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IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems
Part I—Introduction

Sponsor

Surge Protective Devices Committee of the
IEEE Power Engineering Society

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Foreword

(This Foreword is not a part of ANSI/IEEE C62.92-1987, IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems, Part I - Introduction.)

This guide is the introduction to a series of on neutral grounding in electrical utility systems. When the series of documents are approved and published they will replace IEEE Std 143-1954, IEEE Guide for Ground-Fault Neutralizers, Grounding of Synchronous Generator Systems, and Neutral Grounding of Transmission Systems. In the new series of documents individual considerations and practices will be given to the grounding of synchronous generator systems, generator-station auxiliary systems, distribution systems, and transmission and subtransmission systems.

IEEE Std 143-1954 is a revision of AIEE No 954, Oct 1954, which was a compilation of the following three AIEE Transaction papers.

AIEE COMMITTEE GUIDE REPORT. Application of Ground-Fault Neutralizers. *AIEE Transactions (Power Apparatus and Systems)* vol 72, pt III, April 1953, pp 183-190.

AIEE COMMITTEE REPORT. Application Guide for the Grounding of Synchronous Generator Systems. *AIEE Transactions (Power Apparatus and Systems)* pt III, June 1953, pp 517-530.

AIEE COMMITTEE REPORT. Application Guide on Methods of Neutral Grounding of Transmission Systems. *AIEE Transactions (Power Apparatus and Systems)* pt III, Aug 1953, pp 663-668.

The contents of Parts I, II, III, IV, and V of the revision of IEEE Std 143-1954 are based on the foregoing documents but are amplified and updated with new material from the IEEE TUTORIAL COURSE, Surge Protection in Power Systems (79EH0144-6-PWR).

In Parts I through V of this revision emphasis is on power-system grounding practices as contrasted with the grounding, for example, of industrial systems, which are covered in other guides and standards. The guides and standards should be referenced, when appropriate, to gain a full picture of other grounding practices.

It is impossible to give recognition to all those who have contributed to the technology and practices of grounding of power systems since work involving the preparation of the supplements has been in progress for over thirty years. However, the assistance of members, past and present, of the Neutral Grounding Devices Subcommittee of the Surge Protective Devices Committee, and other similar groups with comparable purposes should be acknowledged.

The American National Standards Committee C62, Surge Arrestors, had the following members at the time this guide was approved.

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Contents

An American National Standard

IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems
Part I—Introduction

Disclaimer

This part of the guide is specifically written for electric utility systems, and does not recognize the neutral grounding requirements for dispersed storage and generation. These requirements must recognize the restrictions imposed by the specific network to which the dispersed storage or generation is connected. Neutral grounding of dispersed storage and generation needs to be coordinated with the electric utility system.

1. Scope

The purpose of this guide and subsequent revisions to IEEE Std 143-1954 [8][1] is to present some basic considerations for the selection of neutral grounding parameters that will provide for the control of ground-fault current and overvoltage on all portions of three-phase electric utility systems.

Particular attention is given to five discrete reas of the electric utility system and they are ubdivided in Parts II through V.[2]

In these five areas of the utility system, there are certain common considerations, but also there are unique ones that have led to the utilization of different ways of grounding.

There is no one simple answer to the problem of grounding. Each of a number of solutions to a grounding problem has at least one feature that is outstanding, but which is obtained at some sacrifice of other features that may be equally worthy (see ANSI/IEEE Std 142-1982 [7], [8] and [10]).

Various solutions will be discussed in Part II, through Part V for each of the five areas of the system.

This part of the guide (Part I), provides considerations and definitions that are general to all types of systems.

2. Definitions

For the purpose of this guide, the following definitions have been used:

classes of grounding. A specific range of degree of grounding; for example, effectively and non-effectively.

means of grounding. The generic agent by which various degrees of grounding are achieved; for example, inductance grounding, resistance grounding, and resonant grounding.

methods (or types) of grounding. The equipment, procedure, or scheme used for attaining the particular means.

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[1] The numbers in brackets correspond to the references listed in Section 3 of this guide.

[2] In preparation at time of publication:
Part II, Synchronous Generator System
Part III, Generating Station Auxiliary Systems
Part IV, Distribution Systems
Part V, Transmission Systems and Subtransmission Systems

3. References

This guide should be used in conjunction with the following publications.

[1] ANSI C62.2-1981, American National Standard Guide for Application of Valve-Type Surge Arresters for Alternating-Current Systems.[3]

[2] ANSI C92.1-1982, American National Standard for Power Systems—Insulation Coordination.

[3] ANSI/IEEE C62.1-1984, IEEE Standard for Surge Arresters for Alternating-Current Power Circuits.

[4] ANSI/IEEE Std 32-1972 (R1984), IEEE Standard Requirements, Terminology, and Test Procedure for Neutral Grounding Devices.

[5] ANSI/IEEE Std 80-1986, IEEE Guide for Safety in AC Substation Grounding.

[6] ANSI/IEEE Std 100-1984, IEEE Standard Dictionary of Electrical and Electronics Terms.

[7] ANSI/IEEE Std 142-1982, IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems.

[8] IEEE Std 143-1954, IEEE Guide for Ground-Fault Neutralizers, Grounding of Synchronous Generator Systems, and Neutral Grounding on Transmission Systems.[4]

[9] IEEE COMMITTEE REPORT. Voltage Rating Investigation for Application of Lighting Arresters on Distribution Systems. *IEEE Transaction (Power Apparatus and Systems)*, PAS 91, no 3, May/June 1972, pp 1067-1074.

[10] IEEE TUTORIAL COURSE. Surge Protection in Power Systems. 79EH0144-6 PWR.

[11] CLARK, E. *Circuit Analysis of AC Power Systems.* New York: John Wiley & Sons, Inc, vol 1 1943.

[12] CLARKE, E., CRARY, S.B., and PETERSON, H.A. Overvoltages During Power-System Faults. *AIEE Transactions (Power Apparatus and Systems)*, vol 58, Aug 1939, pp 377-385.

[13] WAGNER, C.F. and EVANS, R.D. *Symmetrical Components as Applied to the Analysis of Unbalanced Electrical Circuits.* New York: McGraw-Hill, 1933.

[14] JOHNSON, I.B. *Capacitor Banks for Transmission System Compensation.* Kansas City, MO: Missouri Valley Electric Association, Apr 12, 1973.

[15] PETERSON, H.A. *Transients in Power Systems.* New York: Dover Publications, Inc, 1966, ch 1.

[16] WILLHEIM, R. and WATERS, M. *Neutral Grounding in High-Voltage Transmission.* New York: Elsevier Co (D. Van Nostrand Co), 1956.

4. Basic Considerations

Generally, the basic considerations that have to be evaluated in selecting a grounding scheme for any given system are as follows:

(1) Sensitivity and selectivity of the ground relaying

(2) Limitation of the magnitude of the ground-fault current

(3) Required degree of surge voltage protection with arresters

(4) Limitation of transient line-to-ground (LG) overvoltages [8], [10], [16] through system design

(5) Safety [5]

These basic considerations, when properly evaluated, can have a significant influence on system economics, details of system design and physical layout, and service continuity.

5. General Classes of Grounding

5.1 Grounded Versus Ungrounded Systems. A system that is a combination of lines, cables, or conductors with apparatus may be broadly classified as either grounded or ungrounded. A

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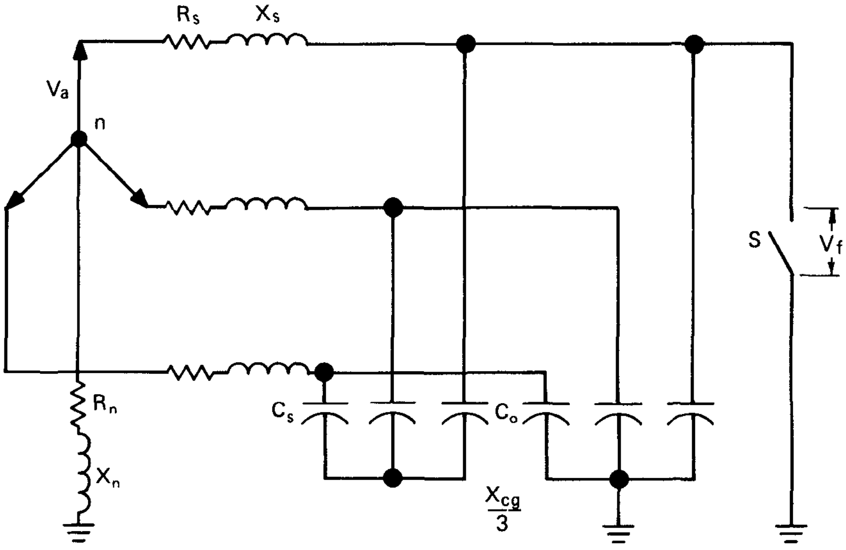
[3] ANSI publications are available from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018.

[4] IEEE publications are available from IEEE Service Center, 445 Hoes Lane, Piscataway, NJ 08854.



$$C_s = C_1 - C_0\,;\ \frac{C_g}{3} = C_0$$

$$X_{Cs} = \frac{1}{\omega C_s},\quad X_{Cg}/3 = \frac{1}{\omega C_g/3},\quad X_{Cg} = \frac{1}{\omega C_g}$$

$C_g/3$ is the grounded-wye partial, or zero-sequence, capacitance of the system.

C_g is obtained by connecting all three phases together, and measuring the capacitance with the neutral grounding branch open-circuited.

C_s is the ungrounded wye equivalent of the interphase partial capacitances of the system, obtained by subtracting the zero-sequence capacitance $C_g/3$ from the positive sequence capacitance C_1.

V_f is the prefault fault line-to-ground voltage, the energization voltage, shown on Fig 2.

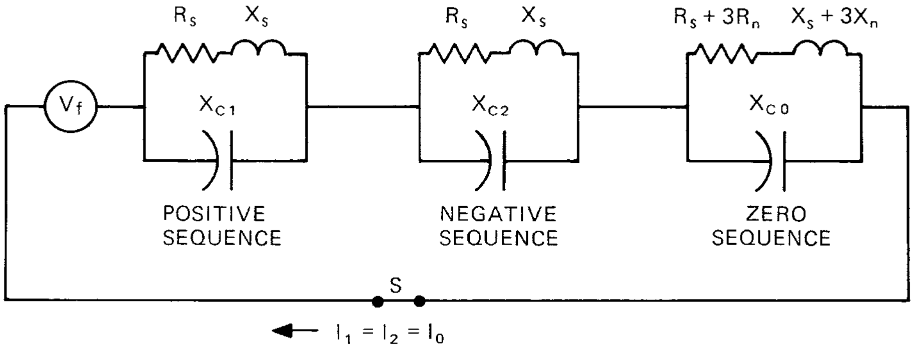
Fig 1
Idealized System

grounded system is a system in which at least one conductor or point (usually the neutral point of the transformer or the generator windings) is intentionally grounded directly or through an impedance. An ungrounded system or apparatus is one without an intentional connection to ground.

5.2 Characteristic Definition of Classes of Grounding. Various classes of grounding are available to the system designer, each having a unique set of attributes. The response characteristics for the various classes of grounding may be defined or classified in terms of the ratios of symmetrical component parameters, such as the positive-sequence reactance X_1, the negative-sequence reactance X_2, the zero-sequence reactance X_0, the positive-sequence resistance R_1, the negative-sequence resistance R_2, and the zero-sequence resistance R_0 [11], [13], [16].

To facilitate an understanding of this approach, reference is made to the simplified idealized three-phase circuit of Fig 1 and its equivalent sequence diagram for a single line-to-ground fault as shown in Fig 2. Subscripts 1, 2, and 0 indicate positive-, negative-, and zero-sequence parameters, respectively.

5.3 Coefficient of Grounding. The term, *coefficient of grounding* (COG) is used in system grounding practice [1], [4], [10]. Coefficient of grounding is defined as the ratio of E_{LG}/E_{LL}, expressed as a percentage, of the highest root-mean-square line-to-ground power-frequency



NOTE:
$R_s + \mathrm{j}\,X_s$ is the same as seen by all three-sequence networks.

$X_{C1} = X_{C2} = 1/(\omega C_s + \frac{\omega C_g}{3})$; $X_{C0} = 1/(\omega \frac{C_g}{3})$;
$\omega = 2\pi f$

$$\frac{1}{R_1 + \mathrm{j}\,X_1} = \frac{1}{R_2 + \mathrm{j}\,X_2} = \frac{1}{R_s + \mathrm{j}\,X_s} - \frac{1}{\mathrm{j}\,X_{C1}}$$

$$\frac{1}{R_0 + \mathrm{j}\,X_0} = \frac{1}{(R_s + 3R_n) + \mathrm{j}(X_s + 3X_n)} - \frac{1}{\mathrm{j}\,X_{C0}}$$

V_f = Thevenin open-circuit, prefault, voltage

$$= \frac{-\mathrm{j}\,X_{C1}}{R_s + \mathrm{j}(X_s - X_{C1})} V_a$$

where

V_a = line-to-neutral source voltage of Fig 1.
$3I_0$ = Fault current I_f through closed switch S of Fig 1

Fig 2
Sequence Diagram for Line-to-Ground Fault, Through Closed Switch S of Fig 1

voltage E_{LG} on a sound phase, at a selected location, during a line-to-ground fault affecting one or more phases, to the line-to-line power-frequency voltage E_{LL} that would be obtained, at the selected location, with the fault removed. Coefficients of grounding for three-phase systems are calculated from the phase-sequence impedance components as viewed from the fault location. The subtransient reactance is used for rotating machines [6]. The coefficient of grounding is useful in the determination of an arrester rating for a selected location [1], [3].

5.4 Earth-Fault Factor (EFF). Earth-fault factor, is, to a limited extent, now used instead of coefficient of grounding. At a selected location on a three-phase system and for a given system configuration, the earth-fault factor is the ratio of the highest root-mean-square line-to-ground power-frequency voltage on a sound phase during a fault to ground (affecting one or more phases at any point) to the root-mean-square line-to-ground power-frequency voltage that would be obtained at the selected location with the fault removed [2]. Thus, the earth-fault factor is related to the coefficient of grounding by $\sqrt{3}$; that is:

$$a = \sqrt{3}b$$

where
a = earth-fault factor
b = coefficient of grounding in percentage

5.5 Symmetrical Components. The ratios of the symmetrical component parameters are used to characterize the classes of grounding as either effectively or noneffectively grounded in accordance with their coefficient of grounding, as defined in 5.5.1 through 5.5.3.

5.5.1 Effectively Grounded. Grounded through a sufficiently low impedance (inherent or intentionally added, or both) so that the coefficient of grounding does not exceed 80% [1], [6], [10]. This value is obtained approximately when for all system conditions the ratio of zero-sequence reactance to positive-sequence reactance X_0/X_1 is positive and less than three, and the ratio of zero-sequence resistance to positive-sequence reactance R_0/X_1 is positive and less than one [3], [6], [10], [16].

5.5.2 Noneffectively Grounded. The coefficient of grounding exceeds 80% [1]. This value can be exceeded when the ratio of zero-sequence reactance to positive-sequence X_0/X_1 is negative or is positive and greater than three, or the ratio of zero-sequence resistance to positive-sequence reactance R_0/X_1 is positive and greater than one.

5.5.3 Other Grounding Classes. The definitions and comments in the following section apply for specific grounding classes.

6. Means of Grounding

6.1 Grounded Solidly. Connected directly through an adequate ground connection in which no impedance has been inserted intentionally [6].

NOTE: This term, *grounded solidly*, though commonly used, is somewhat confusing since a transformer may have its neutral connected solidly to ground, and yet the resulting zero-sequence impedance (see Fig 1) could be so high due to the system or transformer characteristics that high phase-to-ground voltages would develop during ground-fault conditions. Instead, so as to define grounding positively and logically as to degree, the term *effectively grounded* has come into use, as was discussed in section 5.

6.2 Grounded, Impedance. Grounded through an impedance, the characteristics of which are defined in 6.2.1 through 6.2.4.

6.2.1 Grounded, Resistance. Grounded through impedance, the principal element of which is resistance [6]. (This means of grounding is frequently divided into *low* or *high* resistance.)

NOTE: The resistance may be inserted either directly in the connection to ground or indirectly, as for example, in the secondary of a transformer, the primary of which is connected between neutral and ground, or in the corner of the broken delta-connected secondary of a wye-delta grounding transformer [6].

6.2.2 Grounded, Inductance. Grounded through impedance, the principal element of which is inductance. (This means is frequently divided into *low* and *high* inductance.)

NOTE: The inductance may be inserted either directly in the connection to ground, or indirectly by increasing the reactance of the ground return circuit. The latter may be done by intentionally increasing the zero-sequence reactance of apparatus connected to ground or by omitting some of the possible connections from apparatus neutrals to ground.

6.2.3 Grounded, Capacitance. Grounded through impedance, the principle element of which is capacitance.

NOTE: Capacitance is seldom, if ever, inserted directly in the neutral connection to ground. However, capacitance may be connected to ground for voltage surge front-of-wave sloping purposes. Also neutrals of shunt capacitor banks have been connected solidly on ground on otherwise ungrounded circuits. However, such applications should be carefully analyzed for overvoltages during fault conditions [14], [15]. Other uses of capacitance grounding should be carefully analyzed or avoided.

6.2.4 Grounded, Resonant. Inductance grounded through such values of reactance that during a fault between one of the conductors and ground, the power-frequency inductive current flowing in the grounding reactances and the power-frequency capacitance current flowing between the unfaulted conductors and ground shall be substantially equal. (The type of equipment used is commonly referred to as a *ground-fault neutralizer* or a "Peterson coil") [6], [8], [16].

NOTES: (1) In the fault, these two components of fault current are substantially 180° out of phase.

(2) It is expected that the quadrature component of the rated-frequency single-phase-to-ground fault current will be so small that an arcing fault in air is self-extinguishing.

6.3 Ungrounded (Isolated Neutral). A system, circuit or apparatus without an intentional connection to ground except through potential-indicating or measuring devices, or other very-high-impedance devices [6], [10].

NOTE: An ungrounded system is coupled to ground through the distributed capacitance of its phase conductors and machine windings.

7. Characteristics of Means of Grounding

The unique set of attributes of the various means of grounding are briefly discussed in 7.1 through 7.3. Characteristics for the various means are given in Table I.

Table 1
Characteristics of Grounding

Grounding Classes and Means	Ratios of Symmetrical Component Parameters NOTE (1)			Percent Fault Current NOTE (2)	Per Unit Transient LG Voltage NOTE (3)	Reference
	X_0/X_1	R_0/X_1	R_0/X_0			
A. Effectively NOTE (4)						
1. Effective	0-3	0-1	—	>60	≤2	[8],[14]
2. Very effective	0-1	0-0.1	—	>95	<1.5	
B. Noneffectively						
1. Inductance						
a. Low inductance	3-10	0-1		>25	<2.3	
b. High inductance	>10		<2	<25	≤2.73	[8]
2. Resistance						
a. Low resistance	0-10		≥2	<25	<2.5	
b. High resistance		>100	≤(-1)	<1	≤2.73	[10], [12]
3. Inductance and resistance	>10	—	>2	<10	≤2.73	
4. Resonant	NOTE (5)			<1	<2.73	
5. Ungrounded/capacitance						
a. Range A	−∞ to −40 NOTE (6)	—	—	<8	≤3	[12], [14]
b. Range B	−40 to 0	—	—	>8	>3 NOTE (7)	[14]

NOTES: (1) Values of the coefficient of grounding (expressed as a percentage of maximum phase-to-phase voltage) corresponding to various combination of these ratios are shown in the Appendix figures. Coefficient of grounding affects the selection of arrester ratings [1], [9].

(2) Ground-fault current in percentage of the three-phase short-circuit value [7].

(3) Transient line-to-ground voltage, following the sudden initiation of a fault in per unit of the crest of the prefault line-to-ground operating voltage, from [12] and [15], for a simple, linear circuit.

(4) In linear circuits, Class A1 limits the fundamental line-to-ground voltage on an unfaulted phase to 138% of the prefault voltage; Class A2 to less than 110%.

(5) See 7.3 and [16]; and precautions given in application sections.

(6) Usual isolated neutral (ungrounded) system for which the zero-sequence reactance is capacitive (negative).

(7) Same as NOTE (6) and refer to 7.4. Each case should be treated on its own merit.

7.1 Resistance Grounding. When a system is grounded through resistance, the zero-sequence impedance viewed from the fault may be inductive or capacitive, depending on the size, number, and location of the neutral-grounding resistors and the capacitance to ground of the remaining system. With low-resistance grounding X_0 will ordinarily be positive, the fundamental-frequency phase-to-ground voltages will, in general, not exceed normal line-to-line voltage, and the neutral-to-ground voltages will not exceed normal line-to-neutral voltage. With high-resistance grounding, X_0 may be negative. In that event, phase-to-ground voltages may be greater than normal line-to-line voltages, and neutral-to-ground voltages greater than normal line-to-line neutral voltages [12], [15].

If low-resistance grounding is used, the natural-frequency voltages are significantly reduced. The maximum voltages are essentially the fundamental-frequency voltages, which are generally higher than the fundamental-frequency voltages obtained with corresponding values of neutral-ground inductive reactance [12], [15].

7.2 Inductance Grounding. When a system is grounded through an inductance less than that of a ground-fault neutralizer, the zero-sequence impedance viewed from the fault is inductive rather than capacitive and the zero-sequence resistance is relatively small. Accordingly, the fundamental-frequency phase-to-ground voltages will not exceed normal line-to-line voltage, and the neutral-to-ground voltage will not exceed normal line-to-neutral voltage.

Following the initiation of a fault, systems with neutrals grounded through reactance will have maximum transient voltages-to-ground on the unfaulted phase not exceeding 2.73 times normal. The voltage-to-ground at the neutral will not exceed 1.67 times normal line-to-neutral voltage [12], [15].

7.3 Resonant-Grounding. When the system is grounded through a ground-fault neutralizer, the neutral inductance is chosen so that [16]:

$$X_{C_g} = X_n$$

where

X_{C_g} = capacitive reactance to ground
C_g = capacitance to ground
X_n = neutral reactance
(see Figs 1 and 2 for definitions of X_{C_g} and X_n)

In Figs 1 and 2, R_s and X_s are generally neglected because of being very small in comparison to X_n and X_{C_g}

For resonant grounded systems with resistance neglected, X_0 is infinite. With resistance included R_0 is very large with respect to X_0. Based on either assumption, the fundamental-frequency voltages on the unfaulted phases at the fault following a line-to-ground fault are essentially line-to-line voltages. They are not increased by the presence of fault resistance. The maximum transient voltages to ground of the unfaulted phases are less than 2.73 times normal, and of the neutral-to-ground less than 1.67 times normal line-to-neutral voltage [12], [15].

7.4 Ungrounded. In an ungrounded system, X_0 is negative and of the order of magnitude of the zero-sequence capacitive reactance, while R_0/X_1 is relatively small. Under fault conditions, the fundamental-frequency phase-to-ground voltages may be in excess of normal line-to-line voltages; and in some cases, particularly when the system is large in extent, these voltages may be considerably higher [12], [15].

There are a number of economic factors and operating practices governing the choice between grounded and ungrounded systems. Ungrounded systems may require higher insulation levels as a result of possible severe transient overvoltages and series resonant or ferro-nonlinear overvoltages when X_0/X_1 is in the range of -40 to 0. Abnormal insulation stress may be reduced when X_0/X_1 is in the range of $-\infty$ to -40 [12], [15]. However, cases exist showing that ungrounded systems can have satisfactory operating performance.

Severe series resonant overvoltages can occur if the circuit response is linear. However, highly distorted, less severe, oscillations may be generated in ferro-nonlinear circuits over a broad range of $-X_0/X_1$ due to the presence of a saturating transformer [14]. Generally such conditions should be avoided, and each case should be treated on its own merit.

7.5 Information Given in Table 1, References, and the Appendix. A general classification of grounding together with associated means, fault current, and transient voltage characteristics are given in Table 1. This table refers to system or equipment grounding, or both.[5] The figures of the Appendix provide coefficients of grounding for ranges of X_0/X_1 and R_0/X_1, and generally indicate the ranges for the general classification. Requirements and tests for neutral-grounding devices used as methods may be found in [4].

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[5] Parts II through V of this Application Guide will clarify applications. See footnote 2.

Appendix A

(This Appendix is not a part of ANSI/IEEE C62.92-1987, IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems, Part I—Introduction, but is included for information only.)

Calculation of Coefficients of Grounding

The term *coefficient of grounding* is defined as the ratio of E_{LG}/E_{LL}, expressed as a percentage, of the highest root-mean-square line-to-ground power-frequency voltage E_{LG} on a sound phase, at a selected location, during a fault to earth (ground) affecting one or more phases to the line-to-line power-frequency voltage E_{LL} that is obtained, at the selected location, with the fault removed [6]. Coefficients of grounding may be calculated from the known impedances of the system and the fault. For this purpose, it is convenient to express the system impedances in terms of their equivalent symmetrical component impedances Z_1, Z_2, and Z_0 [11], [13].

As defined above, the coefficient of grounding, for a specific location, may vary depending on the type of fault, the fault location, and the impedance in the fault. For the purpose of constructing Fig A2 through A6, the following assumptions were made:

(1) The coefficient of grounding is to be determined for the same location at which the fault is placed.

(2) The fault type (single- or double-phase-to-ground) is that which produces the highest coefficient of grounding.

(3) The fault impedance, if any, is purely resistive and has that value which produces the highest coefficient of grounding.

(4) The negative-sequence impedance of the system at the fault location is equal to the positive-sequence impedance $Z_1 = Z_2$.

For a system with positive X_0, coefficients of grounding for locations other than the fault location are generally the same as or lower than the coefficient for the fault location. In exceptional circumstances, coefficients may be slightly higher at locations where appreciable capacitive zero-sequence current must flow through high-inductance lines to reach the fault location.

In systems with negative X_0 the coefficient of grounding is generally lowest at the fault location and higher at remote locations. For this reason the usefulness of the coefficient on such systems is limited to systems in which line impedances are negligibly small.

Given these assumptions and the definition above, the quantities that must be calculated to determine the coefficient of grounding are the *a*-phase voltage V_{aLLG} for a phase *b*- and phase *c*-to-ground fault, and the *b*- and *c*-phase voltages V_{bLG} and V_{cLG} for an *a*-phase-to-ground fault. These faults and their symmetrical component equivalent networks are shown in Fig A1.

From [11], the significant voltages for these faults are as follows:

$$V_{aLLG} = V_f \frac{3Z_2(Z_0 + 2Z_F)}{Z_1Z_2 + (Z_1 + Z_2)(Z_0 + 3Z_F)} \qquad \text{(Eq A1)}$$

$$V_{bLG} = V_f \frac{3a^2Z_F - j\sqrt{3}\,(Z_2 - aZ_0)}{Z_0 + Z_1 + Z_2 + 3Z_F} \qquad \text{(Eq A2)}$$

$$V_{cLG} = V_f \frac{3aZ_F + j\sqrt{3}\,(Z_2 - a^2Z_0)}{Z_0 + Z_1 + Z_2 + 3Z_F} \qquad \text{(Eq A3)}$$

where $a = -0.5 + j\,\dfrac{\sqrt{3}}{2}$

letting:

$Z_2 = Z_1$

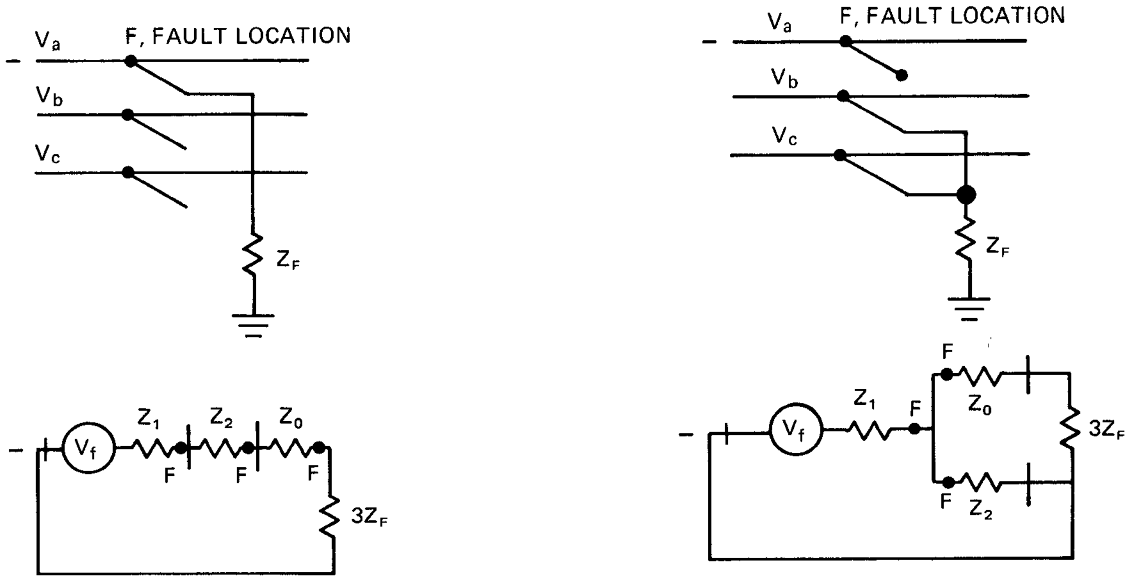
$Z_F = R_F$:

and rearranging

$$V_{aLLG} = V_f \frac{3Z_0 + 6R_F}{Z_1 + 2Z_0 + 6R_F} \qquad \text{(Eq A4)}$$

$$V_{bLG} = V_f \left(a^2 - \frac{Z_0 - Z_1}{2Z_1 + Z_0 + 3R_F}\right) \qquad \text{(Eq A5)}$$

$$V_{cLG} = V_f \left(a - \frac{Z_0 - Z_1}{2Z_1 + Z_0 + 3R_F}\right) \qquad \text{(Eq A6)}$$



a - PHASE-TO-GROUND FAULT

b- and *c*- PHASE-TO-GROUND FAULT

Fig A1
Symmetrical Component Equivalent Networks for Two Fault Types Used in Calculations

By the definition of coefficient of grounding

$$CFG_a = \sqrt{3}\left(\frac{Z_0 + 2R_F}{Z_1 + 2Z_0 + 6R_F}\right) \qquad \text{(Eq A7)}$$

$$CFG_b = \frac{1}{\sqrt{3}}\left(a^2 - \frac{Z_0 - Z_1}{2Z_1 + Z_0 + 3R_F}\right) \qquad \text{(Eq A8)}$$

$$CFG_c = \frac{1}{\sqrt{3}}\left(a - \frac{Z_0 - Z_1}{2Z_1 + Z_0 + 3R_F}\right) \qquad \text{(Eq A9)}$$

where

$$CFG = \max\,(CFG_a, CFG_b, CFG_c) \qquad \text{(Eq A10)}$$

To eliminate one parameter, it is convenient to divide each impedance by X_1. Defining the ratios

$R'_1 = R_1/X_1$, $R'_0 = R_0/X_1$, $X'_0 = X_0/X_1$, and $R'_F = R_F/X_1$

$$CFG_a = \sqrt{3}\left[\frac{(R'_0 + 2R'_F) + jX'_0}{R'_1 + 2R'_0 + 6R'_F + j\,(1 + 2X'_0)}\right] \qquad \text{(Eq A11)}$$

$$CFG_b = \frac{1}{\sqrt{3}}\left[a^2 - \frac{(R'_0 - R'_1) + j(X'_0 - 1)}{(2R'_1 + R'_0 + 3R'_F) + j\,(X'_0 + 2)}\right] \qquad \text{(Eq A12)}$$

$$CFG_c = \frac{1}{\sqrt{3}}\left[a - \frac{(R'_0 - R'_1) + j(X'_0 - 1)}{(2R'_1 + R'_0 + 3R'_F) + j\,(X'_0 + 2)}\right] \qquad \text{(Eq A13)}$$

In Figs A2 through A6, the curves were obtained by means of a digital computer analysis of Eqs A10 through A13. In particular, the computer was programmed to find pairs (R'_0, X'_0) for which

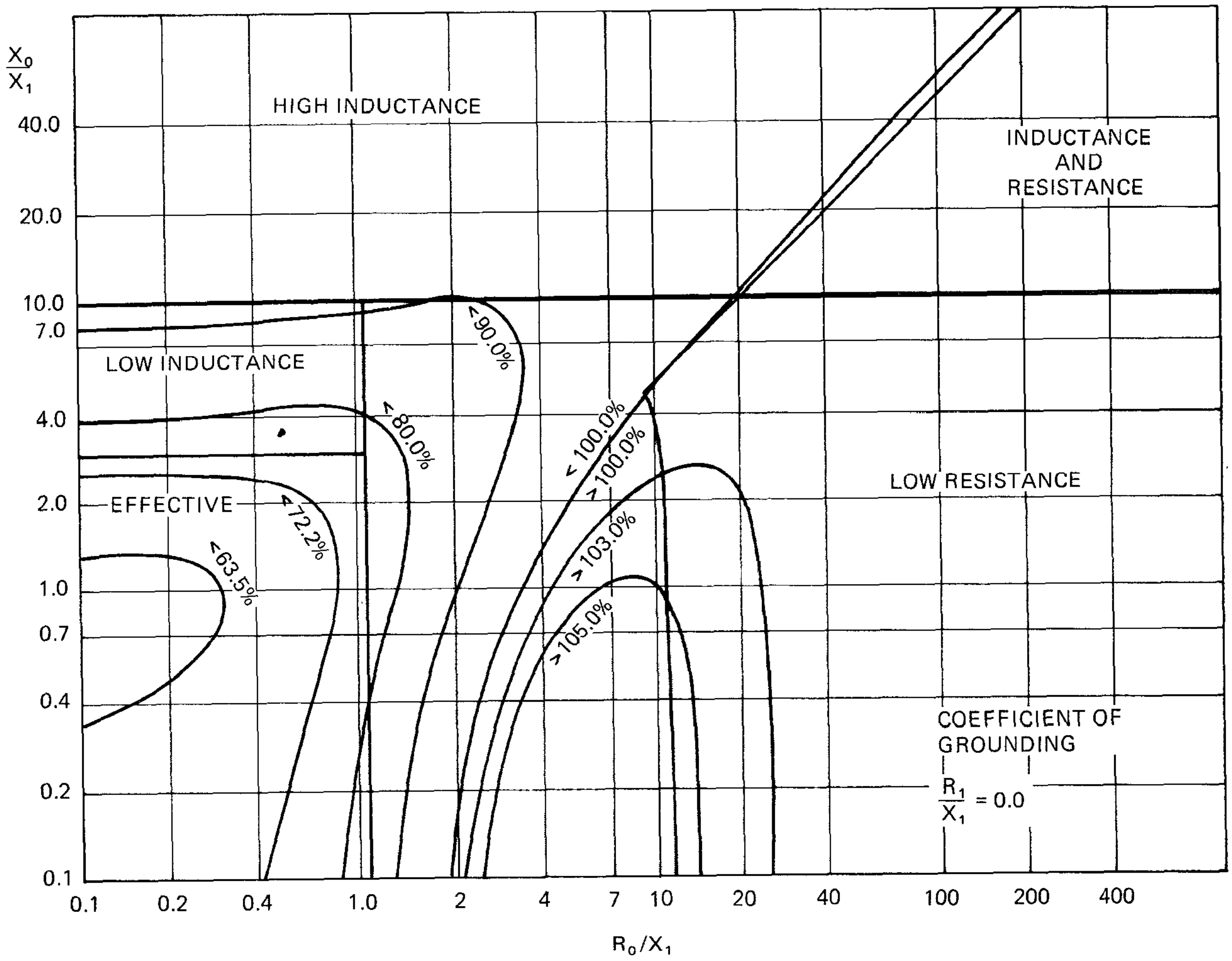
$$CFG = \text{limit } C \qquad \text{(Eq A14)}$$

and

$$\frac{\partial CFG}{\partial R'_F} = 0; \quad R'_F > 0 \qquad \text{(Eq A15)}$$

or

$$\frac{\partial CFG}{\partial R'_F} \leq 0; \quad R'_F = 0 \qquad \text{(Eq A16)}$$



NOTE: Parameters value given against each curve indicate limiting value of coefficient of grounding within area circumscribed by curve. Definitions of grounding class or means is indicated in each area.

Fig A2
Boundaries for Coefficients of Grounding for Ratio of Positive-Sequence Resistance R_1 to Positive-Sequence Reactance X_1 of 0

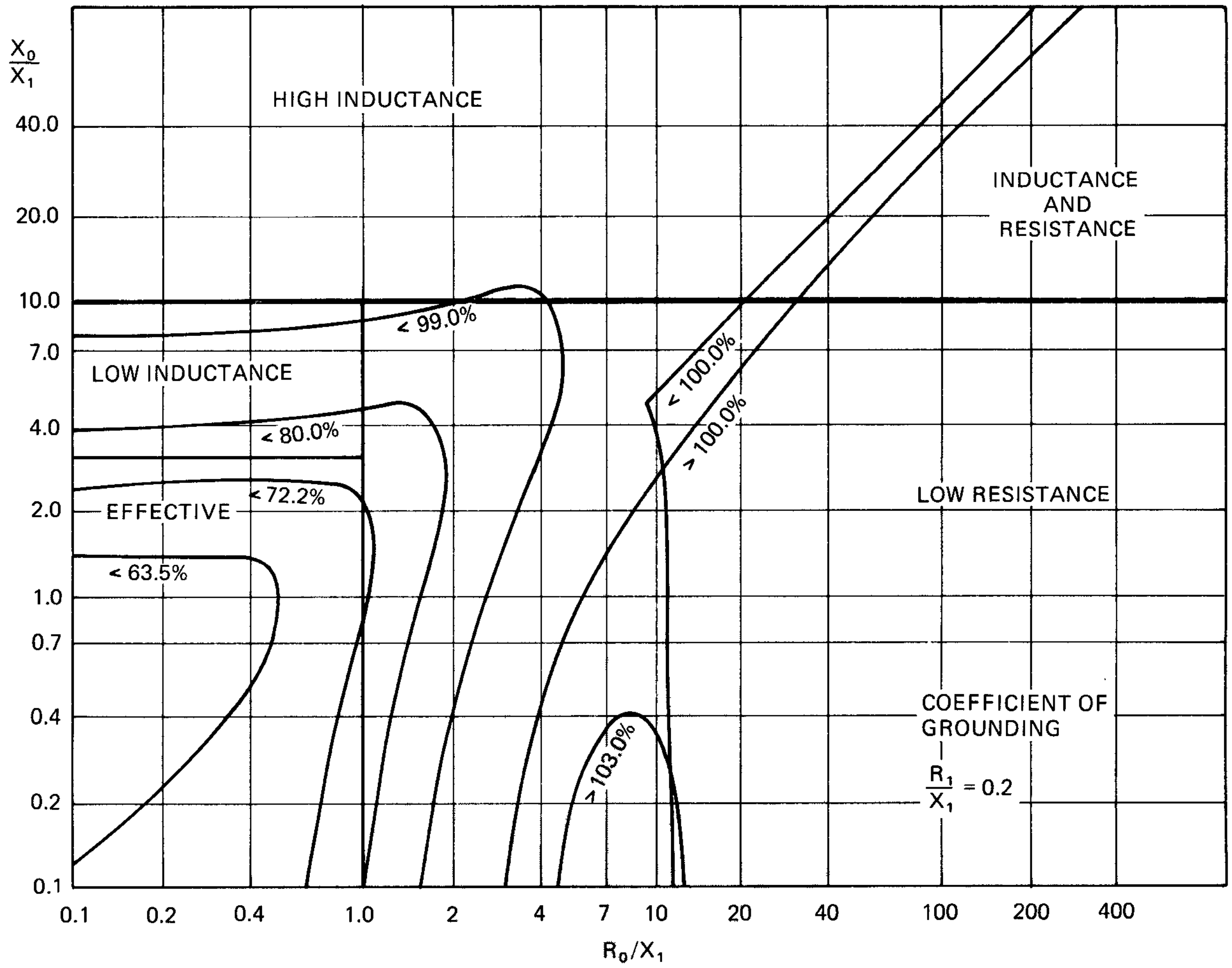
where

$C =$ selected limit (for example, 80%)

$R'_1 =$ fixed at five discrete values between 0 and 2 to produce the five graphs

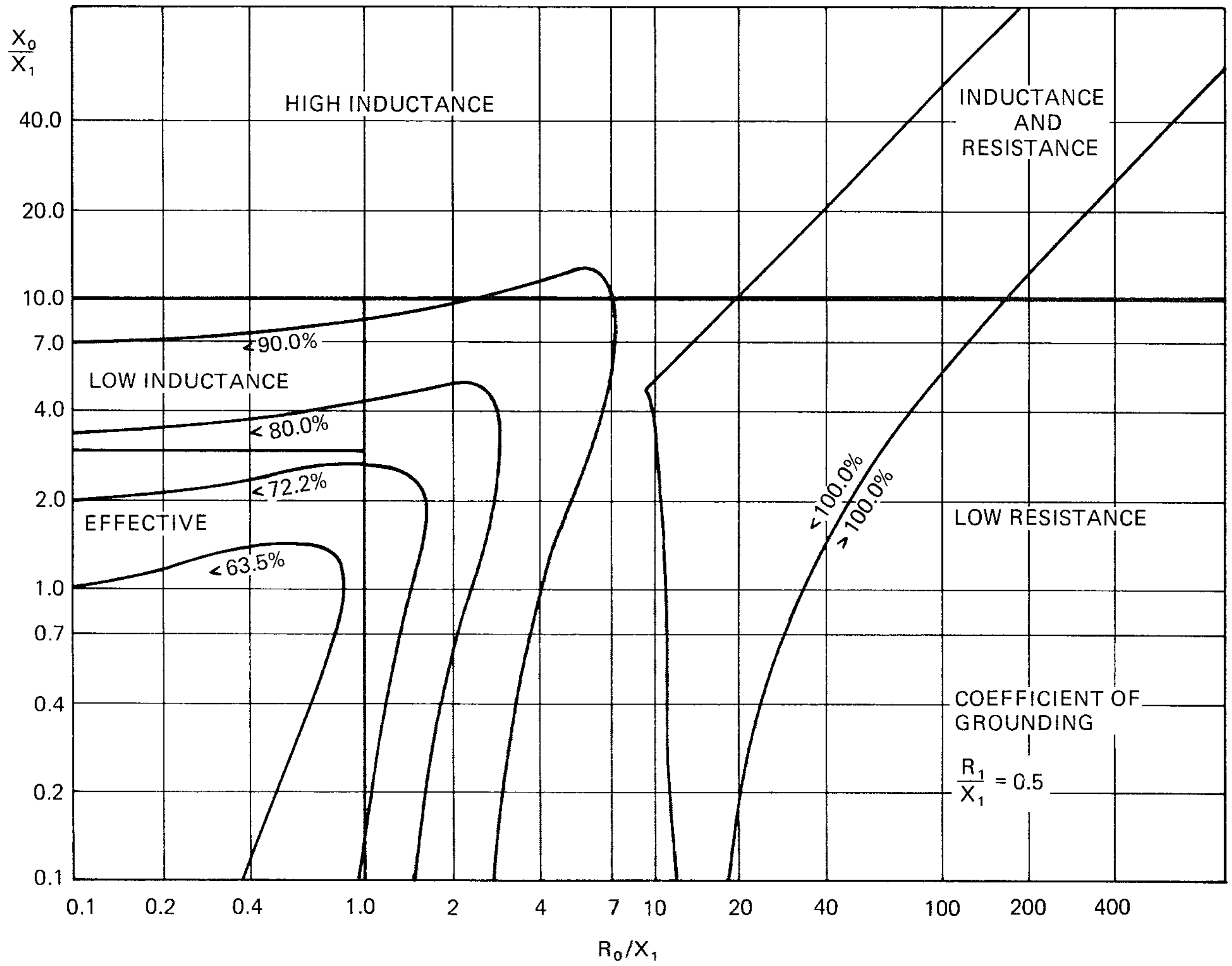
The partial derivative was simulated by a discrete differential.

It should be recognized that, in some circumstances, the assumptions made in producing these curves will not be valid and coefficients of grounding may be higher than shown. For example, a capacitive fault impedance, such as might be obtained from a ground fault in a capacitor bank, could yield a higher coefficient of grounding. Such cases can be analyzed individually by the use of Eqs A1 through A3.



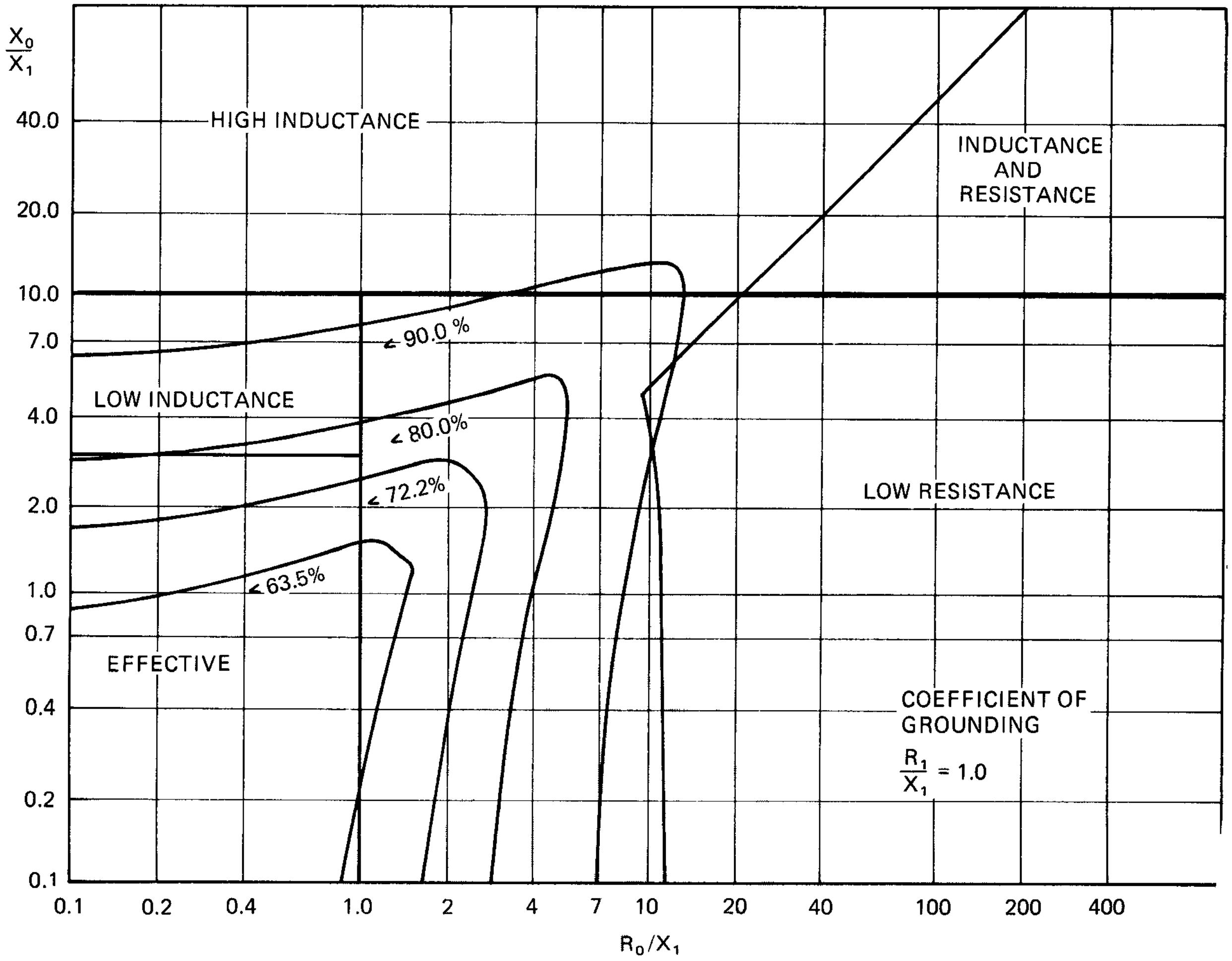
NOTE: Parameters value given against each curve indicate limiting value of coefficient of grounding within area circumscribed by curve. Definitions of grounding class or means is indicated in each area.

Fig A3
Boundaries for Coefficients of Grounding for Ratio of Positive-Sequence Resistance R_1 to Positive-Sequence Reactance X_1 of 0.2



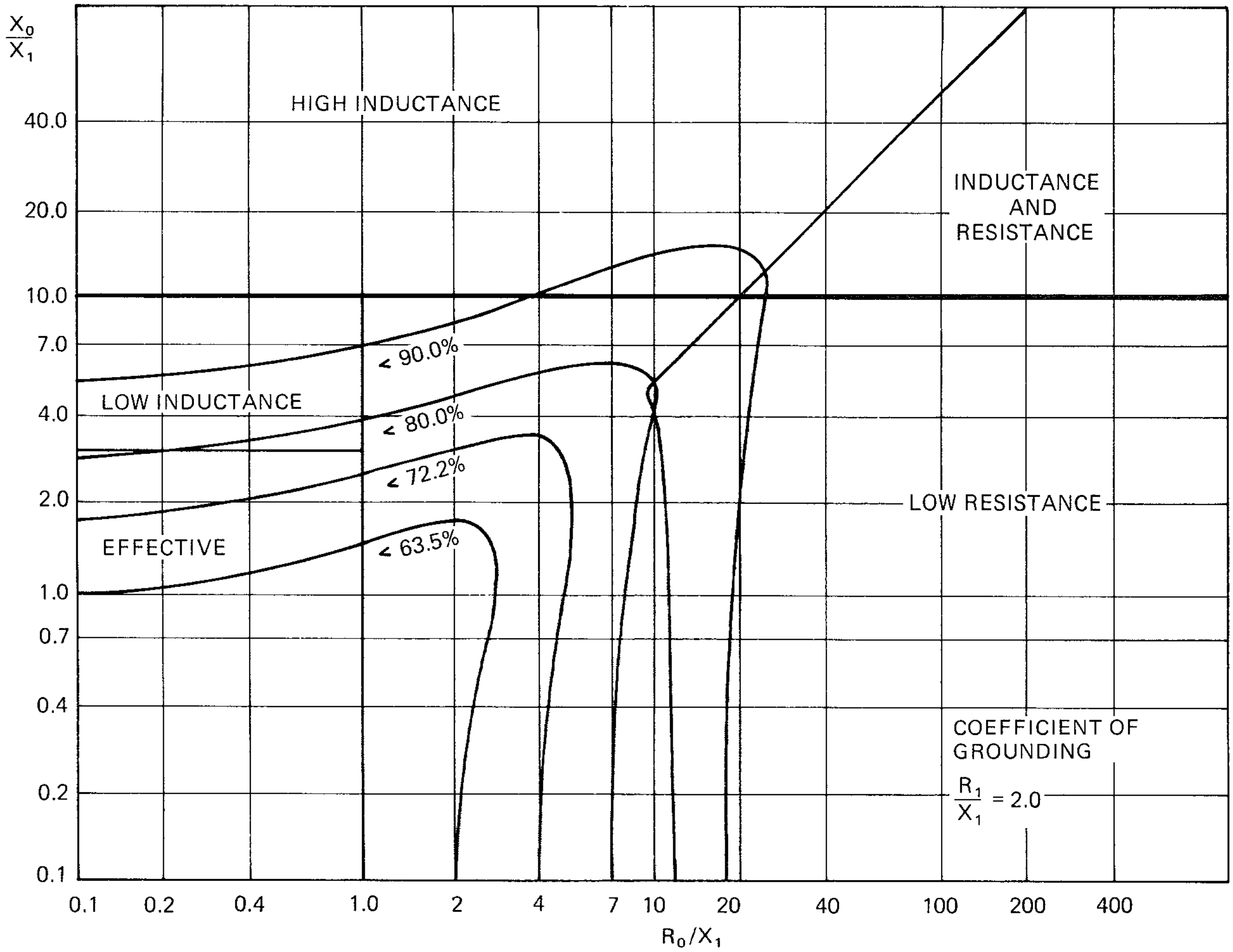
NOTE: Parameters value given against each curve indicate limiting value of coefficient of grounding within area circumscribed by curve. Definitions of grounding class or means is indicated in each area.

Fig A4
Boundaries for Coefficients of Grounding for Ratio of Positive-Sequence Resistance R_1 to Positive-Sequence Reactance X_1 of 0.5



NOTE: Parameters value given against each curve indicate limiting value of coefficient of grounding within area circumscribed by curve. Definitions of grounding class or means is indicated in each area.

Fig A5
Boundaries for Coefficients of Grounding for Ratio of Positive-Sequence Resistance R_1 to Positive-Sequence Reactance X_1 of 1.0



NOTE: Parameters value given against each curve indicate limiting value of coefficient of grounding within area circumscribed by curve. Definitions of grounding class or means is indicated in each area.

Fig A6
Boundaries for Coefficients of Grounding for Ratio of Positive-Sequence Resistance R_1 to Positive-Sequence Reactance X_1 of 2.0