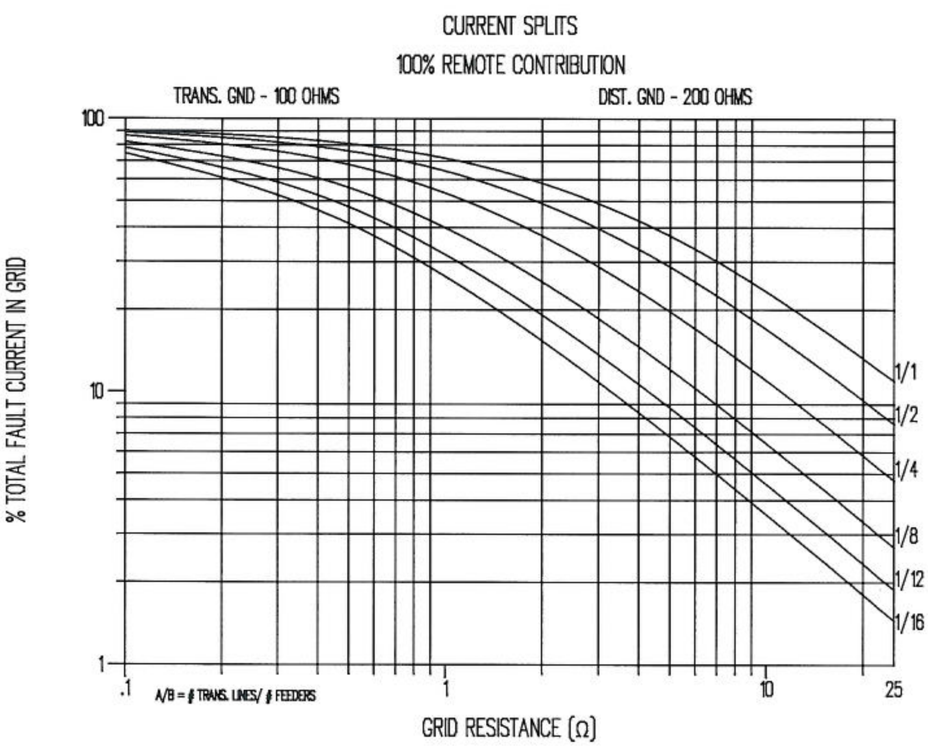

Figure C.2—Curves to approximate split factor S_f

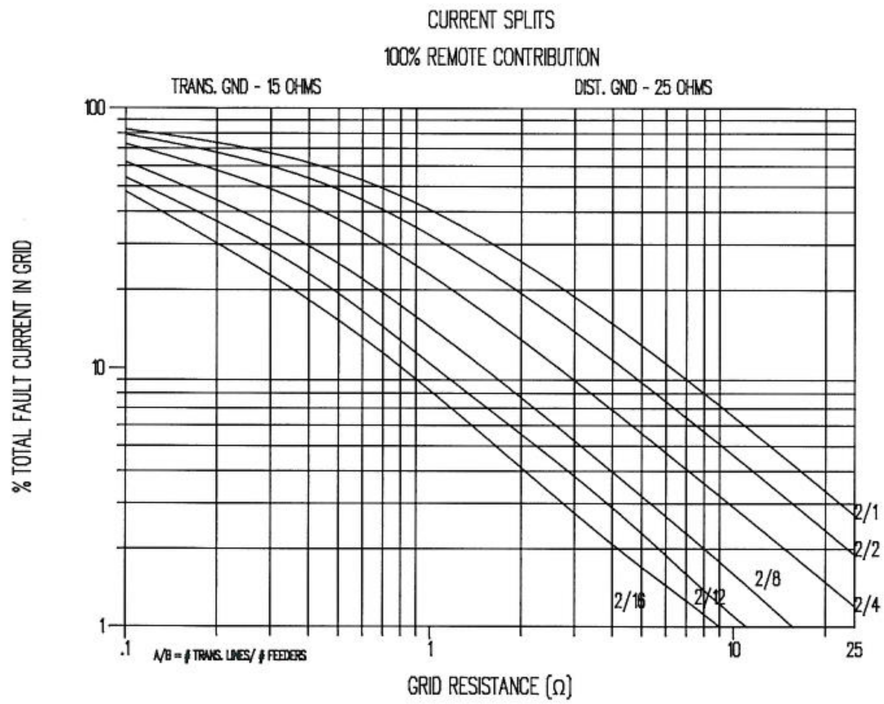

Figure C.3—Curves to approximate split factor S_f

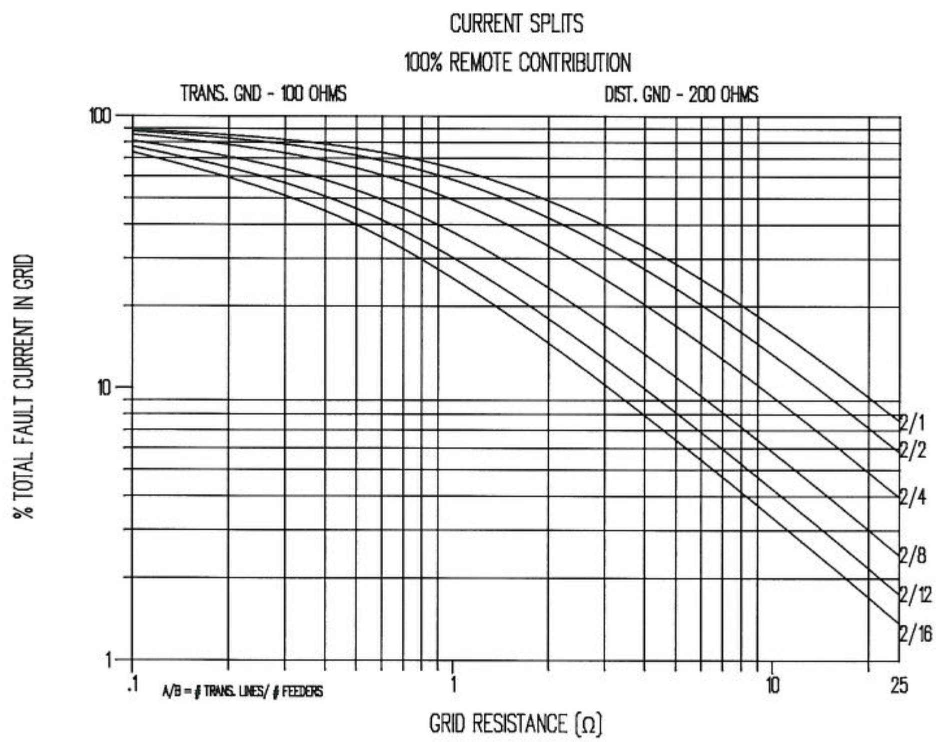

Figure C.4—Curves to approximate split factor S_f

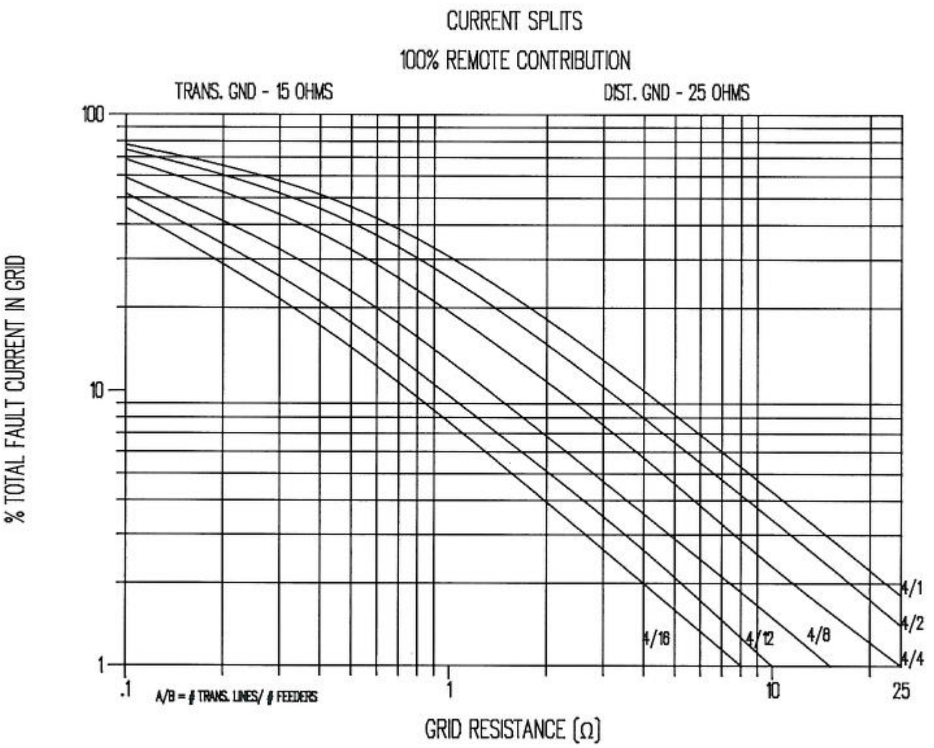

Figure C.5—Curves to approximate split factor S_f

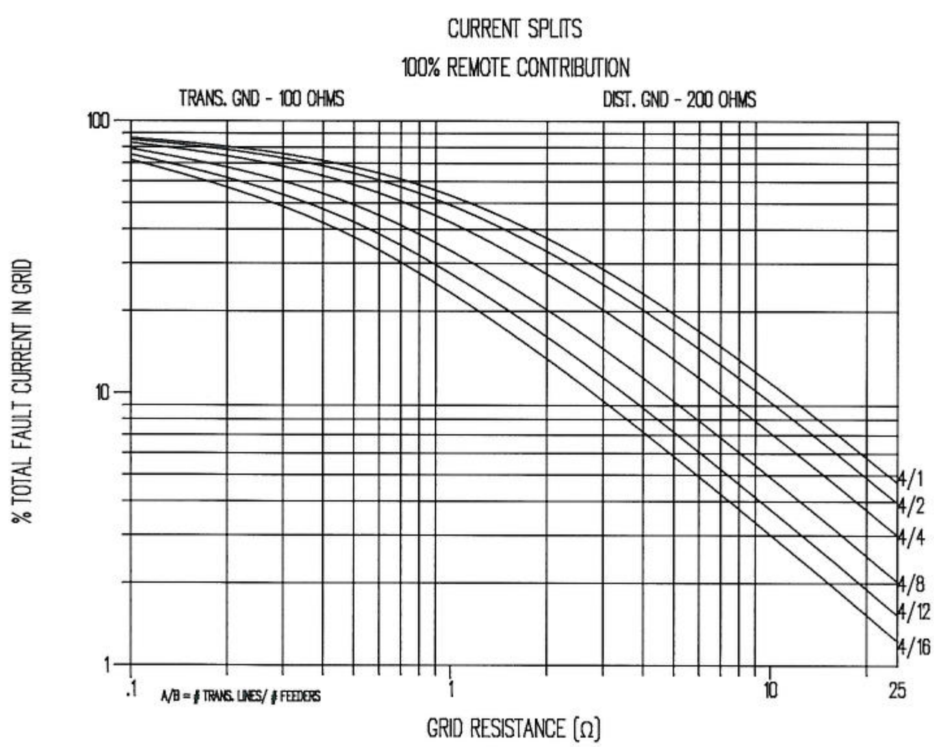

Figure C.6—Curves to approximate split factor S_f

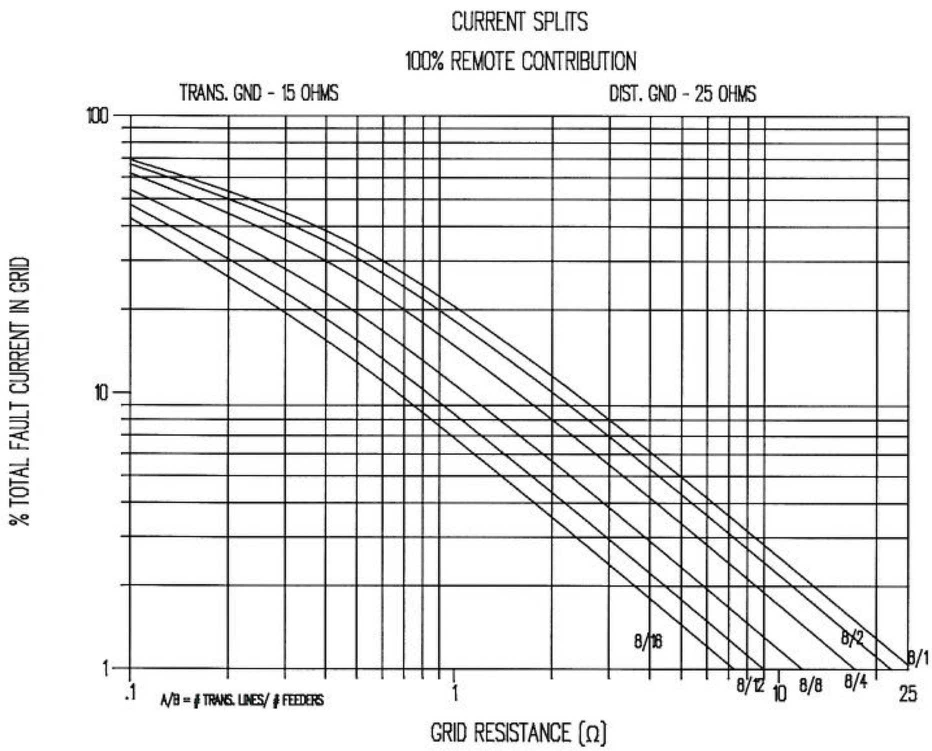

Figure C.7—Curves to approximate split factor S_f

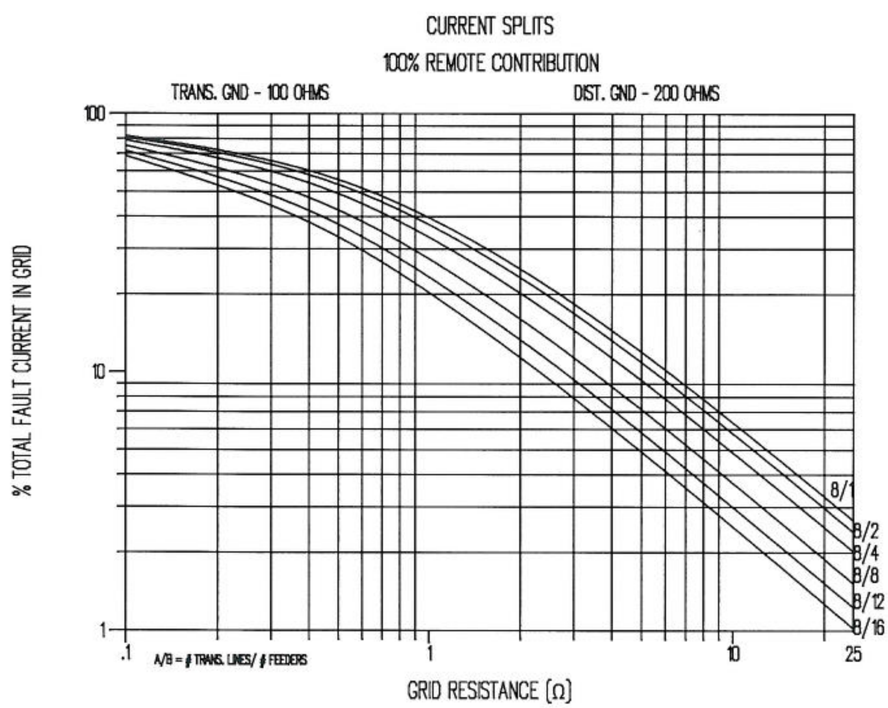

Figure C.8—Curves to approximate split factor S_f

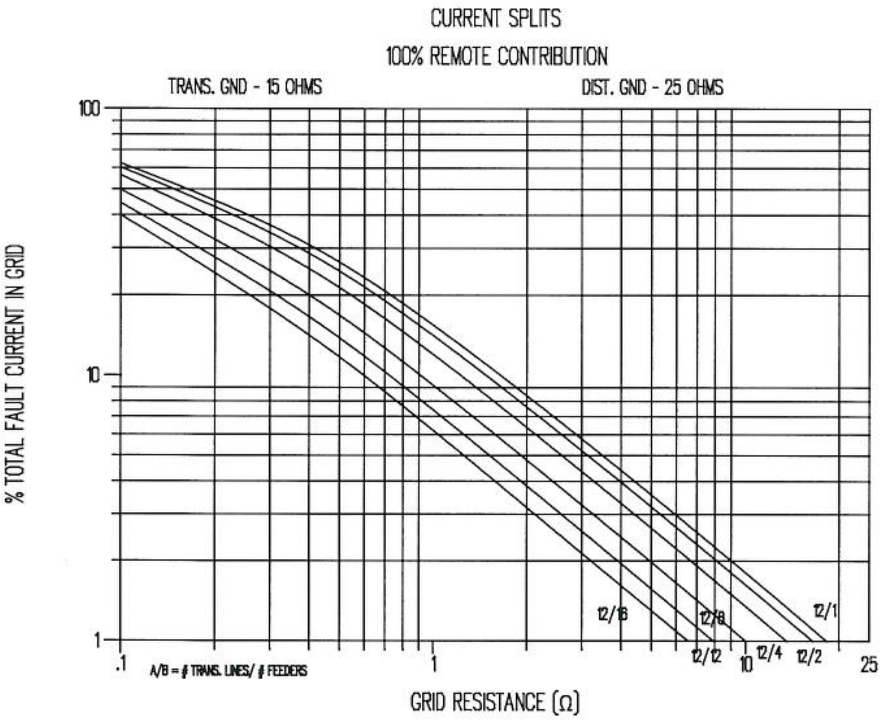

Figure C.9—Curves to approximate split factor S_f

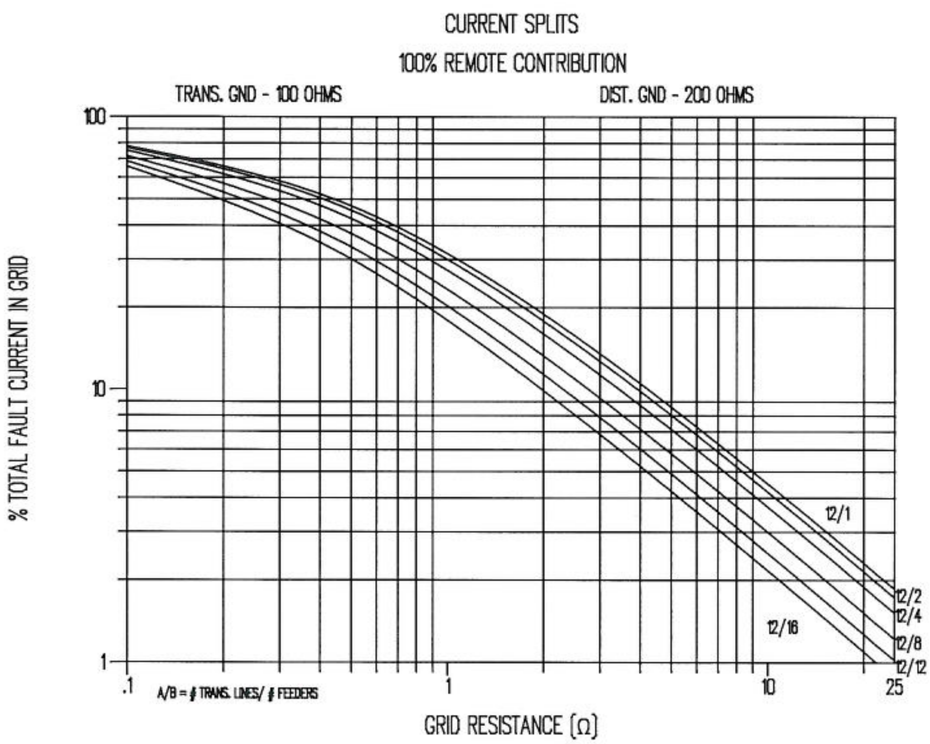

Figure C.10—Curves to approximate split factor S_f

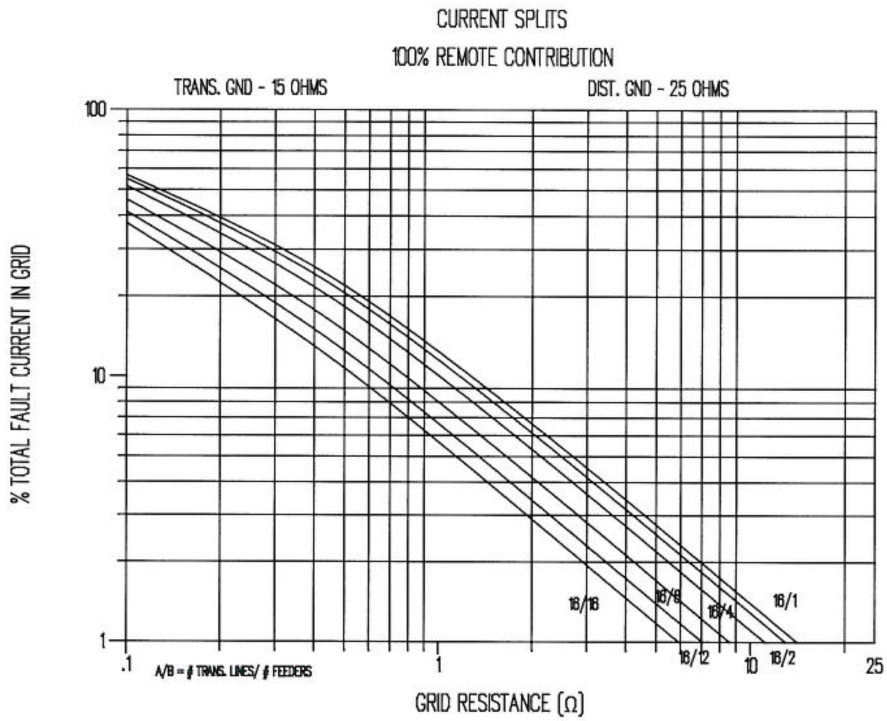

Figure C.11—Curves to approximate split factor S_f

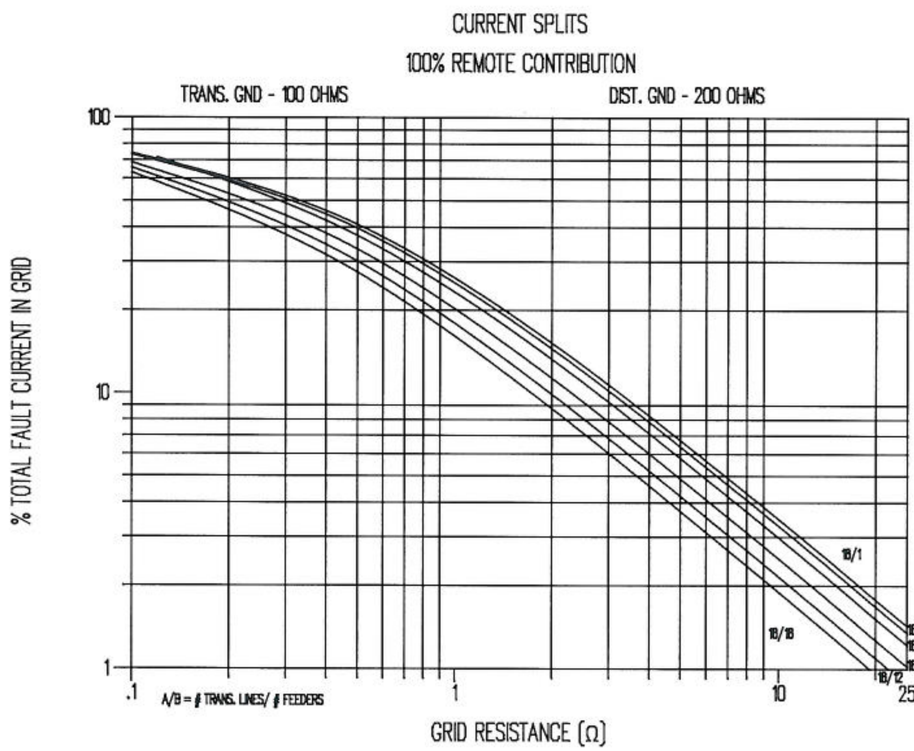

Figure C.12—Curves to approximate split factor S_f

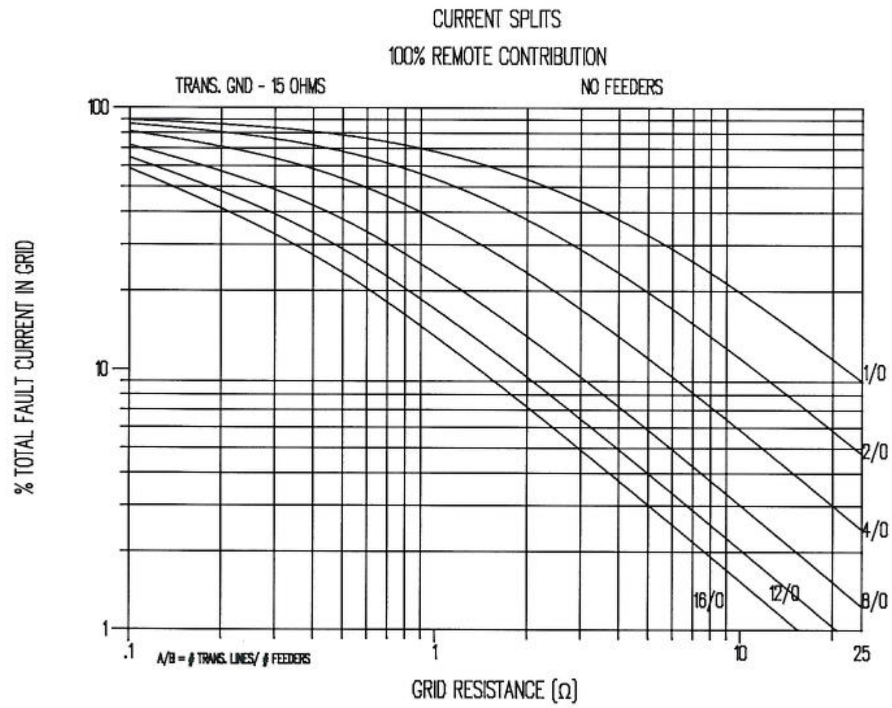

Figure C.13—Curves to approximate split factor S_f

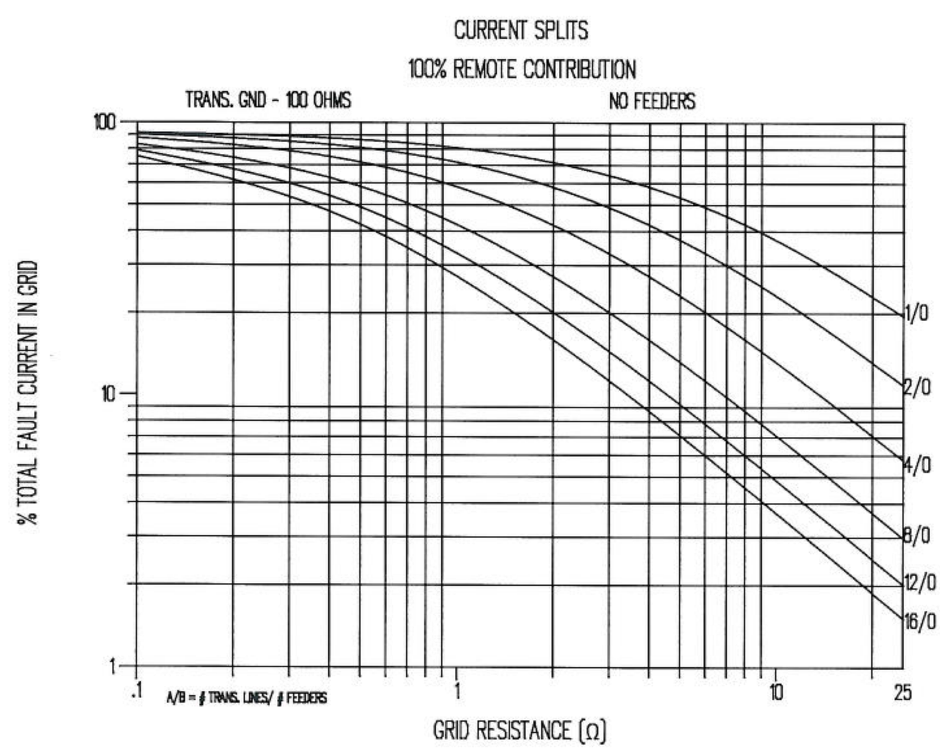

Figure C.14—Curves to approximate split factor S_f

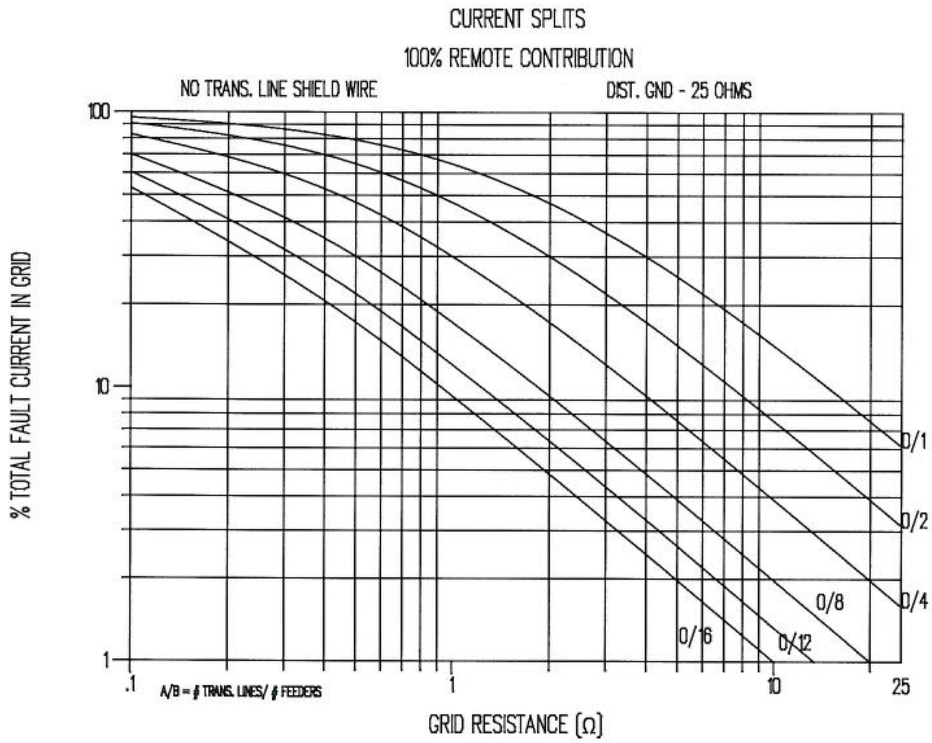

Figure C.15—Curves to approximate split factor S_f

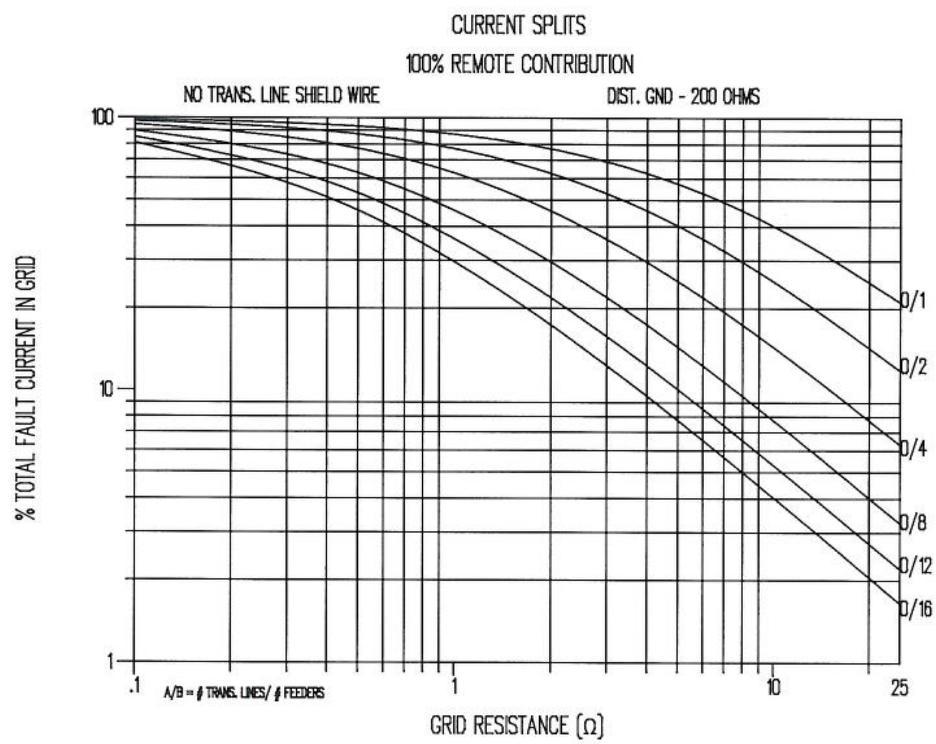

Figure C.16—Curves to approximate split factor S_f

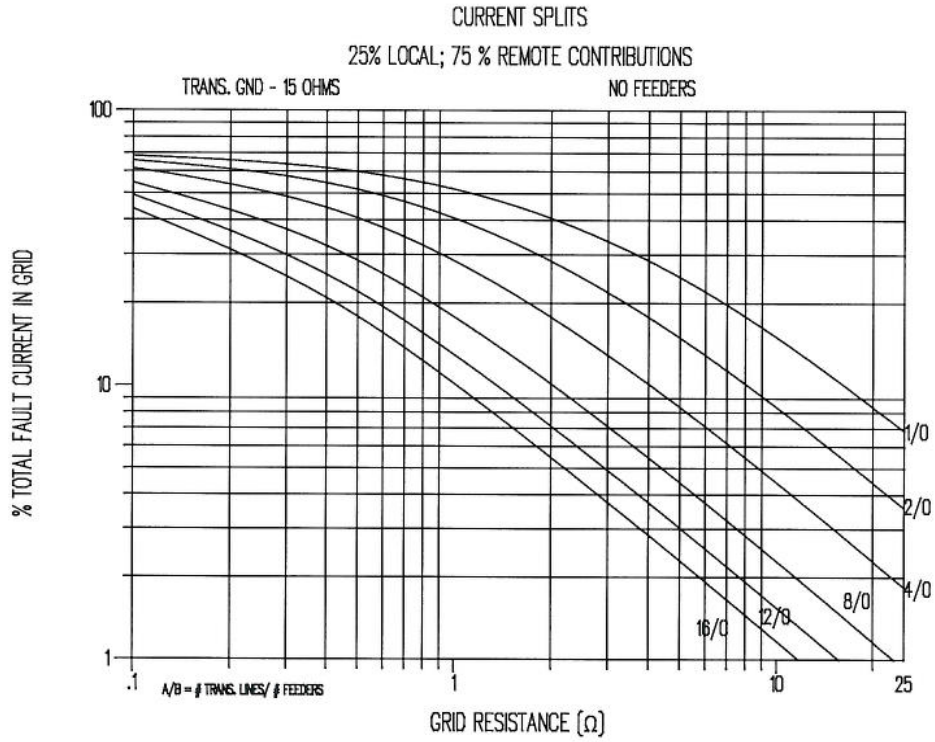

Figure C.17—Curves to approximate split factor S_f

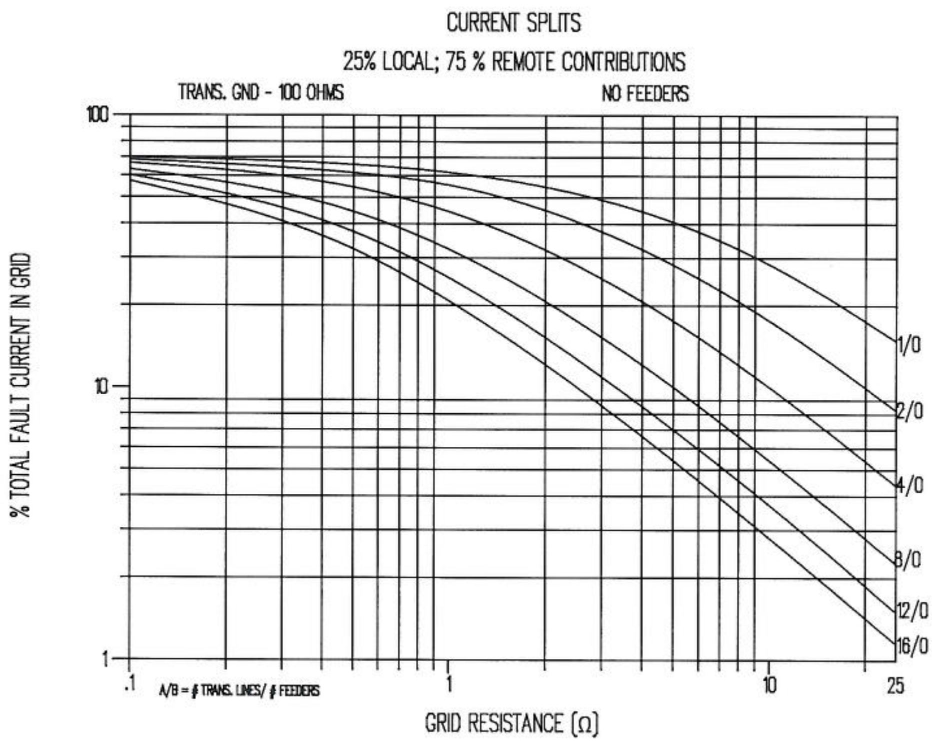

Figure C.18—Curves to approximate split factor S_f

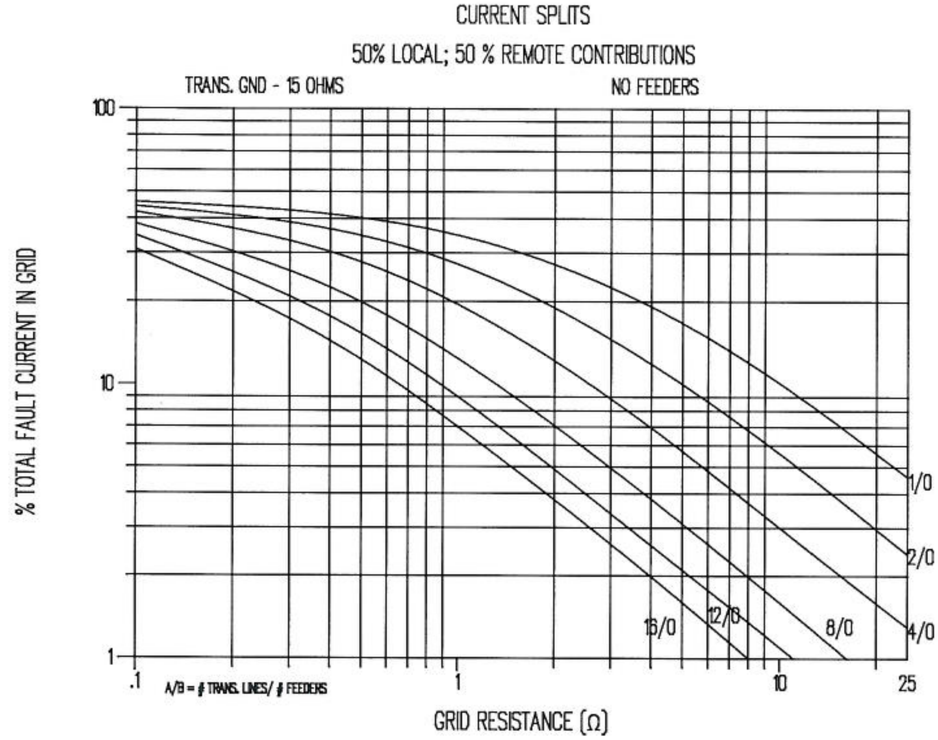

Figure C.19—Curves to approximate split factor S_f

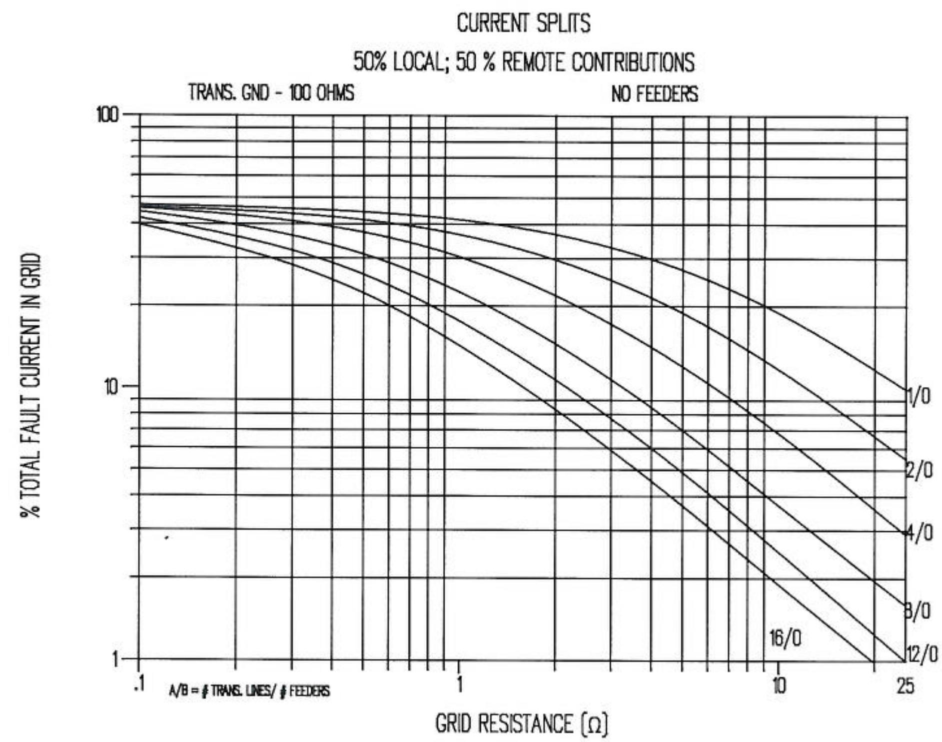

Figure C.20—Curves to approximate split factor S_f

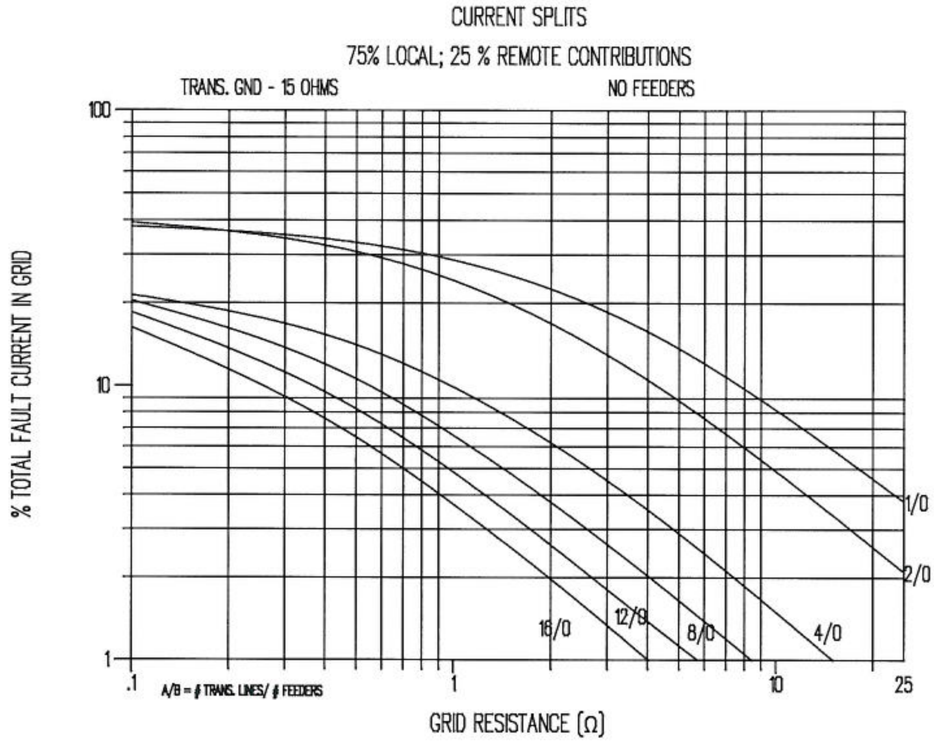

Figure C.21—Curves to approximate split factor S_f

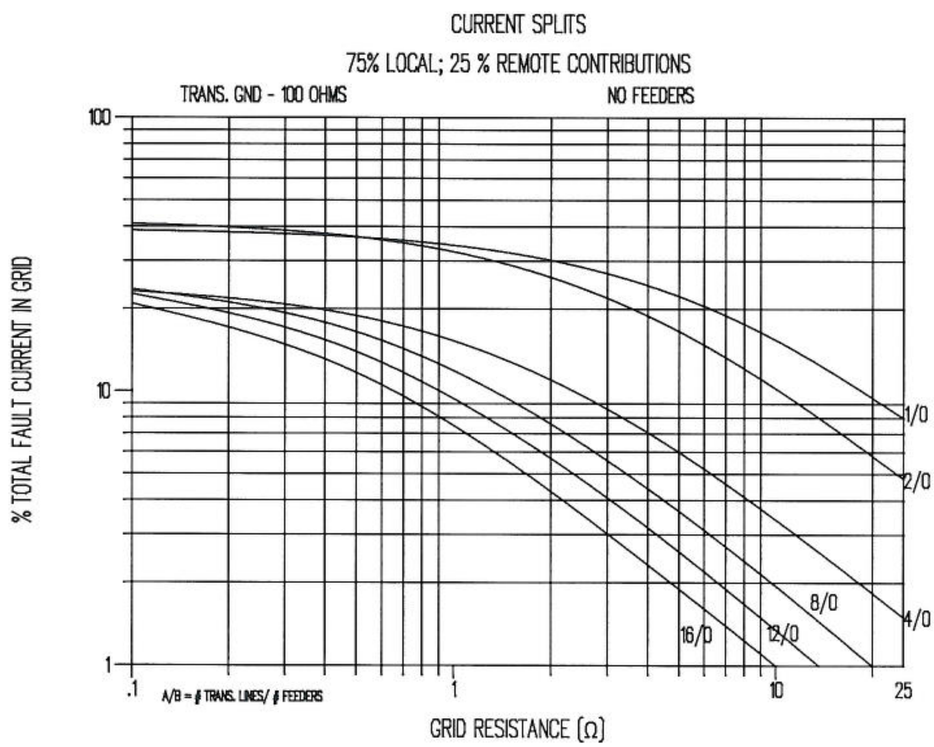

Figure C.22—Curves to approximate split factor S_f

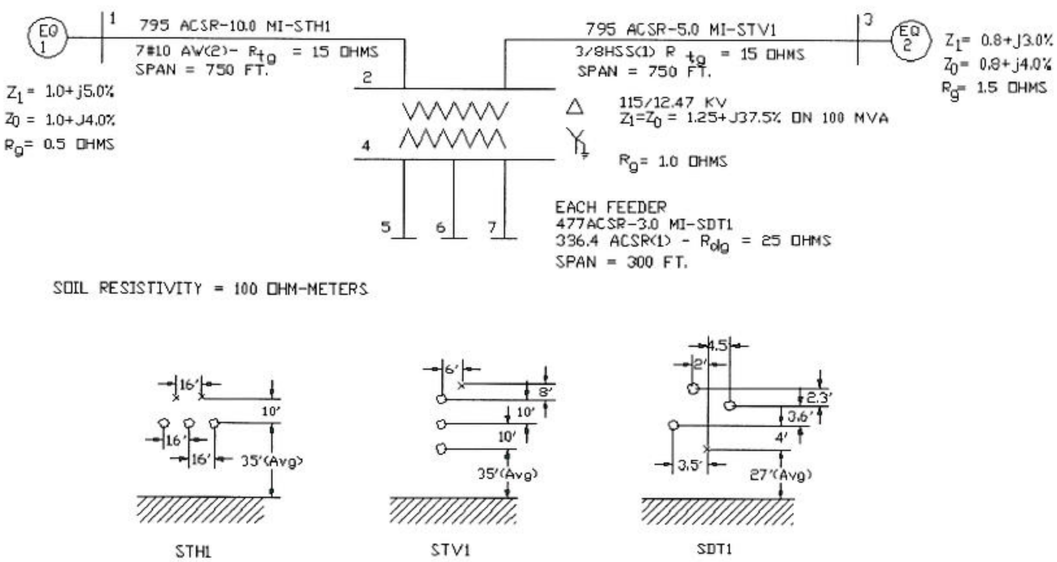

Figure C.23—System and configuration data for example 1 of C.3

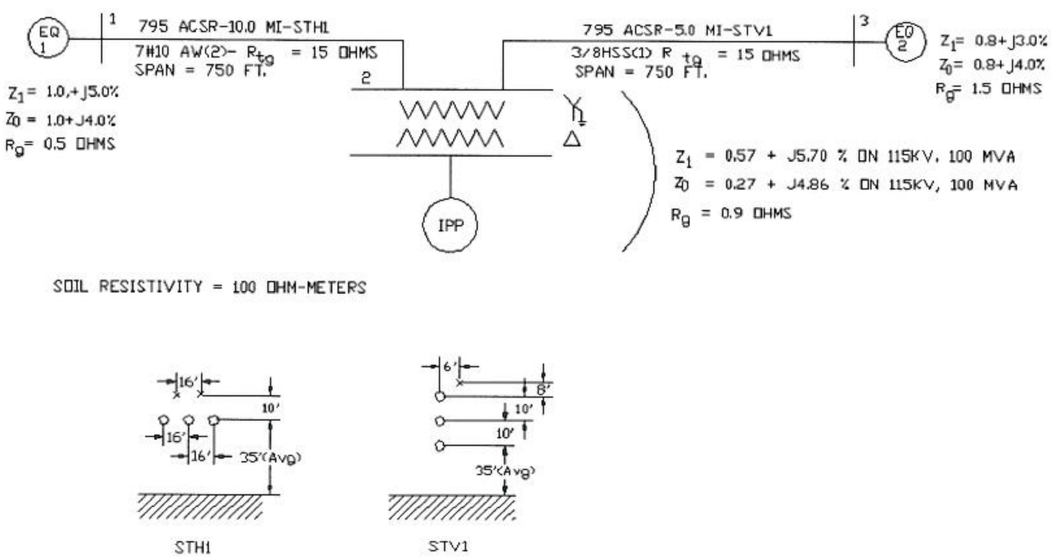

Figure C.24—System and configuration data for example 2 of C.3