

IEEE Recommended Practice for Determining the Electric Power Station Ground Potential Rise and Induced Voltage From a Power Fault

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Abstract: Guidance for the calculation of power station ground potential rise (GPR) and longitudinal induction (LI) voltages is provided, as well as guidance for their appropriate reduction from worst-case values, for use in metallic telecommunication protection design.

Keywords: electric power stations, ground potential rise, induced voltage, longitudinal induction voltages, power faults, power stations, telecommunication protection design, telecommunications

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Introduction

(This introduction is not a part of IEEE Std 367-1996, IEEE Recommended Practice for Determining the Electric Power Station Ground Potential Rise and Induced Voltage From a Power Fault.)

Wire-line telecommunication facilities serving electric power stations often require that extraordinary protection measures be taken to protect against the effects of fault-produced ground potential rise (GPR) or induced voltages, or both. In the presence of a hostile electromagnetic environment, suitably rated protection equipment is required at the power station for personnel safety, for the protection of the serving telecommunication facilities, and to help ensure the desired continuity of telecommunication transmission at times of power system faults. There is a fundamental need, therefore, to determine the appropriate values of fault-produced GPR and induction, including considerations of their probability and duration, to be used in developing the specifications and ratings for the protection equipment to be used in any given application.

This recommended practice provides information for the determination of the appropriate values of fault-produced power station GPR and induction for use in the design of protection systems. Included are

- 1) The determination of the appropriate value of fault current to be used in the GPR calculation
- 2) The consideration of the waveform, probability, and duration of the fault current
- 3) The determination of inducing currents, the mutual impedance between power and telephone facilities, and shield factors
- 4) The vectorial summation of GPR and induction
- 5) The considerations regarding the power station GPR zone of influence
- 6) The communications channel time requirements for noninterruptible services

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1. Overview

Difficulties are experienced by telecommunication, protection, and relay engineers in determining the “appropriate” values of power station ground potential rise (GPR) or the longitudinally induced (LI) voltages into wire-line telecommunication facilities including their probability, waveform, and duration, which are to be used in the developing the specifications for systems and component protection.

Suitably rated protection devices are required for personnel safety and for the protection and continuity of service for wire-line facilities that either enter electric power stations or that are otherwise exposed to the influence of high-voltage electric power circuits. (See IEEE Std 487-1992.¹)

1.1 Scope

This recommended practice provides guidance for the calculation of power station GPR and LI voltages, as well as guidance for their appropriate reduction from worst-case values for use in metallic telecommunication protection design. Information is also included for the determination of the following:

- a) The fault current and the earth return current. (The probability, waveform, and duration of these currents and the impedance to remote earthing points used in these GPR and LI calculations as well as the effective X/R ratio are discussed.)
- b) The zone of influence (ZOI) of the power station GPR.
- c) The calculation of the inducing currents, the mutual impedance between power and metallic telecommunication facilities, and shield factors.
- d) The channel time requirements for metallic telecommunication facilities where noninterruptible channels are required for protective relaying.

¹Information about references can be found in Clause 2.

2. References

This recommended practice shall be used in conjunction with the following publications. When the following standards are superseded by an approved revision, the revision shall apply.

IEEE Std C37.90-1989 (Reaff 1994), IEEE Standard for Relays and Relay Systems Associated with Electric Power Apparatus (ANSI).²

IEEE Std C37.93-1987 (Reaff 1992), IEEE Guide for Power System Protective Relay Applications of Audio Tones Over Telephone Channels (ANSI).

IEEE Std 80-1986 (Reaff 1991), IEEE Guide for Safety in AC Substation Grounding (ANSI).

IEEE Std 81-1983, IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System (Part 1) (ANSI).

IEEE Std 81.2-1991, IEEE Guide for Measurement of Impedance and Safety Characteristics of Large, Extended or Interconnected Grounding Systems (Part 2) (ANSI).

IEEE Std 487-1992, IEEE Recommended Practice for the Protection of Wire-Line Communication Facilities Serving Electric Power Stations (ANSI).

3. Definitions

This clause contains key terms as they are used in this recommended practice.

3.1 auroral effects: Electrical voltages and currents on the earth due to emission of particle energy from the sun.

3.2 direct-current (dc) offset: The difference between the symmetrical current wave and the actual current wave during a power system transient condition. Mathematically, the actual fault current can be broken into two parts: a symmetrical alternating component and a unidirectional dc component, either or both with decreasing magnitudes (usually both). The unidirectional component can be of either polarity, but it will not change polarity during its decay period and will reach zero at some predetermined time.

3.3 direct-current (dc) offset factor: The ratio of the peak asymmetrical fault current to the peak symmetrical value.

3.4 earth resistivity: The measure of the electrical impedance of a unit volume of soil. The commonly used unit is the ohm-meter, ($\Omega \cdot \text{m}$), which refers to the impedance measured between opposite faces of a cubic meter of soil.

3.5 effective X/R ratio: The value of X/R as seen from the fault location looking back into the power system far enough to include the reduction of the X/R ratio due to the effects of the terminal apparatus.

3.6 geomagnetic induced currents (GIC): Spurious, quasidirect currents flowing in grounded systems due to a difference in the earth surface potential caused by geomagnetic storms resulting from the particle emission of solar flares erupting from the surface of the sun.

²IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

3.7 ground potential rise (GPR): The product of a ground electrode impedance, referenced to remote earth, and the current that flows through that electrode impedance.

3.8 inducing current: The current that flows in a single conductor of an electric supply line with ground return to give the same value of induced voltage in a telecommunication line (at a particular separation) as the vectorial sum of all voltages induced by the various currents in the inductive exposure as a result of ground fault.

3.9 longitudinal voltage: A voltage acting in series with the longitudinal circuit.

3.10 mutual impedance: The ratio of the total induced open-circuit voltage on the disturbed circuit to the disturbing electric supply-system phase current, with the effect of all conductors taken into account.

3.11 per-unit system (pu): The reference unit, established as a calculating convenience, for expressing all power system electrical parameters on a common reference base. One per unit (pu) is 100% of the base chosen. The pu system in power systems engineering is used to obtain a better comparison of the performance of the power system elements of different ratings, similar to the decibel system used for equating the losses and levels of different telecommunication systems.

3.12 remote earth: That distant point on the earth's surface where an increase in the distance from a ground electrode will not measurably increase the impedance between that ground electrode and the new distant point.

3.13 subtransient reactance: The reactance of a generator at the initiation of a fault. This reactance is used for the calculation of the initial symmetrical fault current. The current continuously decreases, but it is assumed to be steady at this value as a first step, lasting approximately 0.05 s after a suddenly applied fault.

3.14 susceptibility: The property of equipment that describes its capability to function acceptably when subjected to unwanted interfering energy.

3.15 synchronous reactance: The steady-state reactance of a generator during fault conditions used to calculate the steady-state fault current. The current so calculated excludes the effect of the automatic voltage regulator or governor.

3.16 telluric currents: Currents circulating in the earth or in conductors connecting two grounded points due to voltages in the earth.

3.17 transient reactance: The reactance of a generator between the subtransient and synchronous states. This reactance is used for the calculation of the symmetrical fault current during the period between the subtransient and steady states. The current decreases continuously during this period but is assumed to be steady at this value for approximately 0.25 s.

3.18 volt-time area: The area under a curve plotted with voltage versus time with areas of positive and negative polarities added algebraically. The volt-time area that is generally of concern consists of the net accumulated volt-time area that occurs during a certain number of power frequency cycles of the ground potential rise (GPR). The area is a function of the magnitude and decay rate of the dc offset.

3.19 X/R ratio: The ratio of the system inductive reactance to resistance. It is proportional to the time constant L/R and is, therefore, indicative of the rate of decay of any dc offset. A large X/R ratio corresponds to a large time constant and a slow rate of decay, whereas a small X/R ratio indicates a small time constant and a fast rate of decay of the dc offset.

3.20 zone of influence (ZOI): An area around a ground electrode bounded by points of specified equal potential resulting from the voltage drop through the earth between the ground electrode and remote earth.

4. Overview of technical considerations

This recommended practice considers the following:

- a) The various types of power transmission and distribution systems with respect to fault currents and fault current distribution
- b) The nature (type and location) of the faults and their determination using symmetrical component techniques
- c) The characteristics (impedances, inductances, and capacitances) of the power system and related time constants
- d) The characteristics (impedance, susceptibility, etc.) of the affected wire-line telecommunication systems
- e) The determination of the value of the station ground grid impedance to remote or true earth
- f) The determination of appropriate values of the GPR and the LI voltage and their summation and duration under varying conditions
- g) The application of probability and mitigating factors to provide more realistic and acceptable values consistent with required reliability and safety, which could affect economic decisions and trade-offs
- h) The ZOI of the GPR
- i) The rise, duration, and decay of both symmetric and asymmetric fault currents
- j) The time requirements for telecommunication channels when used for protective relaying
- k) The effects of high-voltage direct-current (HVDC), telluric, or auroral currents, or all, as well as dc power system neutral currents that can affect wireline facilities or protective devices
- l) A few typical examples of GPR and induced voltage calculations

4.1 Telecommunication facilities

Telecommunication facilities that contain metallic components and serve electric power stations provide telecommunication circuits for a wide variety of services. Some of the telecommunication services are used for control and protective relaying purposes and are usually considered noninterruptible with respect to the occurrence of power system faults. Whenever faults involving a particular power station occur, any resulting station GPR or LI, or both, appear between the telecommunication facilities and power-station ground. Telecommunication facilities that merely pass through the ZOI of the power station may also be subject to similar interference; however, their service reliability requirements are usually not the same. The magnitude, waveform, and duration of the abnormal interfering voltages should be accurately determined to protect telecommunication facilities entering the power station or passing through the station ZOI.

4.2 Faults on power systems

Power system faults can occur at any point on a power line or in any type of power station at any voltage level. Each location has different fault characteristics. Faults can be single line-to-ground (L-G), phase-to-phase, open-phase, double line-to-ground (2L-G), or three-phase, and can progress from one to the other. These faults can theoretically be initiated at any point on the voltage or current waveform, and the resulting fault currents can attain values higher than 100 kA in North American systems. The resulting GPR or LI, or both, on adjacent telecommunication facilities can be minimal or quite high. Values of the GPR as high as 25 kV_{rms} are possible under unusual circumstances; however, most values are less than 10 kV. The waveform of the GPR voltage can vary from the symmetrical to the fully offset, as described in 5.1.5. The decay time of the direct-current component (dc offset) of the fault current may have a duration of several cycles.

Fault-current studies should be re-evaluated at least every five years and more often, if required, due to the increasing MVA capacity or changing configuration of these power systems.

4.3 Power station ground grid impedance to remote earth

The power station ground grid impedance to remote earth is required in the determination of the inducing current and is used in both GPR and LI calculations.

The total power station ground grid impedance to remote earth, Z_{SGT} , is the total impedance between the power station ground and remote earth and consists of the parallel combination of

- a) Power station ground grid impedance itself, Z_{SG} .
- b) Combined impedance, Z_L , of all high-voltage (HV) and low-voltage (LV) ladder networks. These ladder networks are composed of overhead ground wires or neutrals with multiple tower or pole footing grounds.
- c) Incidental connected impedances, Z_i , such as rails, pipes, etc.

Z_{SGT} can be obtained by either of two methods:

- *Method A*—Calculations based on measurement of earth resistivity only
- *Method B*—Determinations based upon direct measurements

The choice of method will depend upon a variety of circumstances as discussed in the following subclauses.

4.3.1 Method A—Calculations based on measurement of earth resistivity only

Several mathematical models and computer methods are used by power utilities to derive the power station ground grid impedance, Z_{SG} . For example, a formula derived from IEEE Std 80-1986, Equation (39), and good for homogeneous earth where the depth of the grid is less than 0.25 m, is

$$Z_{SG} = \rho \left(\frac{1}{4r} + \frac{1}{L} \right)$$

where

- Z_{SG} is the power station ground grid impedance (Ω);
- ρ is the earth resistivity (obtained by field measurements) ($\Omega \cdot m$);
- r is the equivalent radius of a power station ground grid (radius of a circle having the same area as the station ground grid) (m);
- L is the total length of buried horizontal ground conductors (m).

In GPR studies, calculations of the impedance of all connected overhead ground wire/tower ladder networks are required.

The impedance of a ladder for sufficiently long lines is

$$Z_L = \frac{Z_s}{2} + \sqrt{\frac{Z_s^2}{4} + Z_s Z_p}$$

where

- Z_L is the combined impedance of ladder networks (Ω);
 Z_s is the per-span self-impedance of the overhead ground wire (Ω);
 Z_p is the tower/pole footing impedance(Ω).

The third component, Z_i (incidental grounds) is not amenable to calculation and is omitted in this method because it can be changed without knowledge of the power utility. This omission results in an estimate of GPR that is conservative.

4.3.2 Method B—Determination based upon direct measurement

The total station ground impedance, Z_{SGT} , can be measured with the station in its operational state (all normally externally grounded metallic conductors connected). Such conductors include ladder network impedance, Z_L , and incidental grounds, Z_i (for example, metallic water, gas, sewer lines, and others).

Since these connections exist when the power station is operational and since they increase the effective area of the ground grid and reduce its impedance to remote earth, they should be in place when the impedance measurement is made. Power utilities generally measure the grid impedance immediately after a new grid is constructed but before any intentional ground connections are made. This measurement is useful to check the grid against its design objective, but in itself would not be the correct value to use for GPR calculations.

The fall-of-potential method of measurement, described in IEEE Std 81.2-1991, is appropriate for the measurement of the magnitude and phase of the impedance to earth of large grids. Refinements of this method using modern instrumentation are described in various IEEE publications (see Clause 2).

If, subsequent to the measurement, any of the incidental connections should be removed, measurements should be repeated.

4.3.3 Evaluations and applications of methods A and B

- a) *Accuracy.* Both methods require measurements, and the accuracy of each depends upon the completeness and care with which such measurements are made. Method A requires only measurements of ρ (earth resistivity). In areas of homogeneous soils a single measurement in the near vicinity of an existing or proposed station is usually all that is required; however, some utilities require that several measurements be made. In nonhomogeneous soils, where ρ may vary markedly with both horizontal displacement and depth, multiple measurements are required to categorize ρ adequately in the area of interest. This requirement is particularly true in the calculation of Z_L for long transmission lines that traverse varying terrains. Method B, on the other hand, requires measurement at an existing station with the test conductors extending outward to points beyond the influence of the station ground grid (including overhead ground wires, neutrals, and incidental grounds). Care should be exercised so that coupling between these extended ground conductors and the test leads does not introduce measurement errors.
- b) *Applications.* Method A is the only way to predict the GPR of electric power stations that have not yet been built. This method is particularly accurate for stations with relatively uncomplicated and singular grid structures. In nonhomogeneous soil earth areas, multiple measurements of earth resistivity are required to ensure accuracy. More complicated ground structures or situations require increasingly complex calculations, to the point that stations with two or more interconnected grids may be beyond the present calculating capabilities of some power utilities. Whether method A or B is used to calculate GPR for an existing station, method A calculation techniques are required to predict the effect of future changes in power line and grounding arrangements.

Method B can only be used on existing stations and is particularly useful for extremely complicated stations such as those that have multiple interconnected ground grids. This method is a practical way to determine the Z_{SGT} of older stations, where growth and modifications have resulted in complex ground structures or

where corrosion may have reduced the effectiveness of the grounding structure. Method B ignores the effects of coupling between fault-current carrying conductors and overhead ground wires or other grounded conductors, resulting in errors in the conservative (higher GPR) direction (unless the phase conductors are used for current injection). Similarly, the test voltages used in Method B are usually too low to flashover the insulators of insulated overhead ground wires; hence, the resulting GPR values will be higher (more conservative) where insulated overhead ground wire systems are in place because such conductors do not form part of the measured circuit.

As discussed in Clause 5, the determination of the location of a line fault producing the worst-case GPR requires many of the same calculations that are used in Method A, so that Method A may be preferable, including the determination of worst-case line fault locations.

With the wide variation of conditions at different power stations, no one method of determining Z_{SGT} is best for all stations. Each power utility or substation should choose the method or methods best suited to its needs and capabilities. Larger power utilities, having more specialized engineering staffs and adequate computer capabilities, may routinely use Method A supplemented by Method B for special situations. Smaller power utilities and private substation owners may find that Method B is more suitable considering their staff and equipment. The relative costs of obtaining accurate measurements in Method B, of purchasing and operating the necessary computers for Method A, and of purchasing and operating any resulting telecommunication protection equipment are all important considerations in determining the method to be used.

4.4 Establishing net fault current values

Power utilities, in their calculations of zero-sequence fault currents, usually do not take into account the conductive effects of the transmission and distribution line grounding network impedances (comprising overhead ground wires, neutrals, transmission tower and distribution pole footing impedances, counterpoises, and station ground grid impedances).

The net fault currents should be recalculated by including the effects of the impedances of power line ladder networks, incidental paths (pipes, rails, etc.), telecommunication cable grounds, station ground grids, and a judicious value of fault impedance.

Additional reduction of the induced voltages caused by the net fault current can be achieved by application of various shielding mechanisms available.

Care should be taken in recalculating positive sequence fault currents to include phase shifts in certain transformer windings. Substantial reduction of the net fault current can thus be achieved. The amount of reduction will depend on earth resistivity, tower/pole footing impedances, type and material of overhead ground wire or neutral conductors, span length, transmission or distribution line length, and whether or not overhead ground wire(s) are connected to the station ground grid and whether or not counterpoises and bonds are present.

4.5 Division of fault current

Generally, fault current will, at the point of fault, divide between the metallic return paths and earth. The metallic return paths will include overhead ground wires, neutrals, counterpoises, bonds, station ground grids, commonly grounded telecommunication circuits, and incidental grounds such as rail and metallic pipes. There are many factors controlling the division of power system fault current into its several paths, and calculations are usually quite complex. The determination of an accurate division of fault current requires knowledge of the earth return path impedance and the grounding system (including all other return path impedances), as shown in Clause 5.

4.6 Calculating the inducing current

The purpose for calculating the inducing current flowing in each transmission or distribution circuit connected to the power station under study is twofold:

- a) To determine the amount of fault current induced in each overhead ground wire or neutral. These currents do not cause any GPR.
- b) To determine the amount of voltage induction into nearby telecommunication circuits.

The inducing current that is used to determine the shielding action of overhead ground wires is also used to determine the LI voltage in telecommunication networks.

NOTE—The terms overhead ground wire(s), shield wire(s), static wire(s), and skywire(s) are synonymous.

4.7 Ground potential rise (GPR)

This is essentially the product of

- a) The total ground grid impedance (Z_{SGT}) at the power system fundamental frequency to a true or remote earthing point (has to be outside the ZOI of the GPR)
- b) The total net fault current that flows through the ground grid impedance

These values should be determined by the electric power utility. See IEEE Std 80-1986 and IEEE Std 81.2-1991 for further information.

4.8 Sources of fault and inducing current information and impedance to remote earth information and related responsibilities of power utilities and serving telecommunication utilities

In some power utilities the necessary fault current information can be obtained from a system planning or protective relaying group. The group responsible for the determination of station ground grid impedance will usually be different from the group responsible for determining an overall impedance to a remote earthing point, including any telecommunication cable shields. Serving telecommunication utilities may be involved in this latter determination. In any event, the power utility is essentially responsible for assessing the validity of these parameters and determining the “appropriate” net fault current value to be used in the GPR calculation, its wave form and duration, and the magnitude of the inducing current. The responsibility for determining the magnitude of the GPR, the induced voltage, and their sum is that of the power utility with the cooperation of the associated telecommunication utility.

Since the electric power system originates the fault-produced interfering voltages into the telecommunication facilities serving the power station, the power utility is responsible for the accurate determination of the GPR and the induced voltage for both present and future power system arrangements by considering

- a) The impedance of the power station ground grid to remote earth
- b) The earth return fault current (its wave form and duration) that flows through the grid and produces the GPR
- c) The effective X/R ratio of the power system at the fault location
- d) The extent of the power station ZOI along the route of the serving telecommunication cable

- e) Fault current values and maps of the relevant power feed routes as required by a serving telecommunication utility for the computation of fault-produced induction on the serving telecommunication cables
- f) The noninterruptible channel time requirements

Since the telecommunication facilities extend into the power station to provide telecommunication service, the power utility or substation owner should advise a serving telecommunication utility of the fault-produced environment. This provision of fault-related data applies even to those cases in which the power utility or substation owner, rather than the serving telecommunication utility, provides the telecommunication protection equipment at the power station.

The telecommunication company and the power utility or substation owner should cooperate closely in determining the sum of the GPR and the induced voltage. A great deal of cooperation and trust should exist between the power utility or substation owner and the serving telecommunication company representatives, as well as with individuals within these organizations, in order to determine satisfactorily the nature of the hostile environment of the power station.

4.9 Transient voltages resulting from power system operation

Surges or transients, either unidirectional or oscillatory and usually having fast rise times, are produced by power system switching operations. These stem from switching operations involving breakers, transformer tap changers, capacitors, etc., and often result in relatively high-magnitude, short-duration voltages being induced into telecommunication wires or cables. This recommended practice is confined to the fundamental frequency and its dc offset and does not discuss surges or transients.

4.10 Types of wire-line telecommunication circuits usually requested for electric power stations as defined by some power utilities

- a) All-metallic circuits between terminals for dc and ac signals, including audio tone, that can be interrupted prior to, during, or after power system faults (noncritical channels)
- b) Nonmetallic (for example, audio tone) circuits that can be interrupted prior to, during, or after power system faults, or both (noncritical channels)
- c) All-metallic circuits between terminals for dc and ac signals, including audio tone, that cannot be interrupted (critical channels)
- d) Nonmetallic (for example, audio tone) circuits that cannot be interrupted (critical channels)

These types of services may have various requirements regarding time and fidelity of output versus input, etc.

A noninterruptible telecommunication channel usually implies that the channel be uninterrupted prior to, during, and immediately following the power fault. This document provides guidance for the time requirements of telecommunication channels relative to the various classes of power system telecommunications, including protective relaying channels prior to, during, and after the fault or circuit breaker operation.

To some degree, the assumed appropriate values of interfering voltages may well be influenced by the reliability requirements.

4.11 Service types and performance objectives for telecommunication services provided at power stations as defined in IEEE Std 487-1992

Wire-line telecommunication services into electric power stations are classified into four major types according to the following definitions:

- a) *Type 1.* Services requiring either dc transmission or ac and dc transmission used for
 - 1) Basic exchange telephone service, private line, or both; voice telephone service, etc.
 - 2) Teletypewriter, telemetering, supervisory control, etc.
- b) *Type 2.* Private line services requiring ac or dc transmission, or both, used for pilot wire protective relaying or dc tripping
- c) *Type 3.* Private line services requiring ac-only transmission used for telemetering, supervisory control, data, any noncritical audio tone applications, etc.
- d) *Type 4.* Private line services requiring ac-only transmission used for audio tone protective relaying

Interruptions or outages due to the effects of power system faults can be minimized through the installation and maintenance of special protection systems that are designed to operate in the fault-produced, electrical environment (GPR and LI) at electric power stations. Because of the critical need for service continuity during power system faults on certain types of telecommunication services provided to power stations, a system of optional service performance objective classifications for the purpose of this recommended practice has been established for all types of telecommunication services provided to power stations. These objectives, with respect to the effects of power system faults, fall into three classifications. They are

- *Class A.* Noninterruptible service performance (should function before, during, and after the power fault condition)
- *Class B.* Self-restoring interruptible service performance (should function before and after the power fault condition)
- *Class C.* Interruptible service performance (can tolerate a station visit to restore service)

5. Electrical power station GPR

In order to determine the appropriate value of voltage that a station ground grid may attain relative to a remote ground point (hereafter called GPR) as a function of time, consideration should be given to the following:

- a) The complete data on the power system impedances, currents, and voltages for power system faults, alternate return paths such as overhead ground wire, water pipes, rails, etc.
- b) The fault locations that produce the worst combination of the GPR and the induction
- c) The duration and waveform (dc offset) of the voltages and currents for the case of the worst fault

NOTE—This assumes an evaluation of the assumed point on the voltage or current waveform for fault initiation.

- d) The ground grid impedance at the power station ground grid with respect to remote earth, and the impedance with respect to remote earth at the remote fault location
- e) The calculation of appropriate fault current values, due to the conductive effects of grounding
- f) The calculation of the GPR, induced voltages, and their vectorial sum
- g) The reduction of induced voltage due to shielding effects of transmission line conductors, overhead ground wires, and telecommunication cable shields
- h) The reduction of the GPR due to overhead ground wires

5.1 Determination of appropriate symmetrical and asymmetrical GPR

5.1.1 GPR

When a ground fault occurs, the zero-sequence fault current returns to the power system ground sources through the earth and also through alternate paths such as neutral conductors, unfaulted phases, overhead ground wires, messengers, counterpoises, and metallic cable shields. The ground sources are the grounded wye-connected windings of power transformers, generator grounds, shunt capacitors, frequency changers, etc. The GPR is equal to the product of the station ground grid impedance and that portion of the total fault current that flows through it. Also, the GPR is equal to the product of the alternate path impedance and that portion of the conductively coupled fault current that flows through it. The volt-time area of GPR to be determined is given in volt-seconds for the duration of the fault.

5.1.2 Ground grid impedance

Since the station ground grid impedance to remote earth is needed to calculate the GPR, the ground grid impedance shall be obtained either by the calculation or measurement methods described in 4.3.

5.1.3 Ground fault studies

A study should be made of various ground faults in order to determine the one that produces the highest GPR and volt-second area (see 5.4.4). The station ground grid impedance, as well as power overhead ground wire and telecommunication grounding networks, tend to limit the fault current and should be included in the calculations.

5.1.4 Power system generators

In the ground fault study (see 5.1.3), the power system generators are usually represented by their subtransient reactances. As the time progresses until fault clearing, their reactances increase to their transient values and possibly to their steady-state synchronous reactances. This change can be neglected in most cases and the initial subtransient reactance retained. All significant impedances should be included, such as for transmission lines.

5.1.5 DC offset

The initial magnitude of the dc offset should be calculated as a function of the voltage magnitude at the time the fault is initiated. The highest dc offset occurs when the change in current, from just before fault initiation to just after fault initiation, is maximum. Since the alternating current cannot change state instantaneously due to the inductance of the circuit, initially the dc offset counter balances the change in alternating current. The dc offset then decreases to zero at a rate determined from the effective reactance-impedance ratio of the power circuit at the fault. With a highly inductive circuit, the maximum dc offset will occur when the fault is initiated close to a voltage zero crossing, a condition that is most unlikely for faults resulting from insulation breakdown. Also, a highly inductive circuit will have a prolonged dc offset. For the application of a multiplication factor for dc offset, refer to Clause 10.

Ground potentials differ from magnetically induced voltages. The transient dc component (dc offset) of the ground fault current produces a proportional but decaying ground potential. Equation (24a), used to determine the instantaneous current considering both the symmetrical and dc offset components, is included in 5.4.3. For induced voltages, the dc component is of minor importance since the induced voltage varies as di/dt . In HV networks when the fault impedance is negligible, the time constant varies; but the rate of decay of the dc component is usually within 5–40 ms and is determined by the effective power system X/R ratio. The ground fault current contains nearly a full transient or dc component if the ground fault is initiated close to voltage zero, the probability of which is very low. This is the instant when the resulting fault current will be at maximum. This near worst-case scenario can happen when the ground fault is caused initially by a light-

ning stroke or when a circuit breaker is closed into a fault. In this latter case, the pre-strike arc impedance of the breaker has the effect of reducing the initial magnitude of the dc offset. Table 1 has multiplication factors to be used on root-mean-square (rms) values to determine the total maximum peak value.

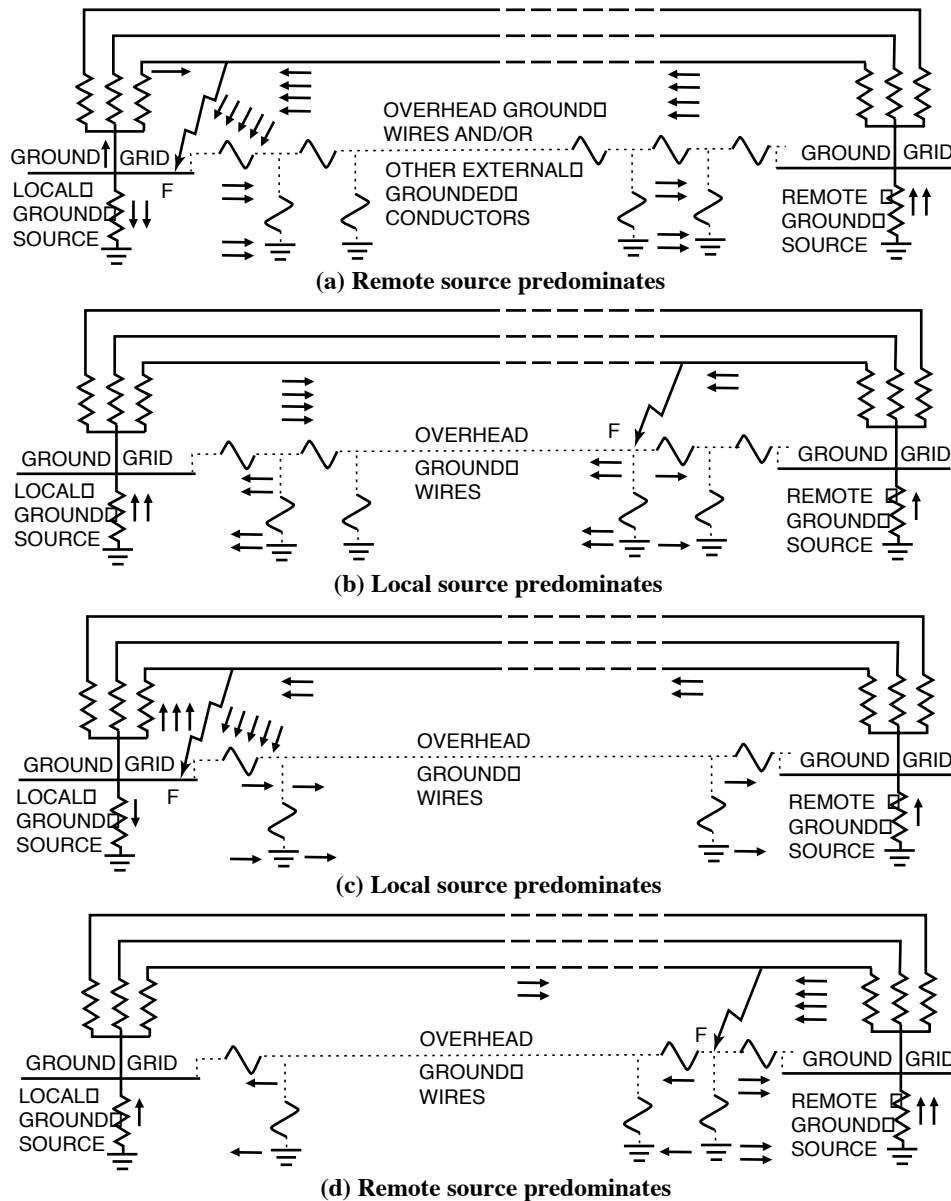
Table 1—Factors to be used to account for maximum effect of dc offset on peak fault current

<i>X/R ratio</i>	Multiplication factor
1	1.04
2	1.21
3	1.35
4	1.46
5	1.53
6	1.59
7	1.64
8	1.68
9	1.71
10	1.73
15	1.81
20	1.85
30	1.90
40	1.92
50	1.94

The shielding factor of cables for the transient dc component is poorer than the value measured at the power frequency. Moreover, a simultaneous dc component may also influence the ac shield factor of armored cables. On the other hand, the effective impedance to earth of ground electrodes containing long buried wires or cable sheaths and of lines equipped with shield wires is lower for the dc component than for the ac component.

5.1.6 Different combinations of GPR

There are four possible combinations of circumstances involving power faults that should be considered in determining the worst-case GPR at a power station. With reference to Figure 1, four different ground fault conditions causing GPR at the local power station (local ground source) will be described. For simplicity, a single-circuit, three-phase power line with two ground sources is illustrated. A ground source at a power station is a component that can supply current to a fault and to which current returns by way of the earth and all available metallic conducting paths. Ground sources include wye-connected transformers with grounded neutrals, grounded autotransformers, and grounded generators.



NOTE 1—For simplicity, a single line with only two ground sources is illustrated.

NOTE 2—Overhead ground wires can be insulated from the towers, resulting in different values.

NOTE 3—F—fault location.

Figure 1—Different combinations of GPR occurring at the local ground source

- a) Figure 1a illustrates the situation involving a fault to the local ground grid where the remote source provides a greater amount of fault current than the local source (the remote source “predominates”). In this case, the current supplied by the local source simply circulates on the metallic grid (very little flows into the earth), therefore not producing any appreciable GPR. However, the relatively large current from the remote source returns to that source by way of the earth and all available metallic conductors, thereby producing a relatively large GPR at the local power station.

- b) Figure 1b illustrates the situation involving a line fault to remote earth (the fault location is outside the ZOI of the local power station) where the local source provides a greater amount of fault current than the remote source (the local source “predominates”). In this case, the fault currents return to their respective sources by way of the earth and all available conductors. Since the local source supplies the high-fault current, the GPR produced at the local power station will be relatively large.
- c) Figure 1c illustrates the situation involving a fault to the local ground grid where the local ground source provides a greater amount of fault current than the remote source (the local source “predominates”). The current supplied by the local source mostly does not flow into the earth and does not produce any appreciable GPR. The relatively small current from the remote source returns to that source by way of the earth and all variable metallic conductors, thereby producing a relatively small GPR at the local station.
- d) Figure 1d illustrates the situation involving a line fault to remote earth where the remote source provides a greater amount of fault current than the local source (the remote source “predominates”). The fault currents return to their respective sources by way of the earth and all available conductors. However, since the local source provides a relatively small current, this GPR produced at the local power station will be relatively small.

NOTE 1—In these examples, the cases described in items a) and b) resulted in the largest GPRs at the local power station. However, all four fault conditions should be evaluated to determine the worst-case GPR at the power station of interest.

NOTE 2—Figure 1 shows a typical system, in which the externally grounded metallic conductors (including overhead ground wires) are indicated by dotted lines. Overhead ground wire systems are constructed in various configurations and may be either directly bonded to the transmission line towers or may be insulated from the towers. In addition, overhead ground wire systems may be directly connected to the station ground grid or may be terminated one or more spans out from the station. The externally grounded metallic conductors, including grounded wires, provide an alternate path for the fault current, reducing the earth return portion of the total fault current.

NOTE 3—Power stations without ground sources (for example, switchyards with transformers having only delta connections) do not experience GPR from line faults occurring off the station grid when the power line overhead ground wire is not connected to the station ground grid. However, such stations do experience a GPR if a fault occurs directly to the grid and the system connection on the other end has a ground path. For example, the transformer at the other end has a grounded winding.

5.1.7 Determination of the worst-fault location

A complex power station may have a large number of rights-of-way (ROW) with multicircuit power lines on each ROW. These circuits may be operated at different voltage levels. A fault current study for an L-G fault at each transformer voltage level should be produced. Each fault current study should be examined as follows:

- a) If the vectorial sum of all zero-sequence fault current contributions to the transformer bus fault from all transmission and distribution lines entering the station under study is greater than the sum of all current contributions from all grounded sources at that station (including generators, grounded transformers, shunt capacitors, etc.), then at the voltage level for which the fault current study is presently being examined, the bus fault will usually produce a worse GPR than the line fault.
- b) If the reverse is true, that is, the vectorial sum of the line contributions is smaller than the local ground source current sum, the line fault will produce a greater GPR. This is because the local ground current will return partially, in the case of the line fault, through the station ground impedance, adding to the GPR caused previously by the line current contribution. In the bus fault case, the current merely circulates through the faulted transformer winding, the station ground bus, and the fault impedance.

Having determined the worst-fault location (bus versus out on-the-line), to select that fault current study with the highest fault current is not appropriate. Variances between grounding networks of lines with the var-

ious voltage levels may, for instance, cause the study showing lower zero-sequence fault currents to result in a GPR greater than that caused by the higher currents. Instead, all faults should be investigated for fault locations as determined above.

5.1.8 Determination of the worst-fault type

Basically, three types of faults should be investigated:

- a) *Line-to-ground faults (L-G)*. These are predominant in terms of frequency of occurrence. Zero-sequence and positive-sequence currents will be required. In practice, GPR is a function of zero-sequence currents only, but positive-sequence currents are required to determine magnitudes of the individual zero-sequence currents flowing in each phase of the faulted circuit.
- b) *Double line-to-ground faults (2L-G)*. These are statistically less frequent than L-G faults but could produce zero-sequence currents far exceeding those caused by L-G faults. Theoretically, this is because of different connections of sequence networks during these faults. For an L-G fault, the positive-sequence, negative-sequence, and zero-sequence networks are connected in series and driven by the prefault voltage source; whereas, for a 2L-G fault, positive-sequence impedance is connected in series with the parallel combination of zero-sequence and negative-sequence impedances, with less overall impedance in the path of the fault current. [For instance, many high MVA autotransformers may be added to power stations. These could have their primary-to-secondary, or primary-to-tertiary, zero-sequence reactance ratios so high that their primary current is small compared with the tertiary (ground) current. In addition to this, if more such transformers are added to the station, the resulting tertiary currents will be very large due to further paralleling of reactances.]
- c) *Three-phase faults*. These are statistically less frequent than L-G and 2L-G faults. Three-phase faults produce positive sequence currents, and detailed calculations are required to determine magnitudes of the individual zero-sequence currents flowing in each phase of the faulted circuit.

If X_1 and X_0 are positive-sequence and zero-sequence reactances, respectively, of the system impedance at the point of fault and X_1 is less than X_0 , the 2L-G fault will result in higher zero-sequence fault currents, often twice as high as the L-G fault currents calculated at the same fault location. The GPR produced by 2L-G faults is not normally considered, due to its low probability.

For an overview of the frequency of occurrence of different types of faults as a function of voltage levels on which they occur and other parameters, see [B12].

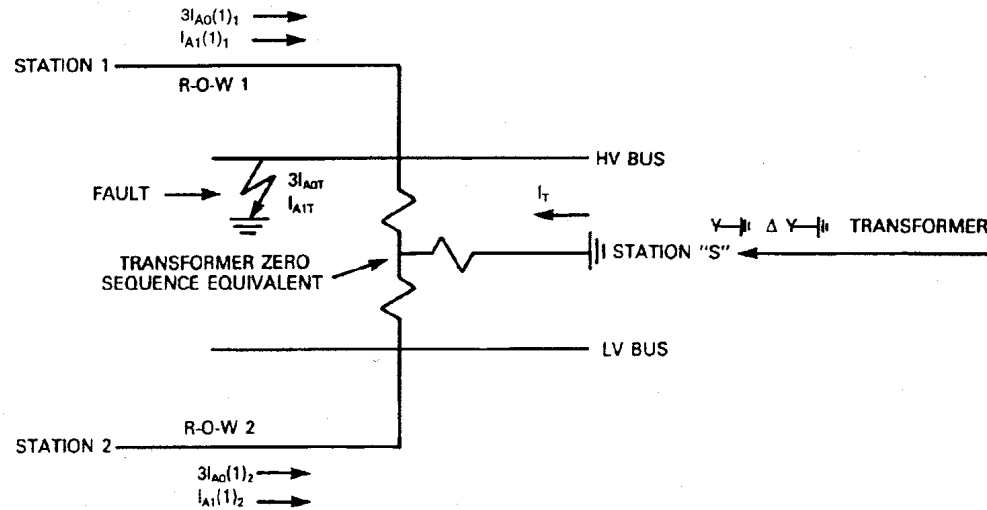
5.1.9 Notes on modeling of ladder networks of long and short lines

As will become clear later, GPR work requires modeling of transmission and multigrounded distribution line grounding networks. This becomes important when determining the amount of fault current carried away from the fault by the grounding network of the line, conductively, by first calculating its impedance to remote earth. This determines the amount of the GPR-causing current.

A modified transmission line theory can be used by modeling the ladder networks by the distributed parameter method. Care should be taken in correcting the classical hyperbolic transmission line equations due to the fact that the series (overhead ground wire self-impedance) and shunt (tower footing impedance) components of the overhead ground wire-tower ladder network are discrete components. This modification should enable one to transform these discrete components into a set of distributed ladder network parameters. This, however, can only be done with lines that are sufficiently long. If the line is short, one should resort to the nodal and mesh analysis that may require considerable computing time, particularly with large ROWs with a multitude of lines and overhead ground wires. The presence of counterpoises and bonds can be extremely complicating, but should be considered.

5.1.10 HV bus fault GPR

By simulating the L-G and three-phase bus faults, power utilities can generally calculate resulting zero-sequence and positive-sequence fault currents as shown in Figure 2.



$3I_{A0}(J)_r$ is the zero-sequence current in the J th circuit on the r th ROW
 $I_{A1}(J)_r$ are the positive-sequence currents in the J th circuit on the r th ROW
 $3I_{A0T}$ is the total zero-sequence fault current
 I_{A1T} is the total positive-sequence fault current
 I_T is the transformer neutral, generator, etc., current

Figure 2—L-G and three-phase fault simulation

NOTE—The fault currents shown in Figure 2 are the per circuit (as opposed to per phase) quantities; that is, all three-phase currents are concentrated in a single equivalent conductor and, in the case of zero-sequence currents, include the inductive effect of ground wires. To account for the conductive effects of the presence of overhead ground wires, station ground impedance, incidental ground path impedances, and phase wire zero-sequence impedances, $3I_{A0T}$ shall be reduced accordingly. A new circuit, valid for electrically long lines, is formed as shown in Figure 3.

Based on Figure 2:

$$\sum_r \left(\sum_J 3I_{A0}(J)_r \right) + I_T = 3I_{A0T} \quad (1)$$

$$\sum_r \left(\sum_J I_{A1}(J)_r \right) = I_{A1T} \quad (2)$$

then

V_p is the prefault voltage;
 Z_c is the zero-sequence self-impedance of the faulted phase conductor, between the source and fault locations;

- $Z_{\infty T}$ is the parallel combination of impedance of all ladder networks (Z_L) and the incidental impedances (Z_i);
- Z_{sy} is the system impedance;
- Z_a is the fault impedance.

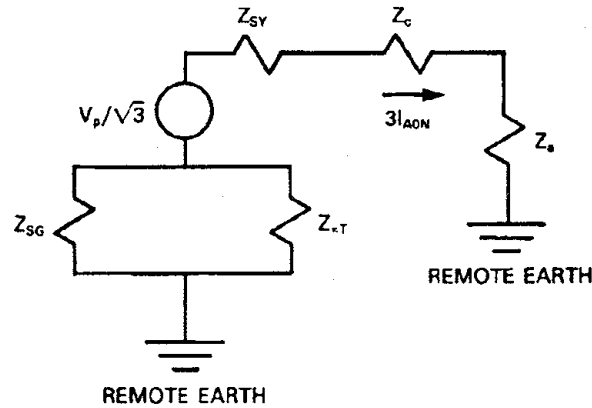


Figure 3—Circuit for total zero-sequence current reduction ($3I_{A0T}$)

Z_{sy} is the impedance seen between the fault terminals, as determined by the power utility in fault calculations, and includes the zero-sequence impedances of lines, transformers, etc.

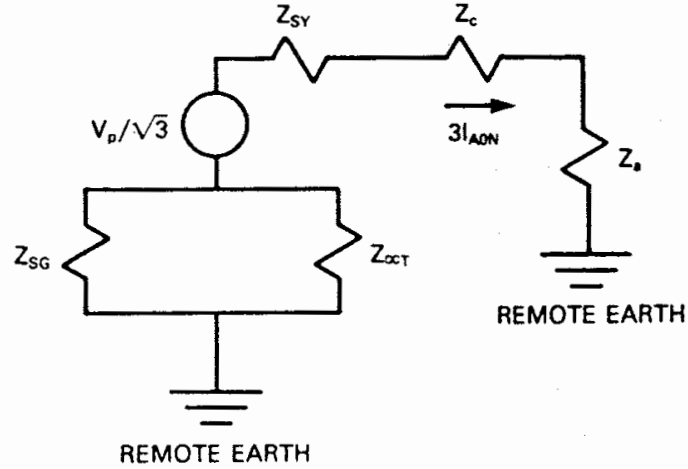
The new zero-sequence fault current ($3I_{A0N}$) resulting from Figure 3 includes the conductive effects of grounding. This new lower interfering current, however, shall be further reduced by the amount it induces into the overhead ground wires of the tower (or pole) line that carries the faulted circuit. Because of the unequal spacings between the phase wires and neutrals and because each phase carries different currents both in amplitude and phase (faulted phase, depending on the corresponding positive-sequence current, generally carries the current toward the fault location, whereas the remaining two unfaulted phases generally carry currents away from the fault location), unequal currents are induced in the overhead ground wires from each phase of the faulted circuit. Overhead ground wire currents induced from the faulted phase will act as a shield, but those induced from the unfaulted phases will usually subtract from the shielding current and act as an “antishield,” as depicted in Figure 4.

Similar shielding or antishielding will be produced by unfaulted circuits of the faulted tower line and unfaulted tower lines with their circuits on the same ROW, depending on their terminal connections in relation to the faulted circuits. Since the induced overhead ground wire current(s) does not enter ground but stays in the overhead ground wire, therefore causing no GPR, the determination of shielding or antishielding currents is important. Also, telecommunication cable sheaths and messenger strands may act as shields if strategically grounded.

Because of the foregoing conclusion, the per-circuit fault quantities shall be broken down into their respective per-phase equivalents, and induction into the overhead ground wire(s) calculated separately from each phase.

Limiting the analysis to two single-circuit tower lines extending in two directions from station S (as in Figure 2) on two ROWs (ROW 1 and ROW 2), the phase current will be determined as shown in Figure 5.

Positive-sequence currents in Figure 5b are coincidental with those in Figure 2, and their source is the three-phase fault study done by the power utility. The positive-sequence currents in Figure 5a have a superscript (')



I_{A0} is the faulted phase zero-sequence current contribution
 I_{B0}, I_{C0} are the unfaulted phase zero-sequence current contributions
 I_{SA}, I_{SB}, I_{SC} are the induced currents in the overhead ground wire
 Z_p is the pole tower footing impedance

Figure 4—Power line shielding

because these currents differ from those in Figure 5b since the voltage sources V_{p1} and V_{p2} drive two different circuits.

Here

$$I_{A'1}(1)_1 = \frac{I_{A1}(1)_1}{I_{A1T}} \times \frac{3I_{A0T}}{3} \quad (3)$$

and

$$I_{A'1}(1)_2 = \frac{I_{A1}(1)_2}{I_{A1T}} \times \frac{3I_{A0T}}{3} \quad (4)$$

Then, assuming positive-sequence currents equal negative-sequence currents, the phase currents (I_A , I_B , and I_C) in circuit 1 on ROW 1 are

$$I_A(1)_1 = I_{A0}(1)_1 + I_{A'1}(1)_1 + I_{A2}(1)_1 \quad (5)$$

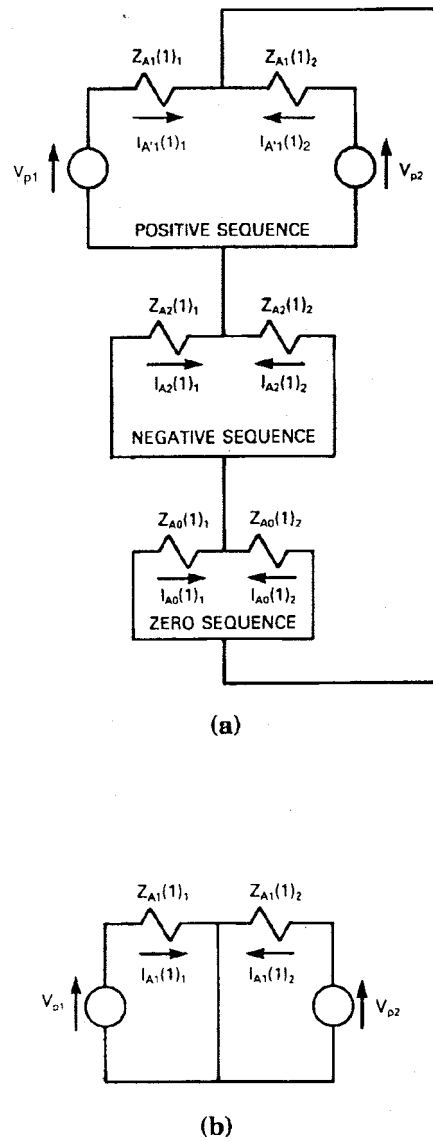


Figure 5— Circuit for L-G and three-phase fault analysis

$$I_B(1)_1 = I_{A0}(1)_1 + a^2 I_{A1}(1)_1 + a I_{A2}(1)_1 \quad (6)$$

$$I_C(1)_1 = I_{A0}(1)_1 + a I_{A1}(1)_1 + a^2 I_{A2}(1)_1 \quad (7)$$

where a is the complex operator ($1 \angle 120^\circ$) and

$$a + a^2 = -1 \quad (8)$$

Similarly, the phase currents I_A , I_B , and I_C in circuit 1 on ROW 2 are

$$I_A(1)_2 = I_{A0}(1)_2 + I_{A1}(1)_2 + I_{A2}(1)_2 \quad (9)$$

$$I_B(1)_2 = I_{A0}(1)_2 + a^2 I_{A1}(1)_2 + a I_{A2}(1)_2 \quad (10)$$

$$I_C(1)_2 = I_{A0}(1)_2 + a I_{A1}(1)_2 + a^2 I_{A2}(1)_2 \quad (11)$$

Substituting the expression for $I_{A1}(1)_1$ [defined in Equation (3)] into Equation (5) and assuming that for one phase-to-ground fault,

$$I_{A1}(1)_1 = I_{A2}(1)_1$$

$$I_{A1T} = I_{A0T}$$

yields the following:

$$I_A(1)_1 = \frac{2I_{A1}(1)_1}{I_{A1T}} \times \frac{3I_{A0T}}{3} + \frac{3I_{A0}(1)_1}{3} \quad (12)$$

Similarly for ROW 2, substituting Equation (4) into Equation (9) and assuming that for one phase-to-ground fault,

$$I_{A1}(1)_2 = I_{A2}(1)_2$$

$$I_{A1T} = I_{A0T}$$

yields the following:

$$I_A(1)_2 = \frac{2I_{A1}(1)_2}{I_{A1T}} \times \frac{3I_{A0T}}{3} + \frac{3I_{A0}(1)_1}{3} \quad (13)$$

Currents in the unfaulted phases are

$$I_B(1)_1 = I_C(1)_1 = \frac{3I_{A0}(1)_1}{3} - \frac{I_{A1}(1)_1}{I_{A1T}} \times \frac{3I_{A0T}}{3} \quad (14)$$

NOTE 1—Equation (14) is obtained by substituting Equation (3) into Equations (6) and (7).

$$I_B(1)_2 = I_C(1)_2 = \frac{3I_{A0}(1)_2}{3} - \frac{I_{A1}(1)_2}{I_{A1T}} \times \frac{3I_{A0T}}{3} \quad (15)$$

NOTE 2—Equation (15) is obtained by substituting Equation (4) into Equations (10) and (11).

Next, mutual impedances between overhead ground wire(s) and each phase conductor on the faulted ROW may be obtained by the use of either the simplified form of Carson's equation [B24] or, more accurately, the "extended complex image" known as Parker's equations [B56]:

Impedance (mutual and self) based on a simplified form of Carson's equation

$$Z_{mCAR} = 0.00159f + j0.004657f \log_{10} \frac{2160 \sqrt{\frac{\rho}{f}}}{d_{ab}} (\Omega/\text{mi}) \quad (16)$$

where

- f is the power system frequency (Hz);
- ρ is the earth resistivity ($\Omega \cdot \text{m}$);
- d_{ab} is the distance between each phase conductor and overhead ground wire(s) (ft);
- Z_{mCAR} is the mutual impedance based on a simplified form of Carson's equation.

NOTE 3—See 6.2 for additional information.

$$Z_{mCAR} = 0.0001f + j0.00289f \log_{10} \frac{2160 \sqrt{\frac{\rho}{f}}}{d_{ab}} (\Omega/\text{km}) \quad (16a)$$

where

- d_{ab} is the distance between each phase conductor and overhead ground wire(s) (m).

Impedance (mutual and self) based on Parker's equation

The self-impedance of each overhead ground wire is calculated as shown in the following equation:

$$Z_{sCAR} = r_c + 0.00159f + j0.004657f \log_{10} \frac{2160 \sqrt{\frac{\rho}{f}}}{GMR} (\Omega/\text{mi}) \quad (17a)$$

where

- r_c is the conductor impedance (Ω/mi);
- GMR is the geometric mean radius of the conductor (ft);
- Z_{sCAR} is the self-impedance of the overhead ground wire based on a simplified form of Carson's equation.

$$Z_{sCAR} = 0.62137r_c + 0.0001f + j0.00289f \log_{10} \frac{2160 \sqrt{\frac{\rho}{f}}}{GMR} (\Omega/\text{km}) \quad (17b)$$

where

- GMR is the geometric mean radius of the conductor (m).

A number of researchers have investigated alternative approximations to Carson's formulation. One formula recommended by CCITT [B10] yields highly accurate results for closely spaced conductors. This, together with Carson's results for far-spaced conductors, forms the basis for the formula derived by J. C. Parker, Jr. of

Bell Laboratories [B56]. The transition between the two formulas is covered by including a term that corrects for close-spaced conductors and that disappears for far-spaced conductors.

The mutual impedance based on Parker's extended complex image equation (Z_{mPAR}) is defined in Equation (25).

It is important that the self-impedance be calculated in the same way as the mutual impedance so that the same approximations and assumptions apply to both. This is necessary because the self-impedance is used in a ratio with the mutual impedance to calculate a shielding factor. Therefore, the accuracy of the shielding factor depends on the relative accuracies of the self- and mutual impedances more so than on the absolute accuracy of each.

An expression for self-impedance can be derived directly from the expression for mutual impedance by assuming that the two conductors are very close together and are separated only by the radius of the conductor in question. A term should be added to this mutual term to account for the flux internal to the conductor to give

$$\left(Z_{sPAR} = r + j \frac{\omega \mu}{8\pi} + Z_{mPAR}(\Omega/\text{km}) \right)$$

internal mutual

where

- r is the dc resistance of conductor (Ω/km);
- ω is the angular frequency (equal to $2\pi f$);
- Z_{sPAR} is the self-impedance of the overhead ground wire based on Parker's extended complex image equation;
- μ is the absolute permeability of conductor; (equal to $\mu_r \mu_0$);

where

- μ_r is the relative permeability of conductor (1 for nonferrous, 50–200 for ferrous);
- μ_0 is the rationalized permeability of free space.

Z_{mPAR} is calculated by Equation (25) (as Z_m), using the conductor radius for separation.

Then, making the substitutions, where

- a is the radius of conductor (m);
- $h_1 = h_2 = h$ is the height of conductor (m);

gives

$$Z_{sPAR} = r + j \frac{\omega \mu_0}{2\pi} \left[\frac{\mu_r}{4} + \ln \left(\frac{D_1}{a} \right) - \frac{1}{12} \left(\frac{2}{\gamma D_1} \right)^4 \right] (\Omega/\text{km}) \quad (17c)$$

where

$$D_1 = \sqrt{a^2 + \left(2h + \frac{2}{\gamma}\right)^2} \text{ (m)}$$

but with h much greater than a ,

$$D_1 = 2h + \frac{2}{\gamma} \text{ (m)}$$

NOTE 4—See Equation (25) for a definition of γ .

The total zero-sequence current induced in each overhead ground wire (I_{sk}) is the sum of the products of each phase current and the coupling factor μ ,

where

$$\mu = \frac{Z_m}{Z_s} \quad (18)$$

and

Z_m is the mutual impedance (Ω/mi or Ω/km);
 Z_s is the self-impedance (Ω/mi or Ω/km).

Z_m and Z_s could be calculated by either simplified Carson's or Parker's formulas depending on spacing of conductors.

Conversely, for the current I_G , flowing in the earth due to induction, the coupling factor $(1 - \mu)$ is

$$(1 - \mu) = 1 - \frac{Z_m}{Z_s} \quad (19)$$

To assess the conductive effects, Z_∞ shall be determined next. Z_∞ is defined as an impedance looking into an overhead ground wire-tower (or neutral-pole) ladder network from the fault terminals. The determination of Z_∞ is complex and can be done by either discrete or distributed parameter methods. In the case of one electrically long line conforming to the inequality,

$$L\sqrt{Z_s Z_p} > 2 \quad (20)$$

where

L is the total length of the line (mi or km);
 Z_s is the per-span self-impedance of the overhead ground wires, (Ω);
 Z_p is the per-span tower (pole) footing impedance (Ω).

then

$$Z_\infty = \frac{Z_s}{2} + \sqrt{\frac{Z_s^2}{4} + Z_s Z_p} \quad (21)$$

The diagram illustrates a single-line model of a faulted circuit. It shows two main sections: 'TO STATION 2' on the left and 'TO STATION 1' on the right. A 'FAULTED PHASE' and 'FAULTED CIRCUIT' are indicated between them. The circuit includes a 'LV BUS' and an 'HV BUS'. Various impedances are shown: Z_{PR} and Z_{SEC} on the transmission lines; Z_{TER} at the fault point; Z_S and Z_P on the series and shunt branches of the faulted circuit; Z_{c1} and Z_{c2} at the station ground buses; and Z_{SG} at the remote earth. Currents are labeled: $3I_{Ad}(1)_2$ and $3I_{Ad}(1)_1$ at the station buses; I_T at the fault point; I_{SK2I} , I_{SK1I} , I_{SK1c} , and I_{SK2c} at the shunt branches; and I_G at the remote earth. A 'REMOTE EARTH' and 'STATION GROUND BUS' are also indicated.

$$\begin{aligned}
 I_{SKi} &= I_{SK1i} + I_{SK2i} & I_{SKi}, I_{SK1i}, \text{ and } I_{SK2i} & \text{ are the induced overhead ground wire fault currents (do not enter ground)} \\
 I_{SKc} &= I_{SK1c} + I_{SK2c} & I_{SKc}, I_{SK1c}, \text{ and } I_{SK2c} & \text{ are the conducted overhead ground wire fault currents (do not enter grounding network)}
 \end{aligned}$$

$$\begin{aligned}
 3I_{A0T} &= (I_{SK1i} + I_{SK1c}) + (I_{SK2i} + I_{SK2c}) + I_G + I_T \\
 3I_{A0(1)_1} &= I_{SK1i} + I_{SK1c} \\
 3I_{A0(1)_2} &= I_{SK2i} + I_{SK2c}
 \end{aligned}$$

In Figure 6 it can be seen that for the fault on the HV bus (the situation is reversible) the transformer ground current I_T circulates through the faulted winding and the fault itself. For simplicity, it can be assumed that it does not enter ground. The GPR causing the zero-sequence current I_{GPR} is

and also

$$I_{\text{GPR}} = 3I_{\text{AOT}} - (I_{\text{SKi}} + I_{\text{T}})$$

This current will enter the following impedance combination:

where

Z_{GPR} is the GPR impedance (Ω);

and the GPR is then

$$GPR = I_{\text{GPR}} \times Z_{\text{GPR}} \quad (24)$$

5.1.11 Low-side bus and line-fault GPR

Theoretically, LV faults can be handled in precisely the same manner as the HV faults. All differences between HV and LV side construction (transformer connections, line conductors, length, pole footing impedance, etc.) will reflect in the calculation of zero- and positive-sequence LV L-G and balanced fault currents. As opposed to HV systems, which usually carry overhead ground wires, some LV lines, delta or wye-connected, carry no neutrals.

When neutrals are present on LV systems, LV bus fault calculations follow the same method described in 5.1.10, and LV line faults will be the same as HV line fault calculations, to be described later.

When neutrals are not present on LV system, both LV bus and line-fault GPR can be calculated using the simplified method shown in 5.1.10. For a LV bus fault, Z_L will consist of the parallel combination of impedances-to-remote earth of all HV overhead ground wire-tower ladder networks only. The rest of the method still applies.

For LV line faults, assuming a radial LV line, a single fault infeed can be assumed if no generation exists on the load side of the line. This assumption is correct for most cases, but it should be pointed out that, for instance, a large induction motor can become a zero-sequence current generator at the instant of the fault, due to the inertia of the rotor and the mechanical load. If this can be neglected, the worst fault then occurs outside and near the station. The HV bus fault is modified by inserting, in series with Z_s , the self-impedance of the faulted phase conductor, and inserting, in series with Z_a , a faulted pole footing impedance. See Figure 3.

The methods described in this subclause should be used for hand calculation and estimation purposes only.

For a more complicated network, that is, the network with a high number of ROWs, circuits, transformers, ground sources, and short lines such as could be found between generating and switching stations, hand calculations cannot be used for either exact or approximate solutions; a computer program shall be used. In such a program, the theoretical approach should include the effect of other forms of grounding, such as rails, pipes, etc.; the effect of the length of lines; the effect of positive-sequence current phase shift in certain transformer windings; etc. For the theoretical basis of such a program, see [B24].

5.1.12 HV line-fault GPR

The theory shown in 5.1.10 is a simplified one. It can, however, be used with confidence to obtain results within some 10–30% of true figures, for estimating purposes.

The present topic is, by contrast, much more complicated not only by the complexity of the problem itself, but also by the vast amount of data input required. No hand calculation methods exist.

When a particular L-G HV bus fault current study indicates that the worst fault is the line fault from the HV bus in question, there is no easy way to determine the exact location of that fault. The only definite condition is that the fault will be at any one tower carrying circuit(s) connected to the bus at the same voltage level for which the aforementioned bus fault current study was produced. This necessitates placing a fault at each tower for *each* circuit of *each* tower line of *each* ROW carrying such circuit(s) and calculating the GPR at the station under study for each of these faults. Because of the tremendous multitude of line faults to be

examined (for complex stations with a number of ROWs and long lines, the number of faults to be examined may reach into the hundreds), to ask the planning section of the utility for so many fault current studies would be impractical. A selective computer program calculating GPR for line faults at all voltage levels shall contain its own short-circuit subprogram. Both positive-sequence and zero-sequence short-circuit current study sets will be required.

The system to be analyzed is modeled as a network consisting of left and right voltage sources with impedances between them. The faulted ROW is the path followed by the faulted circuit. A fault is defined to occur at a transmission tower between a left source and a right source. Ground currents will then flow through the grounding network made up of overhead ground wires, towers, counterpoises, and bond conductors. Because of inductive effects, all unfaulted circuits along the faulted ROW are also affected by the fault. The ground currents and the conductor currents are calculated using symmetrical components. This technique requires calculation or knowledge of the sequence impedances in the system under study. It is not within the scope of this standard to provide the basis for a computer program capable of doing this (see [B24]).

5.1.13 Example 1: HV bus fault and LV bus and line fault

5.1.13.1 System data

The station with Z_{SG} equal to 0.5Ω as shown in Figure 8 has three ROWs entering it.

- a) ROW 1 carries a single-circuit 230 kV transmission line with a conductor configuration as shown in Figure 7. The following data apply:

Conductor resistance and reactance data for 1 ft separation (0.305 m)

- 1) Phase conductors: 1307.4 AS28/19
 $R + jX = 0.0797 + j0.3720 \Omega/\text{mi}$
Diameter: 1.34 in (34.0 mm)
 - 2) Overhead ground wires: 7 AWG No 8
 $R + jX = 2.354 + j6.44 \Omega/\text{mi}$ at 1 ft separation
Diameter: 0.385 in (9.8 mm)
The mutual impedance between ground wires is equal to $0.095 + j0.705 \Omega/\text{mi}$
 - 3) Tower footing impedance: 80Ω
 - 4) Earth resistivity: $1000 \Omega \cdot \text{m}$
 - 5) Average span: 1014 ft (309 m)
 - 6) Line length: 7 mi (11.3 km)
- b) ROW 2 data is the same as for ROW 1. Line length: 5 mi (8 km).
- c) ROW 3 carries a three-phase 44 kV delta-connected circuit. In Figures 8 and 9, two fault-current studies, one for the 230 kV and the other for the 44 kV bus, are shown. Both L-G and symmetrical fault currents were calculated. The future fault condition is assumed.

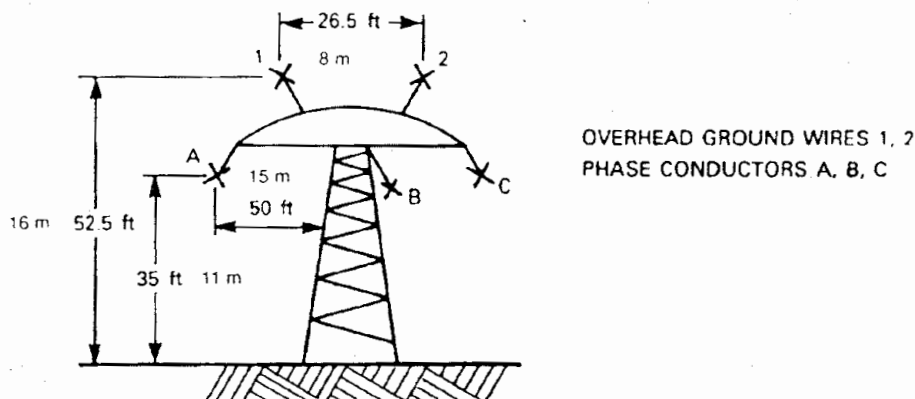


Figure 7—ROW 1 conductor configuration

5.1.13.2 Worst-fault location determination

In Figure 8a, note that in comparing the sum of all transmission and distribution line zero-sequence fault currents ($I = 995.7 - j4967.7$ A) and the sum of all local ground currents ($I = -15.6 - j2076.4$ A), the line current contribution is higher. This indicates that for GPR purposes, the bus fault is the worst case. In Figure 9a, all zero-sequence fault currents will originate from the local source, that is, the line fault will be the worst case.

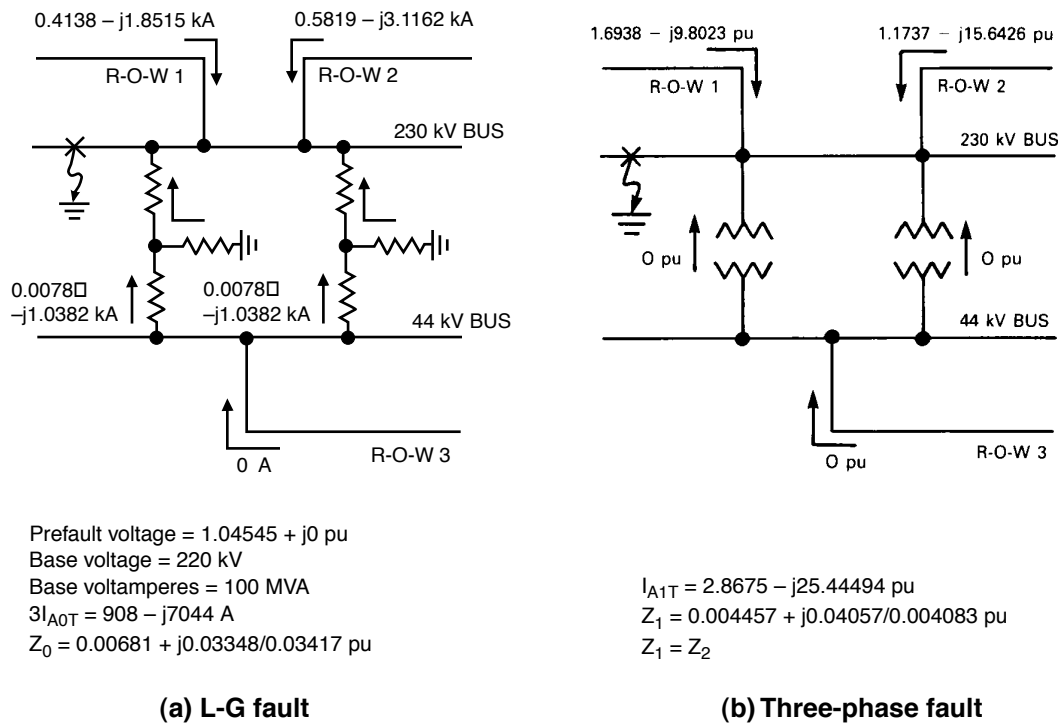


Figure 8—230 kV bus fault

5.1.13.3 Worst-fault type

From Figures 8a and 8b, zero-sequence system reactance as seen from the fault terminal is X_0 equals 0.03348 pu, and the similar positive-sequence reactance is X_1 equals 0.04057 pu. A 2L-G fault will therefore produce higher zero-sequence fault currents than an L-G fault. However, as mentioned earlier, a 2L-G fault seldom evolves and so, for the purpose of this example, an L-G fault will be studied.

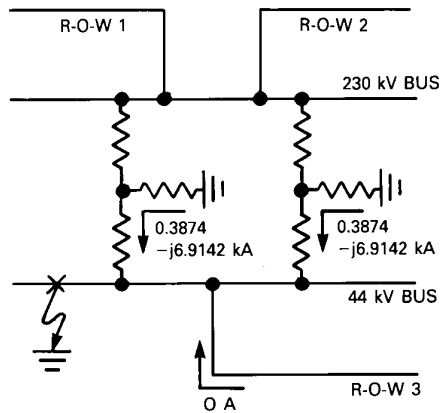
5.1.13.4 GPR calculations

5.1.13.4.1 230 kV bus fault

ROW 1

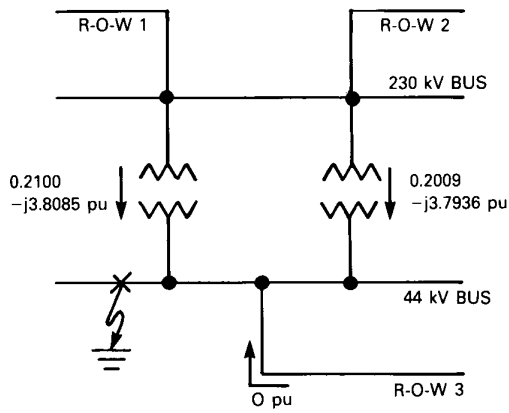
From Figure 8(a), the zero-sequence fault current contribution is

$$3I_{A0}(1)_1 = 413.8 - j1851.5 \text{ A}$$



Prefault voltage = $1.0204 + j0$ pu
Base voltage = 44.92 kV
Base voltamperes = 100 MVA
 $3I_{A0T} = 775 - j13.828$ A
 $Z_0 = 0.00143 + j0.01602/0.01608$ pu

(a) L-G fault



$I_{A1T} = 0.41091 - j7.6021$ pu
 $Z_1 = 0.00726 + j0.13431/0.13431$ pu
 $Z_1 = Z_2$

(b) Three-phase fault

Figure 9—44 kV bus fault

Total zero-sequence fault current is

$$3I_{A0T} = 980 - j7044 \text{ A}$$

Positive-sequence fault current contribution is

$$1I_{A1}(1)_1 = 1.694 - j9.802 \text{ pu}$$

based on a prefault voltage of

$$1.04545 + j0 \text{ (base voltage = 220 kV)}$$

The total positive-sequence fault current is

$$I_{A1T} = 2.87 - j25.44 \text{ pu}$$

The mutual impedances between each phase conductor and overhead ground wire 1 are

$$\text{Conductor A: } 0.0941 + j0.741 \text{ } \Omega/\text{mi}$$

$$\text{Conductor B: } 0.0941 + j0.736 \text{ } \Omega/\text{mi}$$

$$\text{Conductor C: } 0.0939 + j0.706 \text{ } \Omega/\text{mi}$$

Because of symmetry, the same mutual impedances apply to overhead ground wire 2 but in reverse order.

The self-impedances of overhead ground wires 1 and 2 are

Overhead ground wire 1: $2.448 + j1.748 \Omega/\text{mi}$

Overhead ground wire 2: $2.448 + j1.748 \Omega/\text{mi}$

Phase conductor currents [see Equations (5–7) and (12)]:

$$I_A(1)_1 = 13.060 + j287.362 \text{ A} \quad \text{Unfaulted phase}$$

$$I_B(1)_1 = 13.060 + j287.362 \text{ A} \quad \text{Unfaulted phase}$$

$$I_C(1)_1 = 387.681 - j2426.224 \text{ A} \quad \text{Faulted phase}$$

An intelligent choice of the faulted phase should be made to obtain the worst condition. Generally, the phase farthest from the overhead ground wire (or neutral) should be faulted. This implies a lower mutual impedance between the phase and neutral, causing lower shielding current in the neutral and forcing more current into the ground. Since phase C is faulted, the zero-sequence fault current, $I_C(1)_1$, flows in it toward this fault. Currents in the two unfaulted phases A and B are smaller and generally flow in the direction opposite to that of the faulted phase, that is, away from the fault, providing a shielding action and ultimately reducing the GPR. However, in some cases the reverse may be true, thereby producing antishielding. The induced overhead ground wire currents are calculated as shown in Equation (18).

$$I_{SK}(1)_1 = -224.57 + j222.288 \text{ A}$$

$$I_{SK}(2)_1 = -336.383 + j248.635 \text{ A}$$

where

$I_{SK}(1)_1$ is the induced current in the overhead ground wire, circuit 1, ROW 1;

$I_{SK}(2)_1$ is the induced current in the overhead ground wire, circuit 2, ROW 1.

Since the induced overhead ground wire current flows in the direction opposite to that of the faulted phase, it provides shielding action as well. The ratio of overhead ground wire to line current (shielding factor) is calculated as $(-0.030904 - j0.024471)$.

Inequality [Equation (20)] shows that the line becomes electrically infinite after the 31st span. Therefore, Equation (21) can be used and will result in a overhead ground wire/tower ladder network impedance for circuit 1 of $Z_\infty(1)$ of

$$Z_\infty(1) = 4.9536 + j2.0716 \Omega$$

This value is conservative because of the shorter line length.

ROW 2

Similar to ROW 1 calculations:

$$3I_{A0}(1)_2 = 581.9 - j3116.2 \text{ A}$$

$$I_{A1}(1)_2 = 1.774 - j15.64 \text{ pu}$$

Mutual impedances between each phase conductor and overhead ground wires 1 and 2 are the same for ROW 1. The same is true for the $Z_{\infty}(2)$, the network impedance for circuit 2. Phase conductor currents are calculated as

$$I_{A(1)2} = -7.919 - j404.735 \text{ A}$$

$$I_{B(1)2} = -7.919 + j404.735 \text{ A}$$

$$I_{C(1)2} = 597.737 - j3925.671 \text{ A}$$

The induced overhead ground wire currents are

$$I_{SK(1)2} = -398.117 + j390.386 \text{ A}$$

$$I_{SK(1)2} = -544.745 + j432.182 \text{ A}$$

The ratio of overhead ground wire to line current is $-0.30967 - j0.24474$, and the number of spans required for the electrically infinite overhead ground wire/tower ladder network is 31. The residual fault current, I_{GPR} [see Equation (22)], can be shown to be

$$I_{GPR} = -528.12 - j3674.21 \text{ A}$$

The GPR [see Equation (24)] will be 1580.88 V, where Z_{GPR} is equal to $0.43 + j0.03 \Omega$, calculated with Z_{SG} equal to 0.5Ω .

5.1.13.4.2 44 kV bus fault

For all of the 44 kV bus faults, $3I_{A0T}$ is generated locally, resulting in a negligible GPR.

5.1.13.4.3 44 kV line fault

Because ROW 3 carries a three-wire (no neutral) circuit, the circuit in Figure 10 can be used to calculate the 44 kV line fault as follows:

- The prefault voltage (V_p) is 46 000 V.
- The 44 kV line zero-sequence current contribution (see Figure 10a) is $3I_{A0}(1)_3$ equals 0 A.

The low-side (LS) transformer contribution, I_T , is $855 - j16\,911 \text{ A}$. The total LS fault current is $3I_{A0T} = 855 - j16\,911 \text{ A}$; and the 230 kV zero-sequence current contribution, I_N , is 0 A. The system impedance at the faulted 44 kV (bus) terminal, Z_S , is $0.11 + j1.91 \Omega$. The calculated LS line fault GPR, which takes into account the impedance of the line up to the point of the fault, is 5620.64 V. As a matter of interest, the fault impedance, Z_a (see Figure 3), of 5Ω will reduce the GPR to 1929.2 V and illustrates the need to include the appropriate value of the fault impedance in some cases.

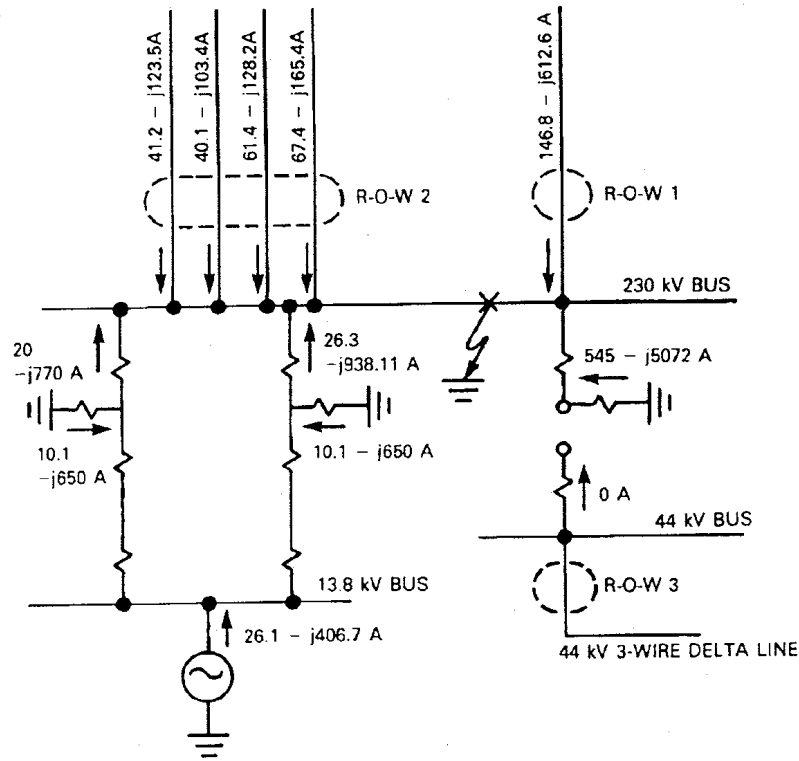
5.1.14 Example 2: HV line fault

5.1.14.1 System data

The generating station (Figure 10) has three voltage levels:

- ROW 1 has a tower line carrying a single 230 kV circuit with 795.0 ACSR 26/7 conductors and two 3/8 in (9.5 mm) steel overhead ground wires. The tower-footing impedance is 79.57Ω , and the average span is 924 ft (282 m). Earth resistivity, assumed to be uniform, is $1000 \Omega\cdot\text{m}$.

- b) ROW 2 has tower lines carrying four 230 kV circuits with 795.0 ACSR 26/7 conductors and four 3/8 in (9.5 mm) steel overhead ground wires. The average span and the earth resistivity are the same as in ROW 1.
- c) The 44 kV bus is connected to the 230 kV bus by means of a delta grounded wye-connected transformer. A three-wire (no neutral) 44 kV circuit is on ROW 3.
- d) 13.8 kV is the generation voltage level.



Prefault voltage = $1.04545 + j0$ pu
 Base voltage = 220 kV
 $3I_{A0T} = 948 - j8714$ A
 $Z_0 = 0.00295 + j0.02518/0.02555$ pu

(a) L-G fault

Figure 10—230 kV bus fault

5.1.14.2 Worst-fault location determination

- a) *230 kV fault.* In Figure 10a, the vectorial sum of all transmission and distribution line contributions for the 230 kV bus fault is I_L .

$$I_L = \sum_r \sum_j (3I_{A0}(J)_r) = 3I_{A0T} = 356.9 - j1133.3 \text{ A}$$

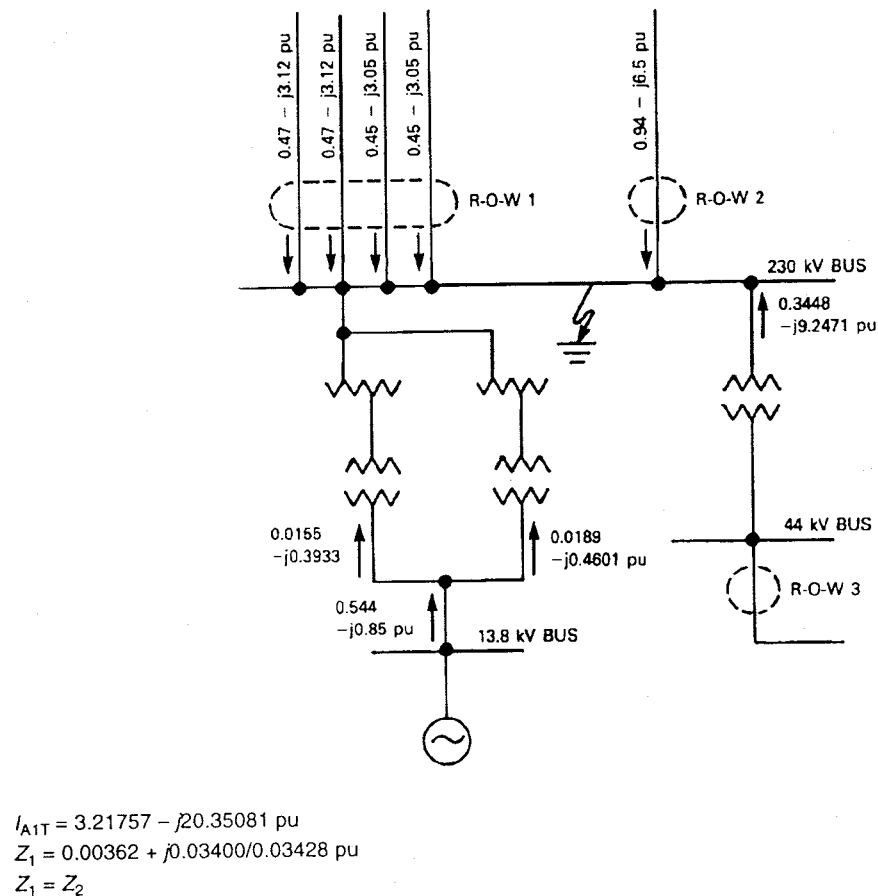
Local ground sources contribute $I_T = 591.1 - j7580.7$ A.

Because I_T is greater than I_L , the greatest GPR will be caused by a fault occurring along one of the four HV lines. The 230 kV bus fault will produce less GPR than the line fault.

- b) *44 kV fault.* As seen in Figure 10a, the station 230/44 kV transformer has a delta-connected secondary. Assuming a delta-connected primary at the station to which the 44 kV line is connected (at the other end), zero-sequence fault currents are negligible. The only impedance-to-ground is due to capacitive coupling, that is, line charging currents will flow, which implies that both 44 kV bus and line faults will produce an insignificant GPR at the station under study.
- c) *13.8 kV fault.* Essentially all the 13.8 kV fault current generated circulates locally; therefore, no appreciable GPR will be developed due to the L-G fault at the generator terminals.

5.1.14.3 Worst-fault type

In Figures 10a and 10b, for the 230 kV faults, the positive-sequence system reactance as seen from the fault terminals is X_1 equals 0.03408 pu and zero-sequence reactance is X_0 equals 0.02518 pu.



(b) Three-phase fault

Figure 10—230 kV bus fault

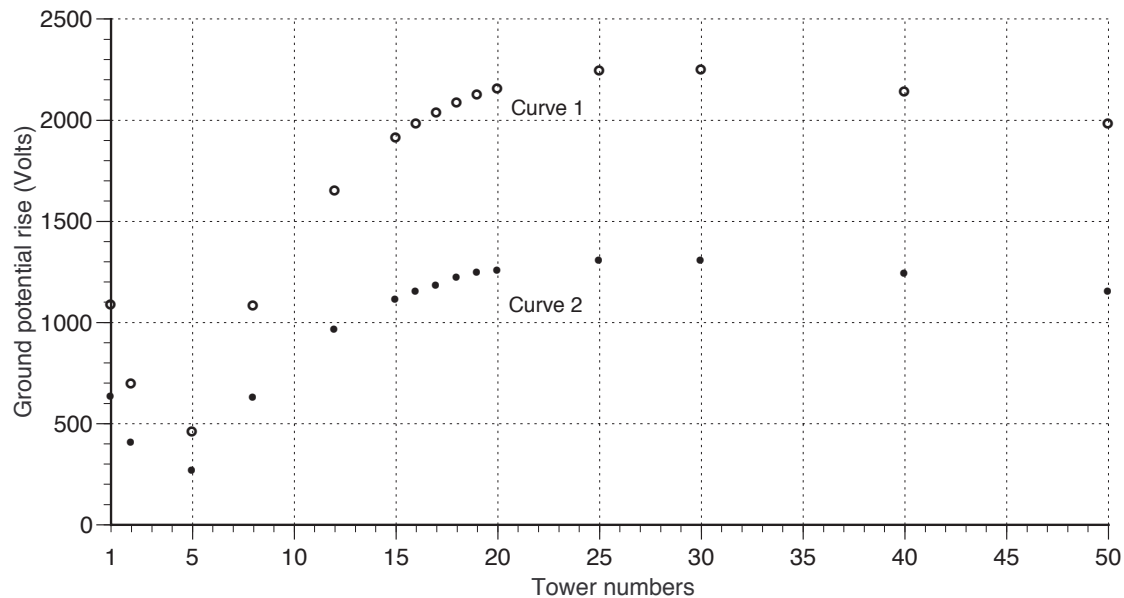
Because X_1 is greater than X_0 , a 2L-G fault will cause a higher zero-sequence fault current, resulting in a greater GPR than a single L-G fault. However, this example is limited to a single L-G fault.

5.1.14.4 GPR calculations

As mentioned in 5.1.11, this calculation is complex and will not be shown here.

A sample of a computer program output is shown in Table 2.

Left station GPR versus tower number, as counted from the left station, is shown in Figure 11 and is seen peaking for the fault occurring on the 30th tower out of the left station, at 2216.965 V.



Curves 1 and 2 correspond to the following left and right grid resistance values (RGL, RGR):

	RGL	RGR
Curve 1	1.000 Ω	1.000 Ω
Curve 2	0.500 Ω	0.500 Ω

Maximum GPR (2216.965 V) peaks for the fault occurring on the 30th tower out of the left station.

Figure 11 — Left station potential versus tower numbers

5.2 Duration of the fault and its relationship to wire-line telecommunication requirements for power system protection

The duration of the fault currents and resulting interfering voltages depends upon the power system protective relay scheme and its equipment, as well as the power system layout and equipment. The relaying schemes often employ wire-line telecommunication facilities.

5.2.1 Time required to clear a fault

The time required to clear a fault usually falls into one of the following categories:

- Surge arresters.* Lightning surges that are cleared by arresters on the power circuits in less than half a cycle require no circuit breakers to open and no fuses to melt. When rapid clearing takes place, no power system telecommunication is necessary to clear this fault.

Table 2—Sample computer program output

From Left Station (Tower)	Left station ground resistance (L Res) (Ω)	Right station ground resistance (R Res) (Ω)	Ground current from left station ($L I_g$) (A)	Ground current from right station ($R I_g$) (A)	Skywire current from left (Max L I_{skwire}) (A)	Skywire current from right (Max R I_{skwire}) (A)	Faulted tower current from left (I_{T1}) (A)	Faulted tower current from right (I_{T2}) (A)
1	1.000	1.000	1057.450	435.603	3355.020	391.797	69.018	0.000
1	0.500	0.500	1230.460	506.631	3392.419	356.077	63.996	0.000
2	1.000	1.000	667.482	443.967	3095.051	591.347	109.798	0.000
2	0.500	0.500	776.396	516.409	3100.512	566.984	106.911	0.000
5	1.000	1.000	426.452	468.129	2510.236	380.940	190.726	0.000
5	0.500	0.500	496.037	544.514	2505.393	985.201	191.699	0.000
8	1.000	1.000	1050.195	491.035	2166.461	1135.743	232.181	0.000
8	0.500	0.500	1221.556	571.159	2154.902	1196.713	234.482	0.000
12	1.000	1.000	1617.079	519.809	1901.428	1300.497	255.396	0.000
12	0.500	0.500	1890.932	604.719	1999.775	1912.195	257.842	0.000
15	1.000	1.000	1882.202	540.435	1779.510	1325.923	260.495	0.000
15	0.500	0.500	2189.322	628.618	1769.961	1335.929	262.598	0.000
16	1.000	1.000	1947.792	547.099	1747.486	1327.927	260.978	0.000
16	0.500	0.500	2265.602	636.369	1738.723	1337.254	262.841	0.000
17	1.000	1.000	2003.913	553.674	1719.599	1327.717	260.903	0.000
17	0.500	0.500	2330.892	664.020	1710.607	1336.331	262.623	0.000
18	1.000	1.000	2051.594	560.172	1692.302	1325.706	260.361	0.000
18	0.500	0.500	2406.354	651.575	1685.076	1333.620	262.038	0.000
19	1.000	1.000	2091.729	566.599	1669.200	1322.265	259.625	0.000
19	0.500	0.500	2453.036	659.039	1661.694	1329.450	261.162	0.000
20	1.000	1.000	2125.121	572.929	1645.937	1317.691	259.656	0.000
20	0.500	0.500	2471.879	666.414	1640.106	1924.270	260.059	0.000
25	1.000	1.000	2214.006	603.607	1553.872	1294.921	251.747	0.000
25	0.500	0.500	2575.266	702.099	1550.695	1239.795	252.599	0.000