



ENERGY SYSTEMS  
**APPLICATION ENGINEERING  
INFORMATION**

# **Let's Be More Specific About Equipment Grounding**

**R. H. KAUFMANN**

**Consulting Electrical Engineer**

Formerly a Consulting Application Engineer  
with Industrial Power Systems  
General Electric Company, Schenectady, N. Y.

*Reprinted from  
Proceedings of the American Power Conference, 1962*

reprinted by

**INDUSTRY SALES & ENGINEERING OPERATION**

**INDUSTRIAL SALES DIVISION**

**SCHENECTADY, N. Y.**

**GENERAL  ELECTRIC**



## LET'S BE MORE SPECIFIC ABOUT EQUIPMENT GROUNDING

R. H. KAUFMANN  
Consulting Application Engineer  
Industrial Power Systems  
General Electric Company  
Schenectady, New York

### INTRODUCTION

Within the past ten years, great strides have been made in advancing the technology of equipment grounding for a-c electric power systems. The prominent part played by inductive reactance as a controlling factor in a-c system grounding circuits is more widely understood. The manner in which ferromagnetic material in conduct and raceways influences the grounding circuit behavior is beginning to be realized. Through knowledge and understanding comes a familiarity which leads to superior design performance and at the same time, perhaps, improved economy.

There is currently available a wealth of published material revealing the properties of components forming equipment grounding circuits and the fundamental behavior patterns of equipment grounding circuits. Mackenzie<sup>2</sup> presents data about the 60-cycle a-c impedance presented by a wide variety of common steel structural members and conduit used extensively as conductors in equipment grounding circuits. Bisson and Rochau<sup>1</sup> provide a clear understanding of the electrical behavior of steel conduit used as a grounding conductor or as an enclosure for a grounding cable conductor. This paper discloses clearly the circumstances which lead to the flow of induced currents along the inner conduit surface, the outer conduit surface, and on both inner and outer conduit surfaces simultaneously, and comments on the practical significance of these effects. The author, in a previous paper,<sup>3</sup> describes fundamental behavior patterns of practical equipment grounding systems as found in industrial plants and commercial buildings. This paper features the fact that circuit reactance will force the ground return current to seek a path

in close physical proximity to the power conductor over which the fault current is being carried from the supply source. The manner in which magnetic material in enclosures or raceways tends to accentuate this action is described and explained. It is this effect which accounts for the concentration of current on one surface of steel conduit, as described in Reference 1.

Of course, it continues to be true that certain types of a-c system grounding circuits will be predominantly controlled by the circuit resistance. The circuit to an earthing electrode is an example. The resistance of the earthing connection may be 25 ohms, which will likely completely overshadow the circuit reactance. Reference 5 deals expertly with the problem of potential gradients in the earth, and, incidentally, contains an exceptionally complete bibliography of published material, world wide, on the subject of grounding. Another area in which circuit resistance will play the predominate part is that of low current circuits, including those using a conductor smaller than No. 8.

The prime purpose of this paper is to develop analysis procedures and make available necessary missing circuit constants which will allow (1) the determination of actual ground fault current magnitudes, (2) the voltage drop along the circuit grounding conductor during the existence of a ground fault, and (3) the voltage levels and current flow patterns in building structural and metallic systems caused by bonding electric circuit grounding conductors to the building metallic system.

### IMPORTANT CONSIDERATIONS

Some of the more important properties of the equipment grounding system include:

1. The impedance reflected into the power circuit under a line-to-ground fault condition should be sufficiently low as not to reduce

the fault current magnitude objectionably; that is, to the point where fault sensing overcurrent protectors are inoperative or unduly delayed in operation.

2. The conductivity built into the equipment grounding conductor, through which the ground-fault current actually passes, needs to be ample for the current magnitude maintained for the duration controlled by the protective overcurrent interrupters without excessive temperature rise.
3. The grounding system design shall be such that the passage of maximum possible ground-fault currents will not create potential differences between adjacent metallic structures which would result in dangerous shock-hazard exposure to personnel who can reasonably make bodily contact with this potential difference.
4. At all junction points in the grounding network where a substantial transfer of ground fault current is likely to take place, a firm mechanical bonding connection should be made which can accept the transfer current without flashing or excessive heating.

### GROUND-FAULT CURRENT MAGNITUDE DETERMINATION

A basic starting point in any treatment of an equipment grounding system is a determination of the ground-fault current magnitude. Whether the power circuit contains a cable conductor or a metal raceway as the grounding conductor (refer to Fig. 1), the line-to-ground fault current will be controlled by the circuit impedance (positive, negative, and zero sequence) as viewed from the fault point. The first step will be concerned with establishing the bolted-fault current magnitude, with the effect of an arcing fault condition injected as step two.

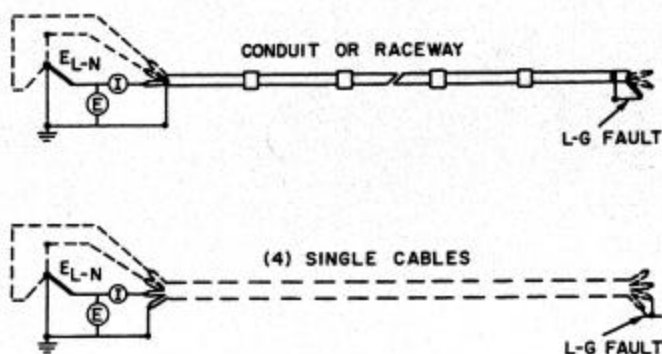


Fig. 1—Cable circuit geometry.

## $Z_0$ IS THE PRINCIPAL NEW PARAMETER

The magnitude of line-to-ground fault current ( $I_{L-G}$ ) in a three-phase system is controlled by the following expression:

$$I_{L-G} = \frac{3E_a}{Z_1 + Z_2 + Z_0}$$

where  $E_a$  is the line-to-neutral operating voltage (shown as  $E$  in Fig. 1), and  $Z_1$ ,  $Z_2$ , and  $Z_0$  are the positive sequence, negative sequence, and zero sequence impedance, respectively.

For the present purposes, the near equality of  $Z_2$  and  $Z_1$  will allow  $Z_1$  to be substituted for  $Z_2$ , allowing the current expression to be reduced to:

$$I_{L-G} = \frac{3E_a}{2Z_1 + Z_0}$$

Dividing both numerator and denominator by  $Z_1$  and separating terms leads to the expression:

$$I_{L-G} = \frac{E_a}{Z_1} \left( \frac{3}{\frac{Z_0}{Z_1} + 2} \right)$$

The quantity  $E_a/Z_1$  will be recognized as the three-phase short-circuit current magnitude (which is generally known or can be rather easily established). The remaining factor identifies the ground-fault current magnitude in multiples of the three-phase fault value, and is seen to be a function of the  $Z_0/Z_1$  ratio alone. Of course, it is the vectorial evaluation of

$$\left( \frac{3}{\frac{Z_0}{Z_1} + 2} \right) \text{ that is called for. Only if}$$

$Z_0$  and  $Z_1$  have the same phase angle is it strictly proper to handle these quan-

ties as arithmetic numbers. It will be shown that practical useful results can be obtained with  $Z_0$  and  $Z_1$  considered simply as scalars.

There is a surprising amount of data available about the magnitude of circuit zero-sequence impedance ( $Z_0$ ), but seldom is the phase angle given. The positive-sequence impedance ( $Z_1$ ) for the heavier circuit constructions will exhibit phase angles generally in the 45 to 90 degree zone. While it is possible that  $Z_0$  may sometimes be highly resistive (0 to 20 degrees), it is also true that in this case the  $Z_0/Z_1$  ratio tends also to be of large value. These conditions minimize the need for accurate phase angle information about  $Z_1$  and  $Z_0$ .

In Fig. 2 is plotted the value of  $I_{L-G}$  in multiples of the three-phase fault current (ordinate) as a function of  $Z_0/Z_1$  ratio (abscissa) for three different phase-angle conditions,  $Z_0$  in phase with  $Z_1$ ,  $Z_0$  displaced from  $Z_1$  by 45 degrees, and  $Z_0$  displaced from  $Z_1$  by 90 degrees. For the reasons already described it is reasonable to consider that the angular difference will be less than 45 degrees whenever the  $Z_0/Z_1$  ratio is less than, say, 6. In resistance grounded systems, the phase-angle difference might enter the 45 to 90

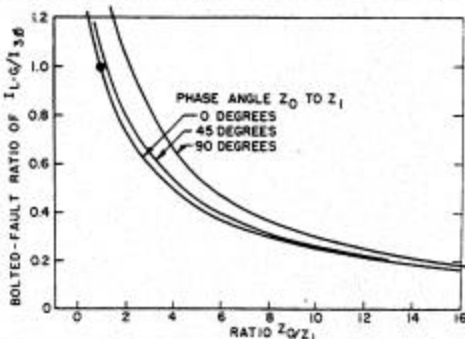


Fig. 2—Line-to-ground fault current in per unit of the three-phase fault current as a function of  $Z_0/Z_1$  ratio.

degree zone, but the  $Z_0/Z_1$  ratio will now likely be in excess of 10.

Here, then, is a useful simple tool for easily estimating  $I_{L-G}$  when circuit  $Z_0/Z_1$  ratios are known. A useful benchmark to remember is that a  $Z_0/Z_1$  ratio of 10 makes the line-to-ground fault current about  $\frac{1}{4}$  the three-phase value at the same location.

## PRACTICAL CIRCUIT $Z_0/Z_1$ RATIOS

Representative values of  $Z_0/Z_1$  ratios for a wide variety of cable conductor circuits, as measured under conditions of simulated severe fault (current magnitudes of 20 times continuous rating or more), are displayed in Fig. 3. The data are based directly on copper conductors and a raceway sized to accommodate three power conductors of the size indicated. The variety of raceways examined include rigid conduit (RC), thin wall (EMT), extruded aluminum sheath (AL SH.), lead sheath, interlocked armor cable (steel armor, with aluminum armor also in 4/0 conductor size), greenfield (GRN. FLD.) and No. 12 conductor BX. The shaded block segments indicate the  $Z_0/Z_1$  ratio when an internal grounding conductor is present. The up-

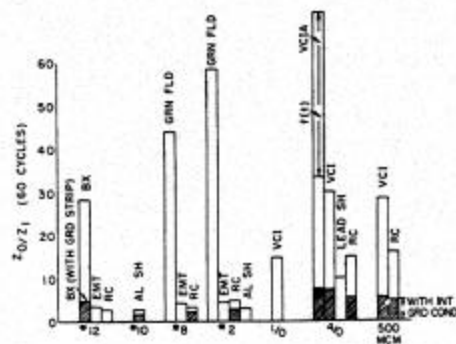


Fig. 3—Typical  $Z_0/Z_1$  ratios for cable circuit construction.

per portion of the block on 4/0 cable with aluminum armor is associated with a marked reduction which occurs in  $Z_0$ , which was observed to occur during the first several cycles of fault current flow. The presence of internal grounding conductors or the installation of such cable in metallic channels or on metallic racks renders this property unimportant.

From the exploratory work reported by Gienger, Davidson, and Brendel<sup>4</sup> comes



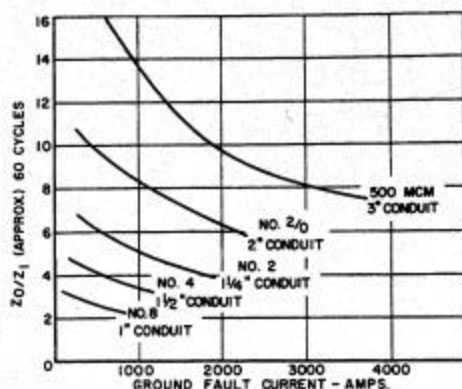


Fig. 4—The effect of rigid steel conduit on cable-circuit  $Z_0/Z_1$  ratio.

quantitative information on the effective  $Z_0/Z_1$  ratios of conductors in steel conduit (see Fig. 4). It is the tendency for the return ground-fault current to be forced to flow on a thin inner skin of the conduit, which accounts for the elevated  $Z_0/Z_1$  ratio at low current. Increased current magnitude produces magnetic saturation of successive shells of conduit material, thus lessening the effect. At higher currents, increased magnetic saturation causes the performance to approach that of nonmagnetic conduit. The presence of a full-size internal cable grounding conductor was observed to hold the  $Z_0/Z_1$  ratio to a value not greater than about 4 at any current level. Aluminum conduit was observed to exhibit a slightly lower value of  $Z_0/Z_1$ , remaining close to a value of 2, quite independent of current. The installation of an internal cable grounding conductor in steel conduit, or the use of nonmagnetic metallic conduit, may be an effective way of maintaining higher levels of ground-fault current to satisfy the objectives of Point 1 under "Important Considerations."

Typical values of  $Z_0/Z_1$  ratio for low-voltage busways relative to the housing as the ground return circuit are shown in Fig. 5. It becomes important here to distinguish between the  $Z_0$  relative to the busway housing and the  $Z_0$  relative to internal insulated neutral conductors. The two  $Z_0$  values will generally be different, and may be greatly different. The  $Z_0$  value relative to the neutral conductor would be significant in relation to voltage unbalance created by neutral unbalance current. The interleaved bus construction commonly used for low-voltage-drop feed-

er busway accounts for a high  $Z_0/Z_1$  ratio because the  $Z_1$  has been purposely reduced to low level. In the case of current-limiting busway, a low  $Z_0/Z_1$  ratio is to be expected because the  $Z_1$  has been made large, intentionally.

### SERIES CONNECTION OF CIRCUIT SECTIONS

Often, the total circuit to a particular reference fault may contain several series-connected sections having different  $Z_0/Z_1$

TABLE I

Element $Z_1$		$Z_0/Z_1$ Ratio		Element $Z_0$
( )	x	( )	=	( )
( )	x	( )	=	( )
( )	x	( )	=	( )
( )	x	( )	=	( )
$\Sigma(Z_1)$				$\Sigma(Z_0)$
Effective Overall $Z_0/Z_1 =$				$\frac{\Sigma(Z_0)}{\Sigma(Z_1)}$

ratios, with no one section exercising a predominate effect. To facilitate analysis of such cases, the creation of a summary table will be helpful (see Table I). In the left column, list the  $Z_1$  values for each unique section of the circuit. In the center column, list the  $Z_0/Z_1$  ratio associated with each impedance item. In the third column, insert the product of the entries in Columns 1 and 2, which is the value of  $Z_0$  for the particular impedance item. The summation of Column 1 gives the total  $Z_1$ , while the summation of Column 3 gives the total  $Z_0$ . The ratio of the third column to the first column sum is the effective  $Z_0/Z_1$  ratio to the selected fault location. From the  $Z_1$  value can be deter-

mined the three-phase fault current and from this, in company with the  $Z_0/Z_1$  ratio, the ground-fault current can be estimated. The  $Z_0/Z_1$  ratios and the resulting  $Z_0$  values can be treated as scalar quantities, as justified earlier.

### CURRENT REDUCTION DUE TO FAULT ARC VOLTAGE

The fault arc voltage drop may reduce substantially the magnitude of fault current in low-voltage a-c systems (600 volts and less). The Kaufmann-Page paper<sup>6</sup> deals exclusively with this problem. The important concepts are: (1) The voltage drop in the fault arc tends to remain remarkably close to a fixed value independent of current magnitude. Thus, the most appropriate representation of the fault is a square wave voltage drop which reverses polarity as the current reverses direction. (2) When the arcing fault becomes single phase, all arcs go out at each current zero, requiring a recovery voltage considerably greater than the normal arc drop for arc reignition after each current zero. The result is a current loop of lesser magnitude, resulting in a correspondingly reduced rms value of current.

The problem analysis discloses that the arcing fault current magnitude can be derived from the bolted fault value by application of a simple multiplier which is a function of the system operating voltage and the type of fault. In Table II are listed a family of multipliers by which the bolted-fault values of line-to-ground fault current can be converted to likely minimum values of arcing fault current.

### EXTERNAL POTENTIAL GRADIENTS

A knowledge of the potential gradient (voltage drop) along the circuit grounding conductor is important. It is this quantity which can result in dangerous shock-hazard potentials between nearby metallic structures. It also represents the driving force which tends to divert a portion of the ground return current into adjacent

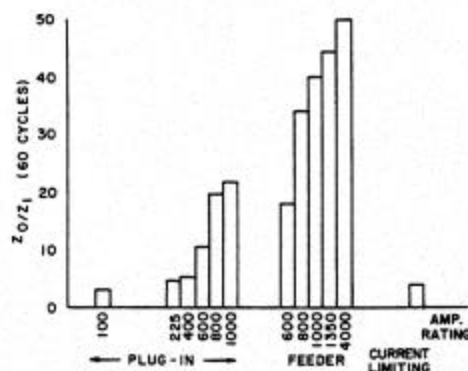


Fig. 5—Typical  $Z_0/Z_1$  ratios for low-voltage busway circuits.

TABLE II

Multipliers for Estimating Minimum Likely Values of Arcing L-G Fault Current			
Operating Voltage	600	480	208
Multiplier, K	0.4	0.19	*

\*Likely to be self-extinguishing, but not dependably so.

conducting paths, with possible flash and fire or explosion hazard.

One might rather easily conclude, erroneously, that the reduction in line-to-ground fault current displayed in Fig. 2 results from the insertion of a voltage drop in the grounding conductor. Actually, a substantial to major part of the circuit voltage drop appears as an increased voltage drop along the outgoing phase conductor.

When the grounding conductor takes the form of a continuous conducting sheet enclosing the power conductors (metal raceways in general), all of the inductive voltage drop in the complete circuit becomes associated with the internal phase conductor. The return current in the raceway distributes itself over the raceway surface in a manner to cancel the mmf external to the enclosing shell. With no magnetic field encircling the raceway, there is no inductive voltage drop along its length. The enclosing shell gives the circuit much the property of a coaxial line, with the entire electric and magnetic field confined to the interior of the raceway. If the raceway shell were made of resistanceless material, no evidence of current flow would be evident on the outside of the raceway. The fact that the raceway does possess resistance means there will be observed a voltage drop along its exterior surface which will not exceed the product of raceway resistance and ground-fault current magnitude.

The fact that the external voltage gradient is a function of the raceway construction and not the external environment allows these data to be tabulated as a property of each particular raceway. A family of such data giving the raceway exterior voltage drop in volts per 1000 amperes per 100 feet of length appears in Fig. 6. These figures apply to high-magnitude fault current conditions. The variety of raceway construction is essentially the same as was covered in the  $Z_0/Z_1$  ratio graph, Fig. 3. The numerical values near the top of the bar for Greenfield and BX designate the upper limit, being far beyond the end of the chart scale. The ramp on the chart bar for the aluminum armor 4/0 conductor cable designates the observed decrease in voltage drop during the  $\frac{1}{2}$  second duration of fault-current flow. The effect of inter-

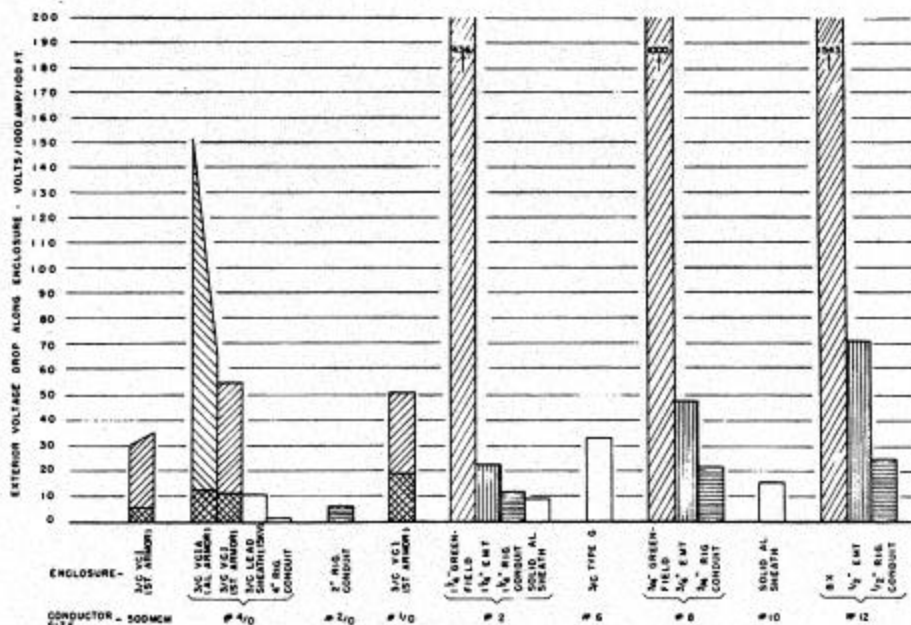


Fig. 6—Measured voltage drop along exterior of conductor enclosure during high-magnitude L-G short-circuit tests.

nal grounding cable conductors in reducing the voltage gradient for interlocked armor cable construction is indicated by the darker cross-hatched sections of the bar.

In the case of steel raceways, the effect of the magnetic material in concentrating the return ground-fault current on the inner surface of the raceway is, at the same time, acting to diminish the density of current along the exterior surface. Thus, until the current magnitude is high enough to saturate the magnetic material, the measured voltage along the exterior surface will be less than (and perhaps far less than) the product of ground-fault current and the raceway resistance. For example, in the case of 4/0 cable conductors in 2½ in. rigid steel conduit (from data given in Reference 3), the measured exterior potential gradient in volts per 1000 amperes per 100 feet is 3.55 at 11,000 amperes, 1.29 at 350 amperes, and 0.75 at 200 amperes.

#### COMPARISON WITH RESISTANCE-DEDUCED VOLTAGE DROPS

The concepts developed under the previous heading contend that only the raceway resistance voltage drop will appear as a measurable voltage along the exterior of the raceway (which is very much in contrast with an independent cable grounding conductor, which will ex-

hibit a reactive as well as a resistive component of voltage drop along its length). A comparison of the measured raceway voltage drops under actual simulated fault conditions, with the voltage drop interpreted from measured resistance values, would certainly be of interest. In Table III are listed the measured d-c resistance values in ohms per 100 feet for most of the raceways examined. In the next column is shown the interpreted resistive voltage drop in volts per 1000 amperes per 100 feet of length. A comparison of

TABLE III

Conductor Size	Type	Enclosure Properties	
		D-C Resistance, OHM/100 Ft	Computed RI Drop, V/1000 A/100 Ft
500 Mcm	VCI (Steel)	0.0383	38.3
4/0	4" Rigid Conduit	0.0025	2.5
"	Lead Sheath	0.00283	2.83
"	VCI (Alum)	0.286	286.0
2/0	2" Rigid Conduit	0.0095	9.5
1/0	VCI (Steel)	0.0458	45.8
#2	Ext. Al. Sheath	0.01	10.0
"	1½" Rigid Conduit	0.0108	10.8
"	1½" EMT	0.0205	20.5
"	1½" Greenfield	0.435	435.0
#8	¾" Rigid Conduit	0.02	20.0
"	¾" EMT	0.0517	51.7
"	¾" Greenfield	1.28	1280.0
#10	Ext. Al. Sheath	0.015	15.0
#12	½" Rigid Conduit	0.0223	22.3
"	½" EMT	0.0706	70.6
"	BX (3/c without Grd. Strip)	1.79	1790.0



these values with those displayed on Fig. 6 shows excellent correlation. In the case of the 4/0 aluminum armor cable, note that the measured first-cycle value on test was considerably below the time-zero value interpreted from d-c resistance.

## EFFECT OF BONDING TO BUILDING GROUND SYSTEM

Multiple bonding of the electrical grounding conductor to the building metallic system causes the voltage drop along the grounding conductor to be impressed on the closed circuit through the building metallic system created by the bonding connections. The solution to the problem of how much current will be diverted into the building conducting members, how the current will become distributed among the various available paths, and what will be the resulting potential pattern among the building members can be accomplished as an independent step using a Thevenin equivalent.

The voltage drop along the electric circuit grounding conductor for full  $I_{L-G}$  return thereon (as established under the heading "External Potential Gradients") becomes the driving voltage in the Thevenin equivalent closed-circuit impedance network involving building metallic members formed by multiple bonding connections. The impedance network should include all of the next-adjacent building-structure conducting paths, and, of course, include the impedance of the electric circuit grounding conductor itself. Since these building conducting members will be independent and generally widely separated, each branch will exhibit a reactance very likely overshadowing its resistance. Reference 2 will provide knowledge of the internal impedance of steel structural members to which need only be added the inductive reactance associated with the air-space magnetic field to the effective spacing of the return current conductor.

The values of branch current and the potential pattern obtained directly from the Thevenin equivalent circuit for the building conducting elements represent

correctly the values which will exist during the assumed electrical ground-fault condition. For the electrical circuit grounding conductor, however, the values of current and voltage drop observed in the Thevenin equivalent network represent incremental changes ( $\Delta I$  and  $\Delta E$ ) in the value of grounding conductor current and voltage drop. The corrected grounding quantities become:

$$\text{current flow } (I_{L-G} - \Delta I), \text{ voltage drop } (E_{CG} - \Delta E).$$

These quantities have vectorial sense which requires that recognition be given both the magnitude and phase angle of the incremental changes.

## CONCLUSION

This paper treats in successive steps the solution to problems influencing the design and performance of a-c system equipment grounding circuits in the presence of an insulation failure from one phase conductor to the grounding conductor.

As a first step, the means for determining the magnitude of ground-fault current, easily and quickly, is established. The approach is based on the premise that the three-phase fault current is usually known. The magnitude of the ground-fault current can be expressed as a multiple of the three-phase fault current, the multiplier being a direct function of the circuit  $Z_0/Z_1$  ratio. Both the method of analysis and an array of typical circuit  $Z_0/Z_1$  ratios are presented.

To introduce the effect of an arcing fault, the bolted-fault current magnitude can be adjusted by another fixed multiplier, whose value is a function of the system operating voltage. Appropriate multipliers to obtain the likely minimum values of arcing fault current are included.

For the purpose of resolving the problem of electric shock hazard due to potential differences in the equipment grounding system, the first step concerns evaluation of the magnitude of voltage drop along the electric circuit grounding conductor. In the case of a ground-

ing cable conductor, the desired voltage drop is simply the product of ground-fault current and grounding conductor impedance. In the case of enclosing raceways, it develops that only the raceway resistance is effective in creating an external potential gradient along the raceway. If the raceway is made of steel (magnetic material), the exterior voltage drop along the raceway may be much lower, especially at moderate to low current magnitude.

The final step examines the effect of bonding the electric circuit grounding conductor to the building metallic system in creating voltage differences between members of the building structure and diverting some fraction of the ground return current to members of the building metallic system. This resolution is accomplished by the use of a Thevenin equivalent circuit. The voltage drop along the electric circuit grounding conductor is the Thevenin equivalent driving voltage acting on the closed circuit impedance network, formed by the bonding connections to the building structure.

## REFERENCES

1. Bisson, A. J. and Rochau, E. A., "Iron Conduit Impedance Effects in Ground Circuit Systems," *AIEE Trans.*, **73**, Pt. II, 104-06 (1954) July.
2. Mackenzie, W. F., "Impedance and Induced Voltage Measurements on Iron Conductors," *AIEE Trans.*, **73**, Pt. I, 577-81 (1955) January.
3. Kaufmann, R. H., "Some Fundamentals of Equipment-Grounding Circuit Design," *AIEE Trans.*, **73**, Pt. II, 227-32 (1954) November.
4. Gienger, J. A., Davidson, O. C. and Brendel, R. W., "Determination of Ground-Fault Current on Common A-C Grounded-Neutral Systems in Standard Steel or Aluminum Conduit," *AIEE Trans.*, **79**, Pt. II, 84-90 (1960) May.
5. AIEE Committee Report, "Voltage Gradients through the Ground under Fault Conditions," *AIEE Trans.*, **77**, Pt. III, 669-92 (1958) October; also "Guide for Safety in Alternating Current Substation Grounding," *AIEE Bulletin No. 80*, New York: The Institute, 1961.
6. Kaufmann, R. H. and Page, J. C., "Arcing Fault Protection for Low-Voltage Power Distribution Systems—Nature of the Problem," *AIEE Trans.*, **79**, Pt. III, 160-67 (1960) June.

ENERGY SYSTEMS



SCHENECTADY, N. Y.