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Personal Protective Grounding for Electric Power Facilities and Power Lines

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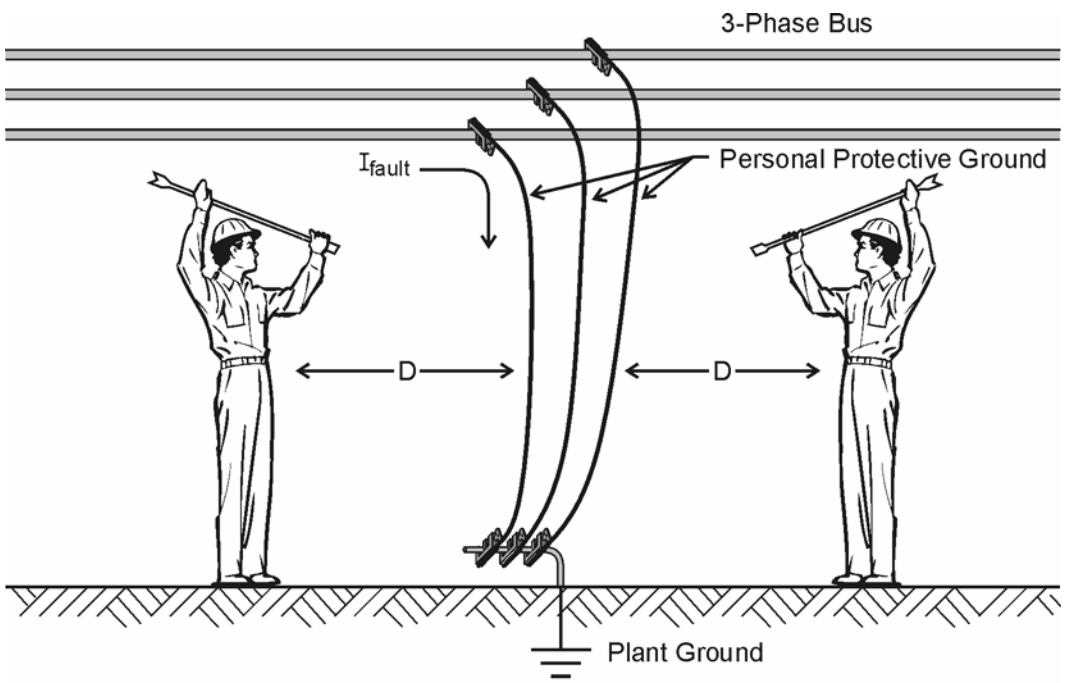
RECLAMATION

Managing Water in the West

Facilities Instructions, Standards, and Techniques
Volume 5-1

Personal Protective Grounding for Electric Power Facilities and Power Lines



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14. ABSTRACT
The purpose of this document is to establish clear and consistent instructions and procedures for temporary grounding of de-energized and isolated high-voltage equipment (over 600 volts) for the purpose of bare-hand contact.

These instructions and procedures supplement the requirements in Reclamation Safety and Health Standards. Adherence to these procedures will enable workers to perform their duties with maximum confidence and safety. In the event of a difference between the requirements in this FIST and those contained in the Reclamation Safety and Health Standard, the more rigorous requirement shall apply.

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Volume 5-1

Personal Protective Grounding for Electric Power Facilities and Power Lines

Hydroelectric Research and Technical Services Group
Infrastructure Services Division

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Bureau of Reclamation
Denver, Colorado

July 2005

DISCLAIMER

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PERSONAL PROTECTIVE GROUNDING FOR ELECTRIC POWER FACILITIES AND POWER LINES

1. PURPOSE AND SCOPE

1.1 Purpose

This Facilities Instructions, Standards, and Techniques (FIST) Volume is to establish clear and consistent instructions and procedures for temporary grounding of de-energized and isolated high-voltage equipment (over 600 volts) for the purpose of bare hand contact. This FIST applies to those facilities of the Federal power and water systems for which the Bureau of Reclamation (Reclamation) and its contractors and agents are responsible, and includes power and pumping plants, switchyards and substations, and transmission lines.

A current copy of this document shall be readily available at each Reclamation office and facility and to each employee that works on equipment required to be protective grounded. A quick reference guide to grounding procedure contained in this FIST is presented in flow chart format in appendix G.

1.2 Scope

These instructions and procedures supplement the requirements in Reclamation Safety and Health Standards, "yellow book". [1] Adherence to these procedures will enable workers to perform their duties with maximum confidence and safety. In the event of a difference between the requirements in this FIST and those contained in the Reclamation Safety and Health Standard, the more rigorous requirement shall apply.

1.3 Responsibility

Any employee working on de-energized high-voltage equipment is responsible for understanding protective grounding requirements and procedure. Facility managers and supervisors are responsible for ensuring that workers are knowledgeable of and comply with grounding procedure in this FIST. Only trained and qualified workers shall apply and remove temporary personal protective grounds.

1.4 Cancellation

This FIST Volume replaces FIST Volume 5-1, Personal Protective Grounding, dated January 1993.

2. DEFINITIONS AND INTERPRETATIONS

Exposure voltage. A short-duration difference in potential between conductive objects that a person may contact when personal protective grounds or a grounding system conduct fault current. Also applicable to transferred potential between separately grounded systems (stations), or difference in earth surface potentials.

Grounding (ground). The connection of conductive parts of lines, structures, and equipment to earth or other conductive medium (grounding system) that substitutes for earth, e.g. station ground mat conductors.

Grounded worksite. A work area that is made an equipotential safe working zone by the application of personal protective grounds.

Personal protective grounding (grounds). Cable connected to de-energized lines and equipment by jumpering and bonding with appropriate clamps, to limit the voltage difference between accessible points at a worksite to safe values if the lines or equipment are accidentally re-energized. Protective grounds are sized to carry the maximum available fault current at the worksite. Also called ground jumper.

Static ground. Any grounding cable or bonding jumper (including clamps) that has an ampacity less than the maximum available fault current at the worksite, or is smaller than #2 A.W.G. (American Wire Gage) copper equivalent. Static grounds are used for potential equalizing between conductive parts in grounding configurations that cannot subject them to significant current. Therefore, smaller wire which provides adequate mechanical strength is sufficient (e.g. #12 A.W.G.).

Station. For protective grounding purposes, any electrical facility with a grounding electrode system (ground mat) which bonds all conductive, non-current carrying parts of equipment and for the control of surface potential gradients. Two or more distinct but adjacent facility grounding electrode systems that are intentionally bonded (e.g. a powerplant and adjacent switchyard grounding systems) may be considered a common station grounding system. Grounding systems that are intentionally bonded but not physically adjacent are considered separately grounded.

Step voltage. The difference in surface potential experienced by a person bridging a distance of one meter with the feet without contacting any other grounded object. [5]

Touch voltage. The difference in potential between a grounded structure or station and the surface potential at the point where a person is standing while at the same time having a hand in contact with the grounded structure or object. [5]

Transferred touch voltage. A special case of touch voltage where a voltage is conducted toward or away from a grounded structure or station to a remote point. A transferred touch voltage (potential) can be contacted between the hands or hands and feet.

Fault circuit impedance X/R ratio. Ratio of reactance to resistance of the electrical impedance of a faulted (short) circuit from the source of fault current to the location of the fault on the circuit.

Line terminal and equipment ground switches. Permanently installed mechanical switches which are kept in the open position until utilized to ground line or equipment conductors during periods of maintenance.

Note: Throughout this document supporting narrative is provided in italic print to emphasize text and offer background information to the reader.

3. DETERMINE NEED FOR PERSONAL PROTECTIVE GROUNDING

3.1 Uses Permitted

The primary purpose of personal protective grounding is to provide adequate protection against electrical shock causing death or injury to personnel while working on de-energized lines or equipment. This is accomplished by grounding and bonding lines and equipment to limit the body contact or exposure voltages at the worksite to a safe value if the lines or equipment are accidentally energized from any source of hazardous energy. The greatest source of hazardous energy in most cases is direct energization of lines or equipment from the power system.

Other sources of hazardous energy may include:

- stored energy (capacitors)
- static build-up
- faulted equipment
- electromagnetic coupling
- high-voltage testing
- instrument transformer back-feed

3.1.1 Over 600 volts (Required). Personal protective grounding shall be applied to de-energized lines and equipment having a nominal voltage rating over 600 volts if exposed normally current-carrying parts are to be contacted or approached within the minimum approach distances given in table 1. Other nearby exposed parts of any electrical equipment rated over 600 volts which are not associated with the work, but may be approached within the minimum distance during the work activities, shall either be de-energized and grounded or suitably isolated to prevent contact.

Table 1
AC Minimum Approach Distance for Electrical Workers

Nominal voltage phase-to-phase (kV)	Altitude (ft.)									
	≤3000	4000	5000	6000	7000	8000	9000	10000	12000	14000
.301 to .750	1-4 for all altitudes									
.751 to 15	2-2	2-3	2-3	2-4	2-5	2-6	2-6	2-7	2-9	2-10
15.1 to 36	2-4	2-5	2-5	2-6	2-7	2-8	2-9	2-10	2-11	3-0
36.1 to 46	2-7	2-8	2-9	2-9	2-10	2-11	3-0	3-1	3-3	3-4
46.1 to 72.5	3-0	3-1	3-2	3-3	3-4	3-5	3-6	3-7	3-9	3-11
72.6 to 121	3-2	3-3	3-4	3-5	3-6	3-7	3-9	3-10	4-0	4-1
138 to 145	3-7	3-8	3-9	3-10	4-0	4-1	4-2	4-4	4-6	4-8
161 to 169	4-0	4-1	4-2	4-4	4-5	4-7	4-8	4-10	5-0	5-2
230 to 242	5-3	5-4	5-6	5-8	5-10	6-0	6-2	6-4	6-7	6-10
345 to 362	8-6	8-8	8-11	9-2	9-5	9-8	9-11	10-2	10-8	11-1
500 to 550	11-3	11-6	11-10	12-2	12-6	12-10	13-2	13-6	14-1	14-8

Note: All distances in feet-inches, phase-to-ground exposure. For phase-to-phase exposure, refer to OSHA CFR 29 1910.269, Table R-6.

3.1.2 Less than 600 volts (Optional). Grounding of equipment and circuits rated 600 volts or less is optional. Equipment and circuits operating below 600 volts can be just as deadly under the right conditions as higher voltage equipment. However, application of personal protective grounds on circuits below 600 volts may create unnecessary hazards due to limited approach distances and close proximity between conductors and grounded parts of equipment. If equipment or circuits are not grounded, they shall be rendered safe from hazardous energy through Job Hazard Analysis and facility Hazardous Energy Control Procedure (clearance, lockout/tagout, personal protective equipment, etc.).

3.2 Uses Not Permitted

3.2.1 Lightning

For de-energized, grounded work on transmission lines, switchyards and substations, personal protective grounds cannot be relied upon to provide adequate safety from a direct or indirect lightning strike within the line of sight. Therefore, work shall not be performed while there is any indication of lightning in the area.

3.2.2 Over 50,000 Amperes Available Fault Current

Extreme electromechanical separation forces are developed in ground cables for currents exceeding 50,000 amperes, symmetrical. Mechanical failure of the ground cable assembly is likely. The method of double-isolation grounding using equipment ground switches (paragraph 7.2) is recommended in lieu of conventional direct application of protective grounds in power and pumping plants.

3.2.3 Non-Temporary Installations

Personal protective grounding is intended for temporary grounding during installation, maintenance, and repair or modification of lines and equipment. It is not intended to substitute for a prolonged or permanent plant or station equipment grounding connection which should be provided by permanent grounding and wiring methods.

4. BASIC CRITERIA FOR SAFE GROUNDING PRACTICES

Personal protective grounds must be designed, fabricated, and applied at the worksite in a manner that satisfies the following six basic criteria:

1) Maximize personal safety while working on de-energized high-voltage equipment through the use of appropriate protective grounding equipment, procedure, and training.

2) Limit worksite exposure voltages to a safe level during accidental energization.

3) Promote prompt operation of protective devices.

4) Ensure that protective grounds will not fail under the most severe fault conditions.

5) Provide the final energy barrier in the facility hazardous energy control program under direct control of personnel at the worksite.

6) Meet minimum maintenance performance tests.

The **Golden Rule** for on the job personal electrical safety around de-energized lines and equipment is:

High-voltage lines and equipment shall be considered energized until protective grounds are installed. Until grounded, minimum approach distance applies.

4.1 Electric Shock Hazard

It is current through the body that causes electric shock or electrocution. The potential difference a person may contact between conductive parts of equipment or between equipment and ground is important because this voltage forces current through the body according to Ohm's law. Therefore, current through the body increases with lower body resistance and also increases with higher contact voltage. Hazardous conditions may develop that place the worker's body in series or parallel with circuits that can produce a current through the body (figure 1). Personal protective grounding is a special case of the parallel circuit where low-resistance grounding cable is in parallel with the worker to shunt current away from the body.

The accepted minimum value of body resistance is 500 ohms for electric shock hazard analysis. Although the resistance between hands with dry skin can range from 5,000 to 50,000 ohms, punctured skin reduces the body resistance to about that of salt water which is very low. Voltages above 240 volts readily penetrate dry skin, leaving a small, deep burn. Appendix A gives established criteria on the effects of current through the body.

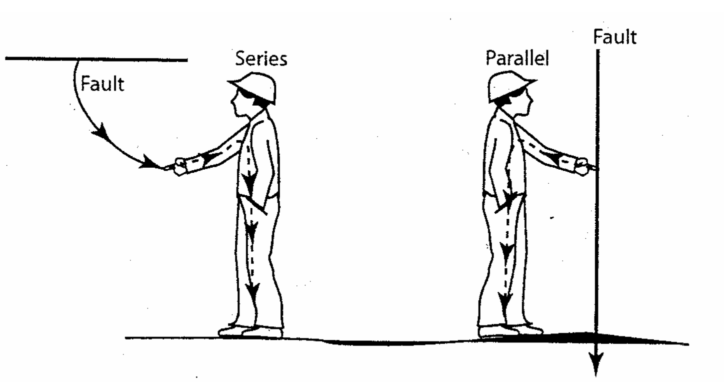


Figure 1. – Body Current Path.

The maximum safe body current for short periods of time is given by Dalziel's equation (appendix B) and is an inverse function of time. Higher currents are permitted for shorter periods of time. Shock durations, or human exposure times for temporary personal protective grounding applications are determined from typical power system fault clearing times as follows:

1) Thirty cycles (1/2 second) for transmission and distribution lines;

2) Fifteen cycles (1/4 second) for switchyards and substations; or

3) Fifteen cycles (1/4 second) for power and pumping plants.

These fault clearing times are based on typical protective relaying and circuit breaker operating times. Plants and switchyards generally are protected by high-speed current differential relays with faster operating times compared to transmission lines employing zone distance relaying. It is emphasized that these fault clearing times are typical; grounding applications with known longer fault clearing times should be used in place of these typical values. However, shorter clearing times should not be used. Consult the TSC Hydroelectric Research and Technical Services Group if different fault clearing times appear necessary for a particular grounding application.

Maximum safe body currents based on the above fault clearing times and the Dalziel equation are 200 milliamperes for 15 cycles and 150 milliamperes for 30 cycles (see derivation, appendix B). The resulting maximum safe body contact voltages are:

15-cycle clearing — 100 volts (200 mA); for plants, switchyards and substations

30-cycle clearing — 75 volts (150 mA); for transmission and distribution lines

4.2 Protective Grounding Requirements

Each region shall implement procedures to ensure the adequacy of protective grounds and shall periodically review grounding practices at each facility to determine the proper size, length, and number (if parallel grounds are required) of protective grounds. Regions shall maintain and periodically update a listing of the maximum fault currents at each facility or location where Reclamation employees apply protective grounds. These reviews should be conducted at 5-year intervals[1] or sooner if change in equipment or system conditions call for specific revision.

Protective ground cables and associated grounding equipment shall meet the following requirements:

[1] Refer to FIST Volume 4-1B, Maintenance Scheduling For Electrical Equipment, Section 25, April 2001

1) Capable of conducting the maximum fault current which could occur at the grounded worksite if the de-energized line or equipment becomes energized from any source and for the fault clearing times stated in paragraph 4.1.

A ground or jumper which is sized to conduct maximum available fault current should be adequate to safely conduct currents from other sources of hazardous energy stated in Section 3, including steady-state currents induced by electromagnetic coupling from nearby energized lines or equipment.

2) Capable of carrying the maximum available fault current, including dc offset current due to waveform asymmetry for high values of fault circuit impedance X/R ratio. Refer to Section 5 for cable ampacity information and Section 6 for conductor sizing procedure.

3) Capable of withstanding a second energization within 30 cycles after a first inadvertent energization (paragraph 6.2.1).

4) Applied at the worksite in a manner that the worker exposure or body contact voltage does not exceed the values given in paragraph 4.1 while the ground cables are conducting fault current. Refer to Section 6 for procedure to determine worker exposure voltage.

5) Connected directly to the equipment, bus, or conductor to be grounded. No impedance or device (circuit breaker, disconnect switch, transformer, line trap, etc.) shall be permitted in series between the point of connection of the protective grounds and location of contact by the workers.

6) Be easy to apply, satisfy the requirements of field application conditions, utilize minimum time and preparation for installation, and cover a wide range of usefulness. Standardization, to the extent practical, is desirable at each location to keep the number of sizes and types to a minimum.

7) Fabricated as an assembly of suitably rated components (conductor, ferrules, clamps) to withstand thermal and electro-mechanical stresses imposed while conducting fault current (Section 5).

8) Stored and transported properly to avoid damage and maintained in good working order (Section 10).

9) Equipment and line terminal ground switches shall not be substituted for personal protective grounds. However, ground switches may be closed in

parallel with protective grounds to reduce fault current through the ground cables and lower the worker exposure voltage at the worksite. Ground cables must be sized for the maximum available fault current, without benefit of any reduction in current due to closed ground switches.

Some types of ground switches are designed for static grounding of equipment and will not carry fault current. Check ground switch ratings before closing in parallel with protective grounds. See also the caution for closing ground switches into generators and motor, Section 7.

10) Temporary removal of protective grounds for testing de-energized equipment not permitted. Rather, protective grounds shall be installed in a manner that allows de-energized equipment under test to be safely isolated from protective grounded circuit(s) for the duration of the test.

The method of double-isolation grounding (paragraph 7.2) provides an effective means of isolating equipment for testing.

5. GROUND CABLE ASSEMBLIES

Personal protective grounds consist of an assembly of appropriate lengths of suitable copper cable with electrically and mechanically compatible ferrules and clamps at each end (figure 2). Cable shall be of continuous length; splices are not permitted. The assembly must withstand thermal and mechanical stresses imposed by fault currents up to the rating of the component parts. Ground cable assemblies shall meet material and electrical specifications of ASTM F 855 [4]. Ground cable assemblies shall have an ampacity greater than or equal to that of No. 2 AWG copper. Therefore, No. 2 AWG conductor is the minimum size allowed.

5.1 Grounding Cable

Most of the grounding cable in use actually is manufactured as welding cable. These extra-flexible copper cables and their insulating jackets are suitable for grounding cable. Annealed copper conductor is mandatory; do not use aluminum.

Continuous flexing of the cable eventually breaks the conductor strands beneath the jacket, typically at the ferrules, and aluminum strands fail faster than copper.

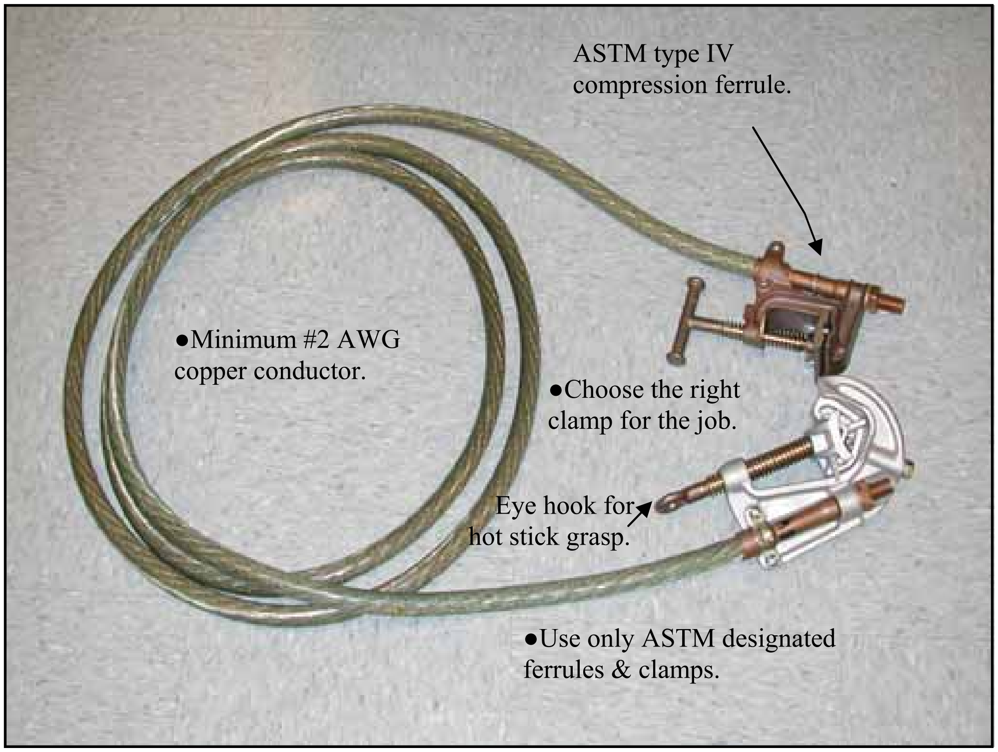


Figure 2. – Personal Protective Ground Cable Assembly.

5.1.1 Cable Ampacity. Grounding cable must be sized adequately to carry the maximum available fault current at the worksite as required in paragraph 4.2. In many cases not all electrical equipment which can contribute fault current is in service or it can be put into a condition that it cannot contribute current. Check the methods in paragraph 6.1 for determining available fault current to avoid unnecessary large ground cable.

Ground cables shall be sized in accordance with the fault current withstand ratings given in tables 2A and 2B. Withstand ratings are approximately 70 percent of the ultimate (melting) current capacity of new copper conductor. This provides a margin of safety to prevent in-service failure and to allow the ground cable to be reused after being subjected to fault current. Use table 2A if the fault circuit impedance X/R ratio is below 10, or table 2B if the ratio is above 10. If the X/R ratio is unknown, use the values in table 2B. Generally, X/R ratios tend to be above 10 for locations near generation sources (plants and switchyards), and lower for transmission lines. Do not use cable smaller than No. 2 AWG even if the maximum available (calculated) fault current is less than shown in the tables.

Table 2A
Withstand Ampacity of Copper Grounding Cable, X/R<10
(currents are kA rms, symmetrical, 60 Hz)

Cable size (AWG or kcmil)	Nominal cross section (mm^2)	15 cycles (250ms)	30 cycles (500ms)	45 cycles (750ms)	60 cycles (1 s)
Less than #2	Not permitted for personal protective grounds.				
#2	33.6	14	9	7	7
#1	42.4	16	12	9	8
1/0	53.5	21	15	12	11
2/0	67.4	27	19	16	14
3/0	85.0	34	24	20	17
4/0	107.2	43	30	25	22
250	126.7	52	37	30	26
350	177.4	72	51	42	36

Note: Cable currents are in rms symmetrical amperes, without ampacity derated for heating effect of dc offset current. Currents are approximately 70% of values from ANSI F855, table 3c. [4]

Table 2B
Withstand Ampacity of Copper Grounding Cable, X/R>10
(currents are kA rms, symmetrical, 60 Hz)

Cable size (AWG or kcmil)	Nominal cross Section (mm^2)	15 cycles (250ms)	30 cycles (500ms)	45 cycles (750ms)	60 cycles (1 s)
Less than #2	Not permitted for personal protective grounds.				
#2	33.6	12	9	7	6
#1	42.4	14	11	9	7
1/0	53.5	18	14	12	10
2/0	67.4	23	18	14	13
3/0	85.0	29	22	19	16
4/0	107.2	37	28	23	21
250	126.7	44	33	28	24
350	177.4	61	47	39	35

Note: Cable currents are in rms symmetrical amperes, with ampacity derated for additional heating effect of dc offset current, illustrated in figure 3 below. Currents are approximately 70% of values from ASTM F855, table 3a. [4]

Figure 3. – Oscillogram showing effect of dc offset current on total asymmetrical current for high value X/R ratios. The dc component of current decays more slowly with increasing X/R ratio. Asymmetrical current produces more heating in protective ground cable than the symmetrical or ac component alone. For X/R ratios below about 10, the dc component decays relatively fast and has negligible effect on cable ampacity given in Table 2A.

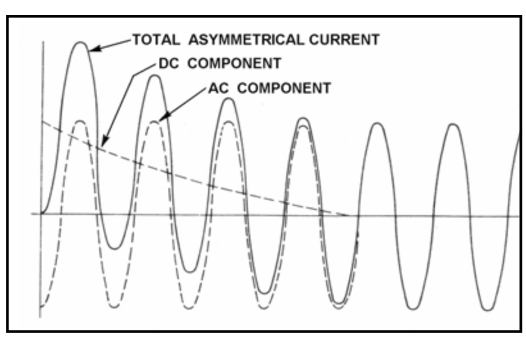


Figure 3.

5.1.2 Parallel Grounds. In grounding applications where a single personal protective ground cable does not have the necessary withstand current rating, or would require an unacceptably large conductor, identical ground cables may be connected in parallel. To account for unequal current division between parallel grounds, derating multipliers should be applied as follows.

Ampacity of Paralleled Protective Ground Cables

Current Rating of	=	Current Rating of One Cable
Two parallel cables		x 1.8
Three parallel cables		x 2.6

For example, two parallel No. 2/0 AWG copper cables, each rated 27,000 amperes for 15 cycles (Table 2A) would have a combined rating of 27,000 x 1.8 = 48,600 amperes (instead of 54,000).

Paralleling more than three ground cables is not recommended. Refer to paragraph 6.6.4 for discussion on proper installation of parallel grounds.

5.2 Grounding Cable Jackets

Welding cables are nominally insulated for 600-volts. When used as grounding cable, the insulation or jacket serves primarily for mechanical protection of the conductor. It also serves to control the point at which the intentional ground, or bonding connection is made. Flexible elastomer or thermoplastic jackets are manufactured, applied and tested according to ASTM F 855. Black, red and yellow jackets are usually neoprene rubber compounds, while clear jackets are ultraviolet-stabilized polyvinyl chloride. Clear jackets are preferred because they allow easy inspection of the conductor strands for breakage, but may not be as resistant to cold weather as rubber compounds. All jackets should have the AWG size and conductor type stamped or printed repeatedly along the length of cable.

5.3 Grounding Clamps

Grounding clamps are normally made of copper or aluminum alloys, are sized to meet or exceed the ampacity of the cable with which they are used, and are designed to provide a strong mechanical and low resistance connection to the conductor or object to be bonded. Clamps, like the cable, should be rated for the maximum fault current and duration to which they can be subjected without damage or separation from the work. Clamps should conform to the material strength and withstand ampacity specifications (grades) of ASTM F 855 and should have a grade number based on the conductor size determined from paragraph 5.1.

5.3.1 Clamp Types. Grounding clamps are manufactured in, but are not limited to, four types according to their function and methods of installation as follows:

a. *Type I* clamps, for installation on de-energized conductors equipped with eyes for installation with removable hot sticks.

b. *Type II* clamps, for installation on de-energized conductors having permanently mounted hot sticks.

c. *Type III* clamps, for installation on permanently grounded conductors or metal structures with tee handles, and/or eyes or square or hexagon head screw(s).

d. Other types of special clamps, such as those for cluster grounds, may be made, tested, and certified by a manufacturer as meeting the requirements of ASTM F 855.

Use the right clamp with jaws for the material and shape of conductor or object to be clamped. The design of commercially available grounding clamps takes into consideration thermal and mechanical stresses developed by the magnitude of fault currents they may be required to conduct. Clamp design and integrity are then proven by rigorous tests before a manufacturer puts the clamp on the market. Therefore, no specialized field-fabricated clamps should be used for personal protective grounding without meeting ASTM specifications. A sample of commercially available ground clamps is shown in figure 4.

The ball-and-socket clamp (*type I*) is recommended for permanent grounding fixtures on generator bus, metal-clad switchgear, and large cables. The ball stud is permanently attached to the bus or cable. Socket clamps only shall be used on a ball of size and shape designed for the specific socket type clamp. An insulating boot is available to protect from flashovers in enclosures (figure 5).

5.3.2 Clamp Jaws. Clamps may be furnished with smooth jaws for installation on copper, aluminum, or silver-plated buswork without marring the bus. Clamps also may be furnished with serrations or crosshatching designed to abrade or bite through corrosion products on surfaces of a conductor or the metal structure. Several styles of conductor and ground-end clamps have jaws

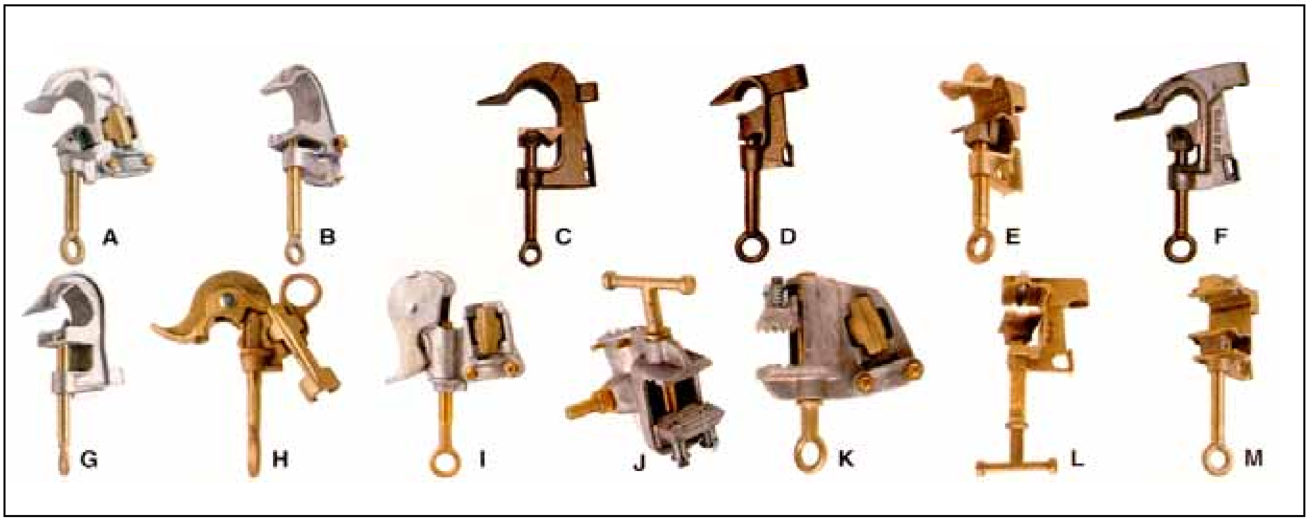


Figure 4. – Example of commercially available ground clamps. Clamps *A* through *I* have jaws suitable for attachment to circular shaped conductor, while *J* through *M* are for flat surface or bus-bar conductor. Only use clamps designed to correctly fit the shape of conductor to be clamped. Note that several of the clamps shown in the figure have wire compression type fittings for attachment of the ground cable; this is not permitted and similar clamps are available with approved threaded-stud type compression ferrules (figure 6.).

which can be replaced when the serrations have worn down. Self-cleaning jaws are recommended for conductor-end clamps used on aluminum or ACSR (aluminum conductor steel reinforced) conductor. Several styles of ground-end clamps provide a cup-point setscrew which can be tightened with a wrench (after serrated jaws have been tightened) to break through paint, rust and corrosion on the surface to be clamped.

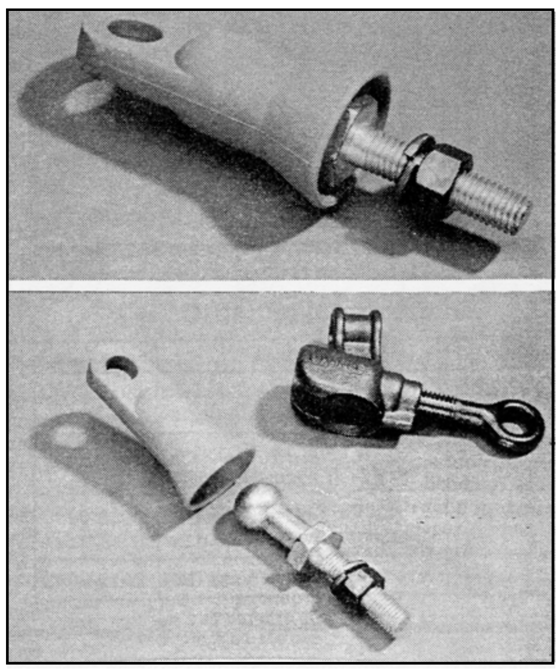


Figure 5. – Example ball-and-socket ground clamp with insulating boot.

5.4 Ground Cable Ferrules

Ferrules are required to attach the fine-stranded grounding cables to the clamps in a connection that is both electrically capable of conducting the required fault current, and mechanically strong enough to sustain the electromagnetically induced forces which may be imposed on the cables during faults. Like the clamps, grades for ferrules are specified in ASTM F 855 and they should have a grade number based on the conductor size determined from paragraph 5.1. Several types of ferrules are available; however, only threaded-stud compression ferrules shall be used. Example of an acceptable compression ferrule vs. an unacceptable wire compression fitting for protective grounds is shown in figure 6.

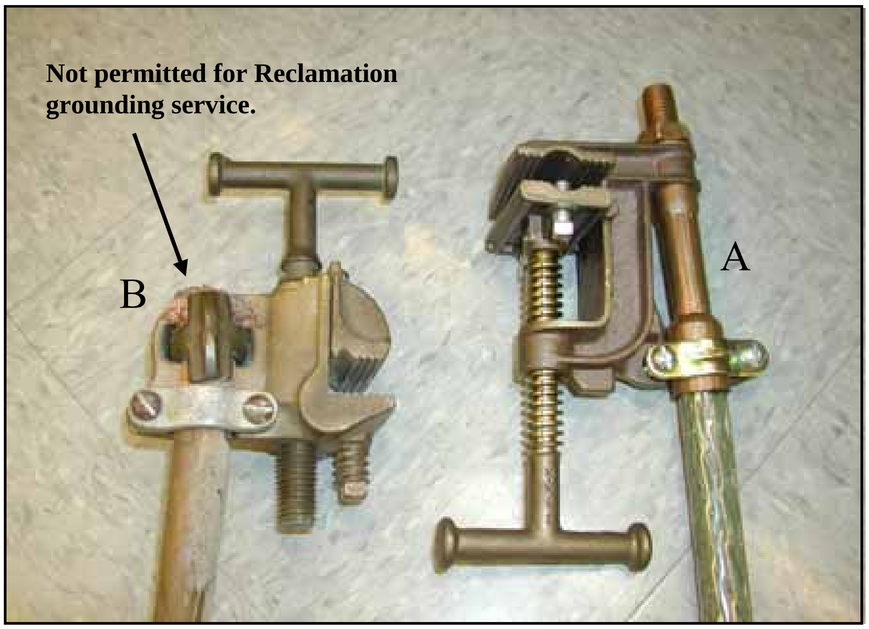


Figure 6. – Attachment of cable to grounding clamp. Acceptable threaded-stud compression ferrule (A) and unacceptable conductor-to-clamp wire compression fitting (B). Note these ground-end clamps provide tee handles for hand-tightening of the jaws (ASTM *type* III). Clamp jaws have setscrews to break through paint/corrosion on conductor to be clamped.

6. APPLICATION OF PROTECTIVE GROUND CABLES

The following procedures should be followed for installing and removing protective grounds. These procedures ensure that protective grounds will withstand the high mechanical stress imposed when conducting fault current while exposing workers to minimum body contact voltages by establishing an equipotential working zone at the worksite. A quick reference grounding procedure flow chart is provided in appendix G.

6.1 Determine Maximum Available Fault Current at Worksite

The maximum fault current for the personal protective ground application should be determined. Both the current magnitude and duration (clearing) time must be established to determine cable size (ampacity) and allowable cable length (worker exposure voltage). For fault studies involving synchronous machines (motors and generators), use subtransient reactance (X") to determine maximum current. The fault circuit impedance X/R ratio from the worksite back to the electrical source also should be determined. Reasonable assumptions may be made in the interest of reducing ground cable size and/or exposure voltage regarding the equipment or lines in service and the fault current that could occur during an unintentional re-energization.

a) For motor or generator bus grounding, only three-phase faults should occur for ungrounded or high-resistance neutral grounded units connected to a delta winding power transformer. Neutral grounding equipment must be properly maintained to make this assumption. Note three-phase bus fault currents are usually lower in magnitude than single-phase faults on rotating machines with solidly grounded neutrals.

b) For motor or generator bus grounding where a single unit is connected to a power transformer, the motor or generator source should be considered separately from the power system (choose the higher current contribution); it is unlikely that both would be energized simultaneously at the worksite.

c) Other plant equipment to be grounded (e.g. double-ended station service unit substation) having multiple sources or feeders which are not likely to be re-energized simultaneously may be considered separately. The source or feeder providing the highest fault current (single-phase-to-ground or three-phase) should be chosen. Multiple sources must be isolated from the grounded worksite under clearance and/or lockout/tagout.

d) For grounding the bus terminal of a transmission line, the bus fault current (single-phase-to-ground or three-phase, whichever is greatest) minus the line fault contribution to the bus should be calculated.

e) For transmission line grounding, consider the fault current contribution from each line terminal source separately (single-phase-to-ground or three-phase, whichever is greatest); it is unlikely that multiple line terminals would re-energize the line at the same time.

Regions may consult the TSC Electrical Design Group for assistance with calculating fault current.

6.2 Size the Cables

Ground cables shall be sized in accordance with the ampacity requirement and worker exposure voltage (ground cable voltage drop) limitation in paragraph 4.2 and the following:

6.2.1 Cable Size. Based on the calculated maximum fault current and circuit impedance X/R ratio and chosen clearing time at the worksite, select a cable size with an equal or higher ampacity from the tables in paragraph 5.1. Cables sized according to these tables should withstand fault current from an accidental first energization at the worksite without damage, the cables may be reused (after inspection), and the cables should withstand a second (reclosing) energization as required in paragraph 4.2. However, ground cables subjected to a second energization may be damaged from excessive heating and not suitable for reuse. A ground cable sizing example is provided in appendix C.

6.2.2 Cable Length. Personal protective grounds should be of adequate length for the job, but without excessive cable that must be laid out of the way. Excessive length increases the cable voltage drop or worker exposure voltage when the protective ground is conducting fault current. Slack in installed cables should also be minimal to reduce possible cable failure or injury to workers due to whipping action from fault currents. This is especially important in grounding applications at plants, where fault currents tend to be higher and ground cables may be closer spaced in proximity to the equipment.

Magnetic separation forces on protective grounds increase in proportion to the fault current magnitude squared and inversely with distance between conductors.

Worker exposure voltage is controlled by the ground cable impedance voltage drop when the grounds are conducting fault current. This voltage drop is dependent on the size and length of ground cable, available fault current at the worksite, and layout of installed cable in relation to the worker. Cable-worker geometry plays a significant role and can cause a substantial rise in exposure voltage due to the cable inductive reactance (ground loop effect), as opposed to considering only the cable resistance.

The following methods for predicting worker exposure voltage may be used to determine maximum length of ground cables. These methods are validated from grounded worksite staged-fault tests conducted by Reclamation at Hoover Powerplant [12] and on various high-voltage transmission lines in cooperation with other agencies. They are accurate for single-phase faulted worksite conditions and reasonably conservative for three-phase fault conditions.

A. Exposure Voltage Calculation for Plants and Switchyards/Substations

Step1: Calculate ground cable resistance (IR) voltage drop using conductor resistance given in Table 3 for the ground cable size determined from paragraph 5.1 (resistance of clamps and ferrules neglected). Multiply the conductor resistance value from the table by the ground conductor length (L), in feet, and by the fault current, in kiloamperes.

Cable resistance volt drop = milliohms/ft. x L(ft.) x fault current(kA)

Table 3
DC Resistance of Copper Welding Cable, in Milliohms per Foot

Conductor size, AWG or kcmil	20ºC	25ºC
2	0.165	0.168
1	0.130	0.133
1/0	0.103	0.105
2/0	0.0829	0.0846
3/0	0.0658	0.0671
4/0	0.0521	0.0532
250	0.0441	0.0450
350	0.0317	0.0323

NEMA WC 58-1997, Table 5-1 (combined ave. value for Class K & M conductors). Note: Choose resistance value from appropriate column for conductor temperature. For conductor temperatures other than shown in table, a resistance correction factor should be applied.

Step 2: Determine worker exposure voltage; multiply the ground cable resistance voltage drop (step 1) by factors K_m from tables 4A and 4B.

Exposure voltage = cable resistance volt drop x K_{m1} x K_{m2}

If grounds are installed between the worker and source of fault current, as shown in figure 7(A), use only Table 4A and make K_{m2} =1 in the equation. If the worker is positioned between the grounds and source of fault current, as shown in figure 7(B), use K_m multipliers from both tables.

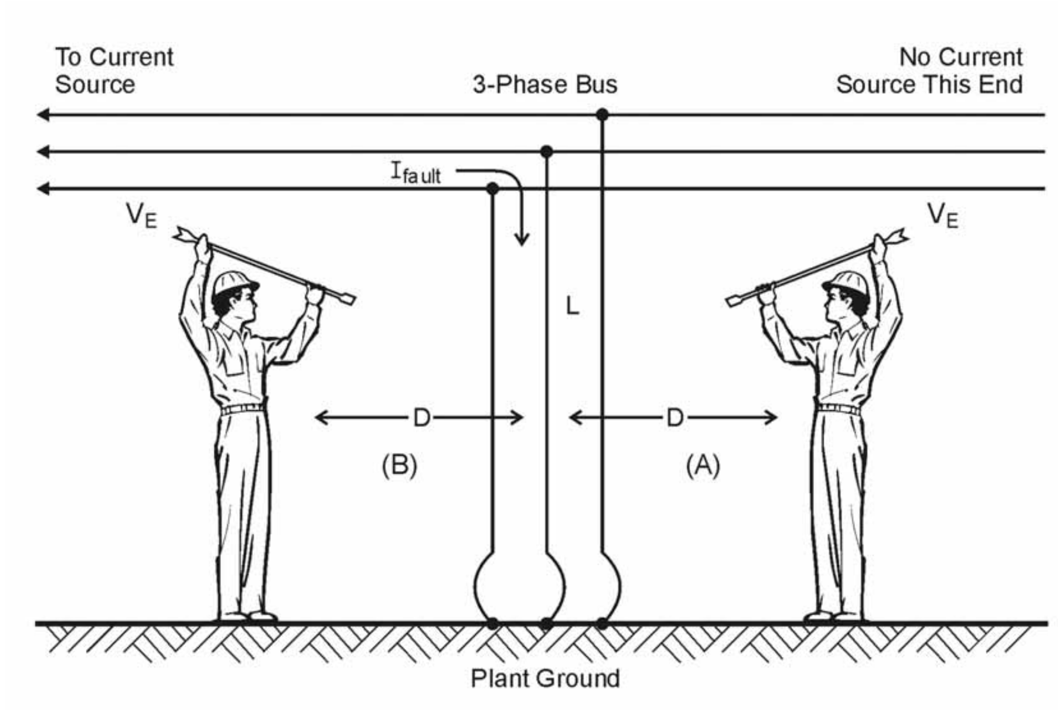


Figure 7. – Illustration of worker relative to protective grounds at worksite and source of fault current for use with Tables 4A and 4B to determine exposure voltage V_E. Protective grounds positioned between worker and source of current (A), and worker between grounds and source of current (B). When Tee grounding is used (paragraph 7.1), dimension L is the length of the common ground cable from grounded circuit to ground electrode (plant ground).

Table 4A
Ground Cable Reactance Multiplier K_{m1}
for use with figure 7(A and B)

<table>
<tr><th rowspan="2">Ground cable size, AWG or kcmil</th><th colspan="5">Depth of ground loop - D(ft.)</th></tr>
<tr><th>1</th><th>5</th><th>10</th><th>15</th><th>20 30</th></tr>
<tr><td>2</td><td>1.3</td><td colspan="3">1.5</td><td>1.6</td></tr>
<tr><td>1</td><td>1.4</td><td colspan="3">1.7</td><td>1.8</td></tr>
<tr><td>1/0</td><td>1.6</td><td colspan="3">1.9</td><td>2.1</td></tr>
<tr><td>2/0</td><td colspan="2">1.8</td><td colspan="2">2.2</td><td>2.4</td></tr>
<tr><td>3/0</td><td>2.0</td><td>2.4</td><td>2.6</td><td>2.7</td><td>2.9</td></tr>
<tr><td>4/0</td><td>2.3</td><td>2.9</td><td>3.1</td><td>3.3</td><td>3.5</td></tr>
<tr><td>250</td><td>2.6</td><td>3.3</td><td>3.6</td><td>3.8</td><td>4.0</td></tr>
<tr><td>350</td><td>3.3</td><td>4.2</td><td>4.7</td><td>5.0</td><td>5.3</td></tr>
</table>

Note: For ease of calculating voltage exposure, values for K_{m1} are adjusted to account for resistance of the ground clamps and ferrules (0.3mΩ), which was omitted in step 1 of calculation procedure.

Table 4B
Ground Cable Reactance Multiplier K_{m2}
for use with figure 7(B)

Ground cable size, AWG or kcmil	Ratio D/L 0.5	1	1.5	2	2.5	3
2	1.2	1.5	1.8	2.1	2.4	2.7
1						
1/0						
2/0	1.5	1.8	2.2	2.6	3.0	3.4
3/0						
4/0						
250						
350						

Notes: 1) Dimensions D & L must be in same unit of measurement (ft.).
2) K_{m2} = 1 for grounding situations as shown in figure 7(A).

Example worker exposure voltage calculations are provided in appendix D.

If the predicted worker exposure voltage exceeds the criteria in Section 4, consider the following to reduce the voltage:

a) Use shorter (more effective) or larger (less effective) ground cable.

b) Position grounds closer to the work.

c) Position grounds on side of worksite toward source of fault current (if practical, as shown in figure 7(A)).

d) Close equipment ground switches in parallel with protective grounds.

e) Reduce maximum available fault current at worksite (reconfigure electrical system).

f) Apply double-isolation grounding (Section 7).

B. Exposure Voltage Calculation for Transmission Lines

Exposure voltage for line crews on transmission structures may be approximated for conservative results. The lineworker exposure voltage (line conductor to structure touch potential) for transmission lines grounded as shown in Section 9 will not exceed about three times the calculated ground cable resistance voltage drop. Therefore, the calculated ground cable resistance voltage drop should not exceed about 25 volts in order to meet the 75-volt safety criteria from paragraph 4.1. Follow step 1) from **A.** above for plants and switchyards to determine ground cable resistance voltage drop. If the calculated ground cable resistance voltage drop exceeds 25 volts, further consideration of the ground cable layout on the structure is necessary to predict the exposure voltage. Consult the Denver Office, Hydroelectric Research and Technical Services Group for assistance.

6.3 Inspect Ground Cable Assemblies

Ground cable assemblies shall be visually and mechanically inspected before each use as provided in paragraph 10.2.

6.4 Obtain a Clearance

The establishment of a safe working condition on de-energized equipment or lines over 600 volts requires a clearance. Lower voltage equipment may be rendered either safe or suitable for grounding with only lockout/tagout procedure, depending on the facility Hazardous Energy Control Program. A clearance is a documented statement that the equipment or line to be worked on has been isolated from all sources of hazardous energy. Workers are prohibited from contacting supposedly de-energized equipment or lines for the purpose of installing protective grounds with only the guarantee of a clearance. Clearance procedure is given in FIST Volume 1-1. [2]

6.5 Confirm De-Energized Status (arc flash hazard analysis required)

After obtaining a clearance (or lockout/tagout), workers shall verify that the equipment, line, or circuit has been isolated by testing for the absence of nominal system voltage at the worksite. This voltage test shall be performed immediately before protective grounds are installed to minimize the chance that the de-energized circuit could be re-energized accidentally before it is grounded. Realize that induced voltage from nearby energized equipment may cause the test to falsely indicate an energized circuit. Voltage detectors (6.5.4) shall be rated for the nominal voltage of the tested circuit. Electrical and electronic indicating type detectors shall be checked for functionality before and after each use.

6.5.1 Hot stick. At higher voltages, the metal ferrule or cap on the end of a hot stick will buzz when brought into contact with the conductor if the circuit is still energized. However, for voltages of 69-kV and below, the buzz is not always audible and therefore not reliable.

6.5.2 Noisy tester. The noisy tester has a two-pronged metal fork with a ball at the end of one prong, and the other prong tapered to a point. The unit can be fitted to a hot stick. Touching the ball prong to an energized conductor will develop a corona (buzz) on the pointed prong which can be heard. This test method is similar to the hot stick test above and is not suitable for lower voltage circuits.

Some people with hearing loss or working in high traffic or noisy areas may not detect the audible buzz, especially on lower voltage circuits.

6.5.3 Hot horn or noisy tester. This device, not to be confused with a noisy tester buzzing device (6.5.2), is battery operated and sounds an alarm to alert personnel that nominal voltage is present. It is fitted to a hot stick and may be used in areas around switchgear, substations, and overhead lines. Typically, all that is involved for operation is turning on the device and placing the detector in the electric field of the conductor. Follow manufacturer recommendations to ensure safe and accurate results.

6.5.4 Multiple range voltage detector. The multiple range voltage detector is essentially a battery operated, multiple range field intensity meter equipped with an internally connected metal contact hook mounted on a live-line tool. The hook is placed in contact with the conductor under test and the approximate nominal circuit phase-to-phase voltage is indicated. Detectors may have manual or automatic voltage range selection and typically function from 600V to 69kV. The device senses the electric field of the energized conductor; therefore, it is not a direct-reading voltmeter and all readings should be regarded as estimates. Follow manufacturer recommendations to ensure safe and accurate results. If the interpretation of the meter reading is questioned, the worker should assume that the circuit is energized and use other methods to determine the electrical status.

6.5.5 Neon-type indicator. The neon indicator is attached to the end of a live-line tool and positioned in the electric field produced by the circuit. It will produce a visual indication of an energized circuit.

6.5.6 Direct-reading voltmeter. For nominal circuit voltages 1000 volts and below, a voltmeter may be connected directly to the circuit. The voltmeter and its test leads should be rated for the circuit voltage.

6.6 Clean Connections (arc flash hazard analysis required)

To ensure the lowest possible worker exposure voltage, grounding connections must be clean. The surface of permanent grounding hardware (ground rods, cable, metal structures) to which the ground-end clamp is to be applied usually is corroded, contaminated with oil, dust, other foreign substance, or insulated by paint. Aluminum bus or conductor will have a high-resistive oxide film. These surfaces must be cleaned by wire brushing before the grounding clamps are installed, or self-cleaning clamps must be used.

6.6.1 Wire Brushing. The clamp jaws should be wire brushed immediately before attachment, and the surface of the object to be clamped should be cleaned before the clamp is attached. De-energized conductors must be cleaned with a wire brush attached to a hot stick or the brush may be hand-held using suitable voltage rated insulated gloves [9] on circuits with nominal voltage ratings below 17 kilovolts. Remember, the conductor is considered energized until properly grounded. The cleaning effect of wire brushing is nearly gone within 20 minutes (re-oxidation) so clamps should be applied as soon as possible.

6.6.2 Self-cleaning Clamps. Flat-faced, self-cleaning ground-end clamps used to connect to tower steel provide an extra margin of corrosion penetration. After the clamp has been tightened lightly, rotated, and then securely tightened on the tower member, the cup-pointed setscrew is tightened with a wrench to ensure penetration of any remaining surface contamination. Self-cleaning conductor-end clamps are installed lightly on the circuit conductor, rotated a few degrees in each direction to clean the conductor, and then tightened.

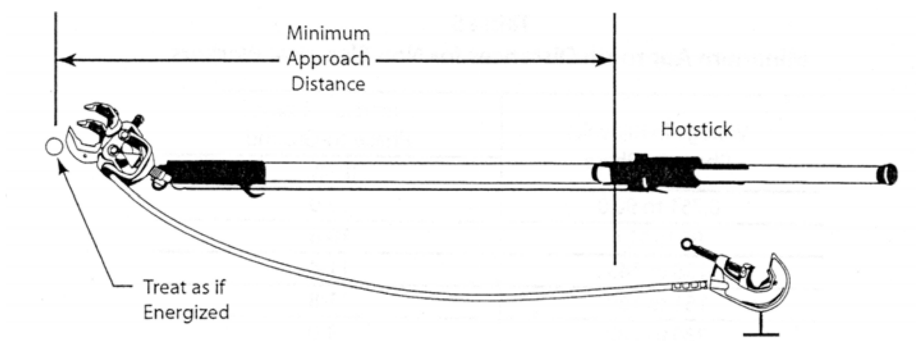
6.7 Grounding Cable Installation

6.7.1 Ground-End Clamps. Ground-end clamps of ground cable assemblies shall always be applied first. Clamp jaws and their point of attachment to a ground electrode (ground mat conductor, equipment ground bus, tower steel, etc.) should be wire brushed immediately before installation. The clamp must be tightened securely to provide a low resistance electrical bond and a secure mechanical connection.

Ground-end clamps should be connected to a grounding point as close as practical to the location where workers are likely to simultaneously contact grounded objects (metal equipment enclosures, circuit breaker and transformer tanks, etc.) and exposed parts of temporary grounded equipment at the worksite. This practice minimizes the effective length of the personal protective grounds or ground loop effect described in paragraph 6.2.2. The grounding point shall be capable of conducting the maximum available fault current, as required for the protective grounds. Check that the permanent ground lead is of equal or larger conductor size than the protective ground.

6.7.2 Circuit-End Clamps (arc flash hazard analysis required)

A. Circuit-end or the working end clamps of ground cable assemblies shall be applied after the ground-end clamps are connected. The circuit or working end clamps shall always be connected and disconnected by means of hot sticks of adequate length to meet minimum approach distances given in Table 1 (Section 3), with the following exception: it is recognized that limiting dimensions in plant equipment often prohibit the use of hot sticks when attaching ground clamps to bus. For those cases where hot sticks are impractical, ground clamps may be attached by hand using suitable voltage rated insulated gloves [9] on circuits with nominal voltage ratings below 17 kilovolts. Remember, the bus is considered energized from a safety standpoint until properly grounded.



Grounding of Conductor or Bus

B. Grounds must be installed close to the workers to minimize exposure voltage (ground loop effect), but not so close as to be endangered by whipping of the cables due to high currents. Grounds should be installed within sight of the workers. For plant, switchyard and substation grounding applications, cables should be restrained with ropes to absorb shock and reduce whipping, but not rigidly fixed in position in an attempt to prevent all movement. Installed cables should not be twisted, coiled, or wound around objects. See cable bundling restrictions in paragraphs 6.7.3 and 6.7.4.

C. In applying grounds, care must be exercised to stay clear of the grounding cables. The practice of holding the cable near the base of the hot stick to lighten the load on the head of the stick is strictly prohibited. A coworker should assist in applying heavy grounds by holding the cable with another hot stick, or by using a shepherd hook with a pulley and nonconductive rope to hoist the ground cable into position.

6.7.3 Multiphase, Worksite Grounding Required. Protective grounding cables shall be installed so that all phases of equipment and transmission lines are visibly (where practical) and effectively bonded together in a multi-phase short and connected to ground at the worksite. Single-phase grounding of multi-phase circuits is prohibited. The conductor-end clamps of grounding cables should be applied in turn to the nearest conductor or bus first, proceeding outward until all phases have been connected. Where practical, cables should be supported by ropes or other suitable means to take the weight off of the clamps. However, never bundle the grounds together as this will increase the magnetic separation forces when the grounds are conducting fault current, possibly causing violent separation of the cables. One exception to this bundling rule is for paralleled cables per phase (paragraph 6.7.4).

6.7.4 Parallel Grounds. If parallel grounds per phase are required, ground cable assemblies shall be of identical length, size, and type clamps. Clamps at either end of the parallel cables should be connected as closely together as possible (side by side) to the circuit and ground points to promote equal current division between cables. Bundling of paralleled cables per phase (not between phases) will further promote equal current division and avoid unnecessary movement due to large attractive forces between them when conducting fault current. See paragraph 5.1.2 for conductor ampacity derating of parallel grounds.

6.7.5 Barricade. Place barricades and/or signs as necessary to protect installed grounds from physical disturbance or accidental removal. If equipment cabinets must be closed with grounds installed inside, the cabinets shall be clearly tagged on the outside indicating GROUNDS INSTALLED – DO NOT ENERGIZE. Tags may also be attached to ground cables to track that all installed grounds have been removed before the worksite equipment is re-energized.

6.7.6 Removal. Protective grounds should be removed in reverse order from installation. The circuit-end clamps should be disconnected in succession, starting first with the farthest ground cable or circuit, in a manner that creates a safe exposure (minimum approach distance) to ungrounded circuit conductors as the grounds are removed. Ground-end clamps must be disconnected after the circuit-end clamps have been removed. Account for all protective grounds to ensure they have been removed before re-energizing the line or equipment.

6.8 Arc Flash Hazard Analysis Required

De-energized equipment and circuits required to be grounded are considered energized until grounded. Certain grounding activities involving voltage testing (paragraph 6.5), cleaning connections (paragraph 6.6), and attaching circuit-end ground clamps (paragraph 6.7.2) require contact with exposed conductors before they are properly grounded. Therefore, these activities must be performed under the assumption of possible arc flash hazard. The responsible office shall ensure that appropriate personal protective equipment for arc flash is used by employees performing these tasks.

Figure 8. – Example arc flash protective gear. Level of protection required is dependant on available arc flash energy.

7. POWER AND PUMPING PLANT PROTECTIVE GROUNDING

Application of protective grounds in power and pumping plants may encounter the following conditions:

1) High available fault current due to concentration of multiple current sources (running generators and synchronous motors, etc.).

2) Less than optimal electrical configuration of power equipment for isolation of worksite from hazardous energy due to limited operating flexibility.

3) Close quarters for installation of protective grounds due to equipment dimensions.

4) Limited access to enclosed bus or equipment conductors for attachment of protective grounds.

5) Availability of multiple grounding points (ground electrode) connected into the plant ground mat.

6) Limited sight distance for installing protective grounds at the worksite.

In all cases, the guiding principle for protective grounding in plants is close proximity, three-phase worksite grounding. Grounds should be installed close to the worksite (workers) as practical in order to provide an effective current shunt around the body and to limit exposure voltage. Keep in mind that the conductor-end and ground-end clamps of protective grounds should be connected near the locations where workers will likely contact de-energized parts of equipment and grounded objects. Avoid connecting the ground-end clamps to a grounding point (plant grounding conductor) that is not bonded directly to permanently grounded parts of the equipment to be worked on. Otherwise, ground loops may be formed with embedded ground mat conductors in plant concrete which can significantly increase the exposure voltage.

Closing equipment ground switches in parallel with protective grounds is recommended to reduce the available fault current through the grounds and lower worker exposure voltage at the worksite. In rare cases, a closed ground switch may cause undesired circulating current in protective grounds due to induction coupling with nearby energized equipment. If circulating current is objectionable, consider keeping ground switches open and maintain worksite grounding only. **Caution:** Never close an equipment ground switch and/or apply protective grounds at the terminals of a synchronous generator or motor while the machine is rotating or coasting at any speed (including creeping). Ground only when the machine is at a complete stop and cannot rotate.

Residual magnetic flux in the rotor poles of synchronous machines can produce large circulating current in the grounding circuit if the machine should rotate at any speed while the stator winding is grounded.

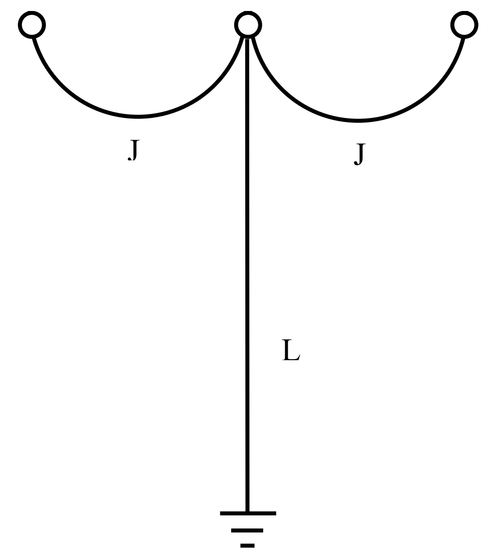
7.1 Three-Phase Tee Grounding

The three-phase Tee method for grounding de-energized parts of equipment, bus and cable is recommended as shown in figures 9 and 10. Tee grounding, in general, will provide the lowest worker exposure voltage for three-phase fault conditions because it practically eliminates current in the protective ground connected to the grounding electrode (plant ground conductor). For this method to be effective, short grounding jumpers must be connected directly between the phases. These grounding jumpers must be shorter than that required if separate grounds were to be attached directly from each phase to the ground electrode connection point. If this condition cannot be met, then separate grounds should be attached from the ground electrode connection point to each phase conductor. Also, do not use Tee grounding if the connection point to the ground electrode is not physically close to the grounded parts of the equipment to be worked on.

For example, three single-phase power transformers make up a three-phase bank connected grounded-wye on the high-voltage windings. The transformers are situated in a lineup with 10 feet spacing between tanks. Each transformer has one high-voltage bushing terminal and has a separate ground mat stub-up conductor bonded to its tank. If Tee grounding were applied to the high-voltage terminals, an unnecessary large ground loop would be formed with the protective grounds at two of the three transformer tanks which are not bonded to the same ground electrode point (stub-up) as the Tee ground. In this case, better grounding (lower exposure voltage) is achieved with a protective ground installed at each transformer tank, from the permanent tank grounding conductor to bushing terminal.

Check worker exposure voltage as provided in paragraph 6.2.2 for the anticipated worksite conditions. If the predicted exposure voltage cannot be adequately controlled, or the available fault current at the worksite exceeds 50,000 amperes symmetrical, then the method of double-isolation grounding should be used. Extreme electromechanical separation forces are developed in ground cables carrying high currents (above 50 kA) and mechanical failure of the ground cable assembly is likely. Mechanical failure can occur within the first few cycles of fault current, leaving the workers unprotected if the grounds should separate or break away from their attachment points. If this happens, an arc flash and blast could present an additional hazard to workers.

Bus or equipment conductors to be grounded.



Ground electrode connection point.
(equipment ground bus, plant ground conductor, etc.)

Figure 9. – Three-phase Tee grounding method for plant equipment. Length of ground jumpers (J) must be less than distance (L) between conductors to be grounded and the ground electrode connection point. If length of jumpers required exceeds (L), then ground each phase separately to the ground electrode connection point.

7.2 Double-Isolation Grounding

Double-isolation grounding is an alternative method of protective grounding for situations where the worksite available fault current is high (above 50 kA), the predicted worker exposure voltage exceeds 100 volts[2], or space limitations prohibit installation of full size protective grounds. It may also be used for testing purposes for the temporary ungrounding of isolated equipment under test without removing all safety grounding. A basic double-isolation grounding scheme is shown in figure 11.

The following general rules must be applied to double-isolation grounding:

1) Eliminate all current sources at the worksite.

2) Electrically isolate worksite from each current source with two open-circuit devices in series. Open-circuit devices must be physically separated to ensure an electrical failure of one device cannot affect the other.

3) Apply personal protective grounds PPG (or close equipment ground switch) on the circuit segment between open isolation devices; item 2.

4) Apply static or protective grounds at the worksite on conductors to be contacted by the workers.

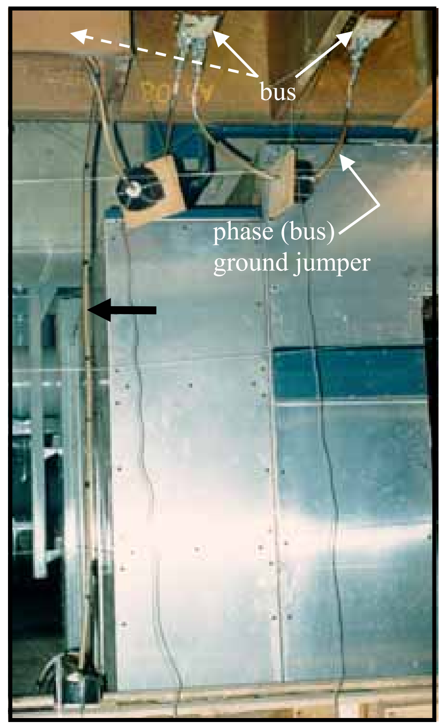


Figure 10. – Three-phase Tee grounding method for generator bus at ceiling, during staged fault grounding tests at Hoover Powerplant. [12] This test verified lowest exposure voltage obtained with Tee grounding. The common ground cable extending down to plant ground (black arrow) should connect to the center phase bus when practical.

Example: The generator stator winding in figure 11 is the desired worksite; therefore all sources of current must be eliminated at this location. This includes rendering the generator no longer capable of being a source of current. The generator must be on an electrical/mechanical clearance equivalent to one that permits workers around and on rotating parts of the machine; therefore it cannot rotate. Under this condition, the generator is not

[2] Maximum exposure voltage permitted may be less than 100 volts for extended fault clearing time, paragraph 4.1.

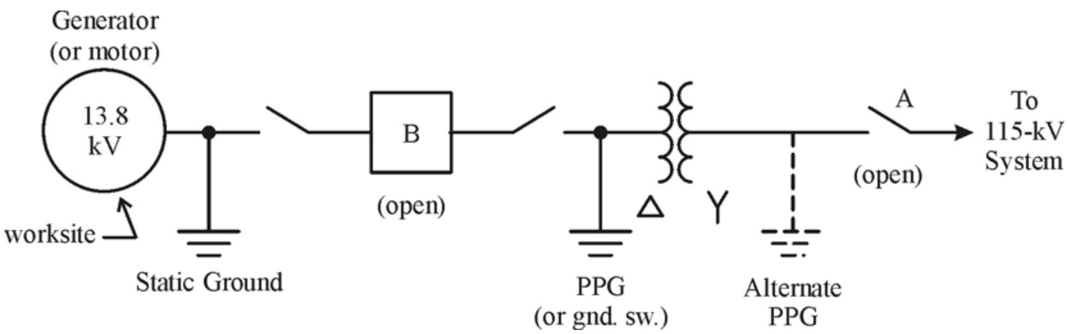


Figure 11. – Basic double-isolation protective grounding scheme.

considered a source of current. Any other devices connected to the generator (rotor field or stator windings) which could be a source of hazardous energy must be disabled/isolated (potential transformers, static excitation systems, etc.).

The worksite (generator) must be isolated from the power system at two places (Disconnect Switch A and Circuit Breaker B). Personal protective grounds (PPG) are installed between the open devices. The protective grounds will conduct fault current and trip upstream power system device(s) if Disconnect Switch A should accidentally close or fail. However, with Circuit Breaker B open, no fault current will appear at the worksite. Therefore, the power system is no longer considered a source of current at the worksite.

For the above example all current sources have been eliminated at the worksite and either static grounds or full size protective grounds may be installed at the generator. It is always preferable to use protective grounds if conditions permit. These grounds may be temporarily removed from the generator when necessary for testing purposes, e.g. stator winding insulation tests. The designated safe working zone in figure 10 includes the generator stator winding and bus to the open disconnect switch (circuit grounded with the static grounds). The ungrounded circuit section containing the circuit breaker and both disconnect switches is *not* included in the safe working zone.

A second alternate location for the fully rated personal protective grounds might be between the open disconnect switches for Circuit Breaker B (not shown). However, isolation here may be compromised if failure of the line side switch (e.g. flashover, explosion) could in any manner involve the generator side switch. Therefore, choose isolation devices with adequate physical isolation. Removable bus links and equipment lead jumpers may be disconnected or removed for this purpose.

Another example of double-isolation grounding involving two generators connected to a common step-up power transformer is given in appendix E.

Double-isolation grounding may be used for other equipment in the plant (or switchyard) where the electrical configuration provides two independent isolation devices for every source of current at the worksite.

8. SWITCHYARD AND SUBSTATION PROTECTIVE GROUNDING

Background

Most transmission level switchyards and substations are electrically configured grounded-wye and therefore electrical faults can involve ground (earth). Both three-phase and single-phase-to-ground faults should be considered when determining the maximum available fault current at a grounded worksite. Buried ground mat conductors should be present within the confines (perimeter fence) of the station. The ground mat provides a common and permanent grounding electrode for bonding all non-current carrying conductive parts of equipment in the station (circuit breaker and transformer tanks, metal structures, fencing, etc.). It also conducts ground fault current into the earth which returns to remote grounded current sources. Earth fault currents from the ground mat create step and touch potentials within and outside the station, depicted in figure 12.

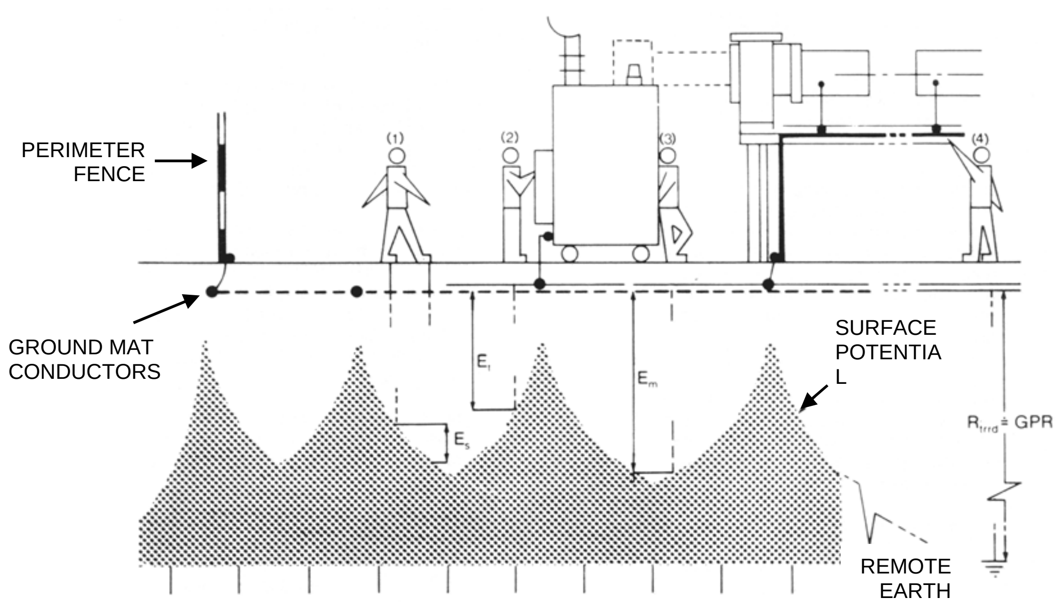


Figure 12. – Basic station exposure voltage situations; step potential (1), touch potential (2), mesh potential (3), and transferred touch potential outside perimeter fence (4).

Within the perimeter fence of the station, the ground mat should control all step and touch potentials to safe levels during a ground fault. An exception to this rule may be in areas of the yard without equipment (empty bays) and lacking buried ground mat conductors. The ground mat also provides the ground electrode connection for protective grounds. External to the station, hazardous transferred potentials may develop up to the ground potential rise GPR of the station during a fault if external equipment or other conductive objects are intentionally or unintentionally grounded (bonded) to the ground mat. Therefore, only equipment within the station is the subject of grounding in this Section.

8.1 General Considerations for Placement of Protective Grounds

Work on de-energized equipment and circuits should be performed with protective grounds installed on each phase at the worksite as shown in figure 13. Grounding cables should be visible from the worksite. No switch or circuit breaker shall be used to maintain continuity between the protective grounds and the worksite.

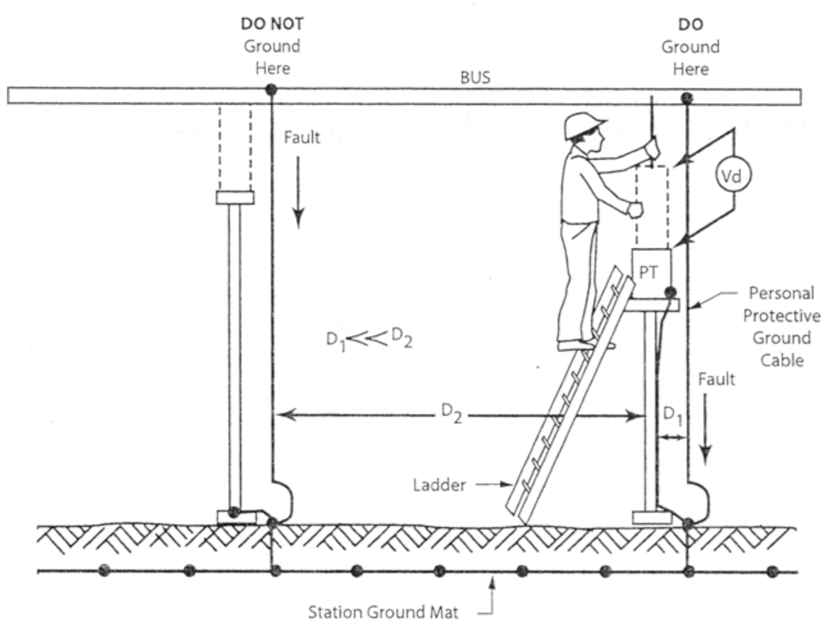


Figure 13 – Station grounding technique applicable to all types of equipment.

Protective grounds should be installed close to the worksite as practical (shorter distance D1) to minimize exposure voltage (ground loop effect, paragraph 6.2.2), but not so close that they may endanger the workers from whipping due to electromechanical separation forces. In general, worksite grounding means the protective grounds are installed within reaching distance of a hot stick.

Conductor-end and ground-end clamps should be connected near the locations where workers will likely contact de-energized exposed parts of equipment and other grounded objects. Ground-end clamps should be connected to a copper equipment or structure ground lead which, in turn, is bonded to the station ground mat. Verify the station ground lead bonding connection to the equipment or structure is intact and therefore grounded before applying protective grounds. Avoid connecting ground-end clamps to a grounding point (ground mat conductor) that is not bonded directly to permanently grounded parts of the equipment to be worked on. Tee grounding is recommended when these conditions above and as set forth in paragraph 7.1 are met.

Tee grounding in switchyards is applicable to devices that share a common grounded enclosure or structure, such as a three-phase, single-tank transformer or a three-phase circuit breaker.

Check the predicted exposure voltage as provided in paragraph 6.2.2 for the anticipated worksite conditions. Double-isolation grounding (paragraph 7.2) may be used to minimize exposure voltage or isolate equipment or bus for testing purposes.

8.2 Power Circuit Breakers and Transformers

Protective grounds shall be installed on both sides (all terminals) of circuit breakers and transformers while workers are inside the equipment tanks or on top of equipment, or within the minimum approach distance (Table 1, Section 3) of de-energized current carrying components such as conductors and bushing terminals. Protective grounds shall be in place before oil is drained from the tanks or the tanks are opened. Bushing leads may be disconnected from bushing terminals as necessary to permit equipment testing that require the equipment terminals to be ungrounded, provided the protective grounds remain connected to the bushing leads. The grounds shall be re-established as soon as testing is completed.

During equipment testing activities, protective grounding must be maintained on circuits (bushing leads) which may be disconnected or isolated from a breaker or transformer under test. Static grounds should be used on the tested device, as appropriate, until testing is completed and the grounded bushing leads reattached.

8.3 Disconnect Switches and Bus

Work on high-voltage disconnect switches and bus conductors shall be performed with visible protective grounds installed at the worksite (figure 13).

8.4 Insulated High-Voltage Cable

Procedure for protective grounding of insulated cable is dependent on the location of the worksite with respect to the cable ends (terminations). Paragraph 8.4.1 applies to situations where the worksite is at a cable termination (pothead) within the station. Paragraph 8.4.2 applies to all other worksites within the station that are not at a cable termination, such as the point at which a cable is to be opened or spliced. For de-energized work on cable outside the station, refer to power line grounding, Section 9.

High-voltage power cable may connect to circuits or equipment within a station, or between separately grounded stations (e.g. a powerplant and remote switchyard). For the latter case, circulating current and transferred potential must especially be taken into consideration for safety grounding the cable conductor and shield. This section describes grounding procedure to create an equipotential work zone at the worksite and to minimize circulating current*

** See definition of station (Section 2) for clarification of separately grounded stations.*

8.4.1 Cable Terminations

A. Work on high-voltage power cable terminations or potheads shall be done with single-point grounding installed at the worksite end of the cable, or as otherwise provided in paragraph B. The non-working end of cable should remain ungrounded and treated as if energized unless all three of the following conditions apply: 1) the non-working end of cable terminates within the same station; 2) the cable does not exceed 30 feet in length; and 3) the predicted exposure voltage (paragraph 6.2.2) is acceptable. If these three conditions are met, both ends of the cable may be worked on with single-point grounding only at one end.

In some cases the worksite conditions may not accommodate full size grounds attached to the cable termination (pothead). Double-isolation grounding may be applied to both ends of the cable with a static ground on the cable conductor only at the worksite end (similar as shown in figure 15 for cable testing); do not multi-point ground the cable with static grounds.

B. Both ends of a high-voltage power cable may be grounded and worked on simultaneously, provided such multi-point grounding does not create objectionable circulating current. Double-isolation grounding may be applied to one or both ends for multi-point cable grounding, but full size protective grounds (not static grounds) shall be connected to the cable terminals (potheads). If objectionable circulating current is present, then work shall be performed only at one end of the cable at a time with single-point worksite grounding.

During a fault at the station, multi-point grounded power cable may carry substantial current in parallel with the grounding system (ground mat), or between separately grounded stations. Static grounds at either end of the cable may not have adequate ampacity.

8.4.2 Midsection and Splices. When high-voltage cable is to be opened or spliced, double-isolation grounding should be applied to both ends of the cable as shown in figure 14, but do not ground the actual cable conductor at either end. Install additional grounds at the worksite to the cable shield and conductor on both sides of the splice, if feasible. These additional worksite grounds should have an ampacity not less than the cable conductor or shield. Worksite grounds shall remain in place until the conductor is joined, after which these grounds may be removed for taping or re-insulation of the splice. If the shield and conductor cannot be grounded at the splice ***and*** one end of the cable terminates external to the station, then treat the shield and conductor as if energized and use appropriate isolation/insulation protection for electric shock at the worksite (splice).

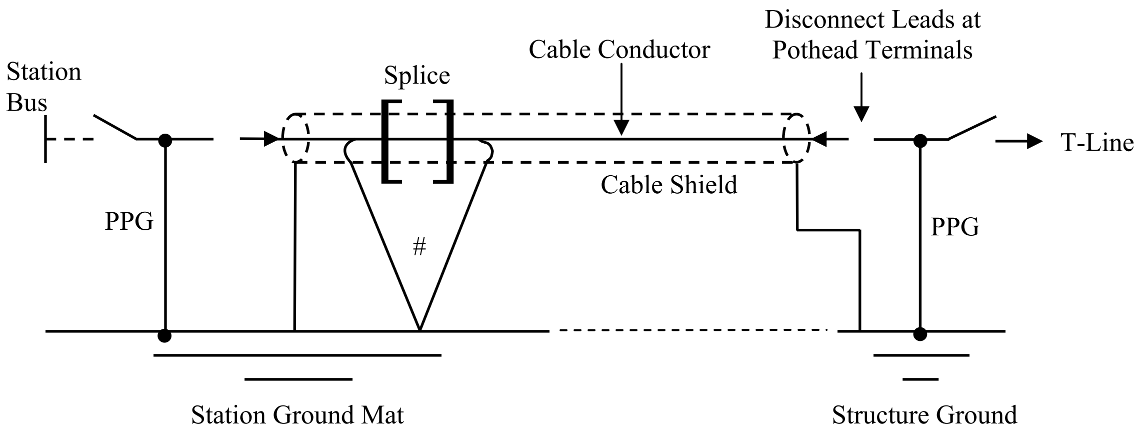


Figure 14. – Example double-isolation grounding for high-voltage cable worksite at a splice. PPG denotes protective ground and pound sign (#) denotes grounding leads having a minimum ampacity of cable conductor or shield. Both cable conductor and shield are grounded adjacent to splice on both sides. Note cable conductor is NOT grounded at either end of cable. Structure ground may be remote from and not bonded to the station ground mat.

8.4.3 Cable Testing. Tests that require high-voltage insulated cable to be isolated and ungrounded, for example hvdc dielectric tests, should be performed with double-isolation grounding at both cable terminals as shown in figure 15. Removing protective grounds from cable terminals without double-isolation grounding is prohibited. Static grounds should also be applied to the cable terminals (potheads) at the test site (test equipment) end of cable, and removed for the duration of a test and then re-applied. Remove the static ground only on the phase to be tested while leaving the other phases grounded.

Remote ends of cable shall be treated as if energized at all times unless static or protective grounds are applied there. However, simultaneous grounding of both ends of cable is not permitted using static grounds. Special precaution must be taken with dc testing to slowly discharge stored energy after a test and before re-applying solid grounds. Cables tested with direct-current must remain grounded for a suitable period to minimize recovery voltage before re-energizing at system voltage.

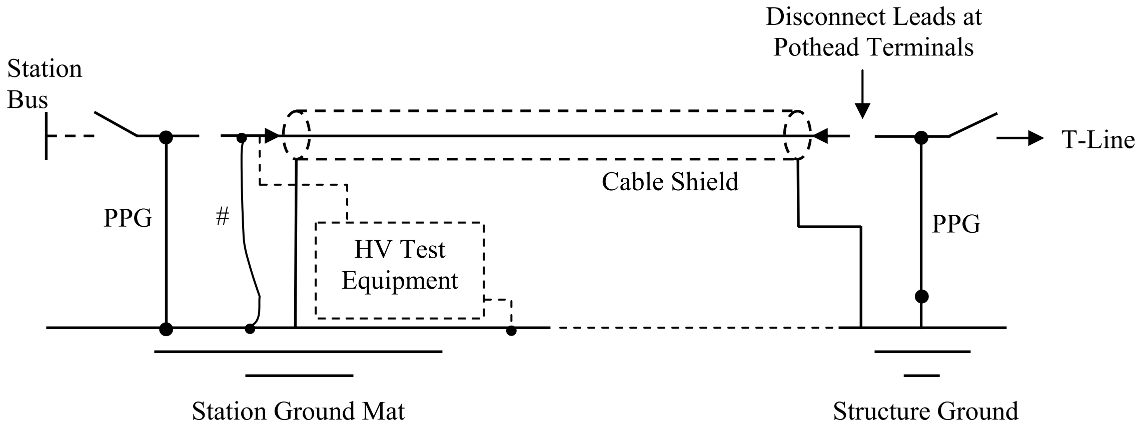


Figure 15. – Example double-isolation grounding for high-voltage cable dielectric test. PPG denotes protective ground and pound sign (#) denotes static ground. Structure ground may be remote from and not bonded to the station ground mat.

8.5 Grounding Transformers and Phase Reactors

Grounding transformers shall not be worked on unless de-energized and grounded. Phase reactors shall be electrically isolated from all energized sources and grounded.

8.6 Capacitor Banks

Protective grounds shall be applied to capacitor banks (series or shunt banks) after a minimum 5-minute waiting period once the bank has been electrically isolated. The wait period allows individual capacitors to drain off stored charge through an internal discharge resistor. Close capacitor grounding switches, if available. Protective grounds shall be applied to all phase terminals of the bank, as well as neutral when wye connected. Protective grounds shall be applied to both sides (terminals) of series capacitor banks and to the capacitor platform. Short the individual capacitors to be contacted from terminal-to-terminal and terminal-to-case by approved means.

8.7 Mobile Equipment

In switchyards and substations having grounds mats, or at other locations where ground mats are used to control earth surface voltage potential, all mobile equipment and vehicles involved at a worksite within the station (ground mat area) shall be grounded (bonded) to the ground mat. Ground cables on reels or looped on the vehicle shall be completely unwound to allow thorough inspection of the cable prior to use and to minimize cable inductance. Once completely unwound from the vehicle, the ground cable should be laid out “S” fashion on the ground with no crossovers. Ground cables used for equipment or vehicle grounding shall be minimum size of #2 AWG copper. Any equipment or vehicle that is capable of extending a conductive object, for example boom, at the worksite toward any exposed circuit (de-energized or energized) within the minimum equipment clearance distance given in Table 5 shall be grounded with a conductor sized for the maximum available fault current (Section 6). Refer to Reclamation Safety and Health Standards [1], for grounding mobile equipment while in transit near exposed high-voltage circuits.

Table 5
Equipment Clearances for Operations Near Exposed Circuits in Switchyards and Substations

Nominal System Voltage (kV) Line-to-Line	Clearance (ft)
50 (or less)	10
69	11
115	12
230	16
500	25

RSHS, Table 12-3. [1]

Cranes can create special touch potential hazards if used to make picks outside the station (beyond perimeter fence or ground mat area). Therefore, if possible, do not have the crane inside the station yard making picks outside the perimeter fence, off the mat. Likewise, do not have the crane off the ground mat or outside the station making picks in the station or delivering material into the station. Hazardous transferred touch potential may develop at the crane hook or frame during an electrical fault for these situations (similar to situation 4, figure 12). When a crane must be used in this capacity, careful consideration must be given to protect workers from electric shock, which is beyond the scope of this FIST.

9. POWER LINE PROTECTIVE GROUNDING

This Section covers protective grounding requirements for steel tower and wood pole supported transmission and distribution lines, and insulated power cable. See Section 8 for grounding insulated power cable within a station. Protective grounds shall be installed so all phases of lines or cable are visibly and effectively bonded together in a multi-phase “short” and connected to ground (earth) at the worksite. Single-phase grounding of multi-phase circuits is prohibited. Conductive objects within reach of any worker, either aerial or on the ground, should be bonded to this grounding system. Therefore, a sufficient quantity of protective grounds should be installed at the worksite in a manner that places them directly in shunt with all points of contact by workers; the earth shall not be used as a protective grounding conductor or as part of a circuit path between protective grounds in this respect.

Single-point worksite (structure) grounding, as opposed to adjacent structure grounding, is required unless performing mid-span work such as a splice (paragraph 9.6). The maximum available fault current at the worksite shall be determined considering single-phase-to-ground and multi-phase faults. Refer to Section 6 for sizing protective grounds.

Installation of protective grounds on power line structures creates an equipotential safe work zone on the structure. However, without benefit of installed ground mats, hazardous step, touch, and transferred touch potentials may exist on the ground near structure footings and objects bonded to the worksite grounding system during an accidental energization of the line (figure 16). Keep in mind that when ground fault current flows there will be a voltage rise at every connection to earth. No one shall approach to within 10 feet of a protective grounded structure or any other conductive object which has been bonded to the worksite grounding system unless protective measures are in place to reduce the hazard of step and touch voltages (refer to paragraph 9.5). Otherwise, only when necessary to gain access to a structure from the ground, linemen shall approach quickly and mount/dismount at the base of the structure.

9.1 Grounding on Metal Transmission Structures

9.1.1 Lattice Steel Structures. The preferred method for installing grounds on higher voltage single-circuit lattice steel transmission line structures, where the conductors are a greater distance from the structure than those on lower voltage structures, is to install them from the bridge above the conductors (figure 17). This configuration minimizes the induction ground loop formed with lineworker contacting the tower bridge steel and line conductor (along side insulator string). It also reduces the lineman exposure voltage.

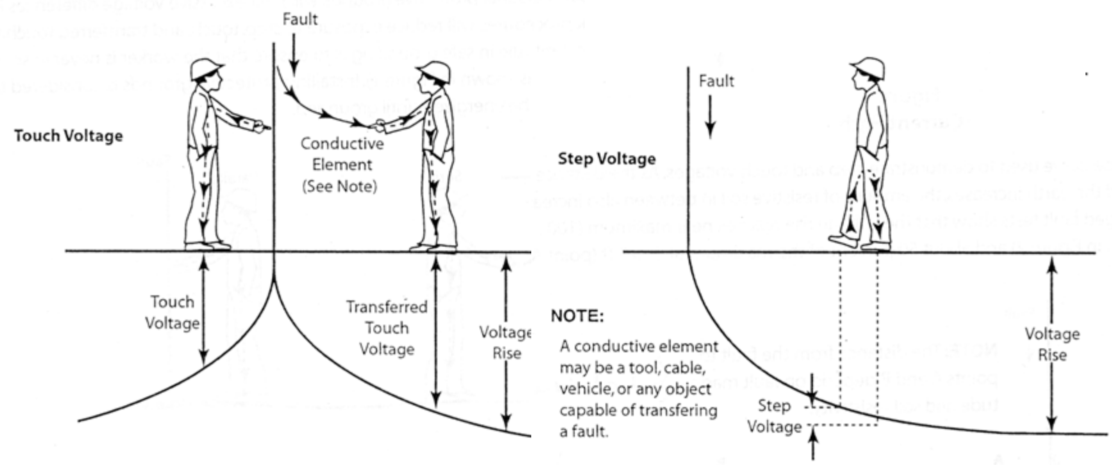


Figure 16. – Graphic depicting step and touch exposure voltages created at earth surface by current flowing into earth from grounded objects.

On double-circuit lattice steel transmission structures, the phase conductors should be grounded to their structure arms above, similar to that shown in figure 17. Protective grounds should be attached from the bottom phase up and removed from the top phase down.

9.1.2 Slip Joint Steel Pole Structures. Slip joint structures either have bonding cables permanently attached to each joint or joint resistance should be measured on selected structures after installation and periodically as maintenance personnel deem necessary. Surfaces where protective grounds are to be attached shall be cleaned prior to cable attachment to ensure a proper electrical contact.

9.1.3 Weathering Steel Pole Structures. The highly resistive protective oxide on weathered steel should not be removed. Protective grounding is best accomplished by welding a copper or steel bar or stainless steel nut to which a threaded copper stud can be inserted at each grounding location. Weathering steel poles should be constructed with bonds between crossarms and poles and between slip joints to ensure electrical continuity. If bonding straps are not part of the structure, protective grounding must be extended to a ground rod and to the overhead ground wire.

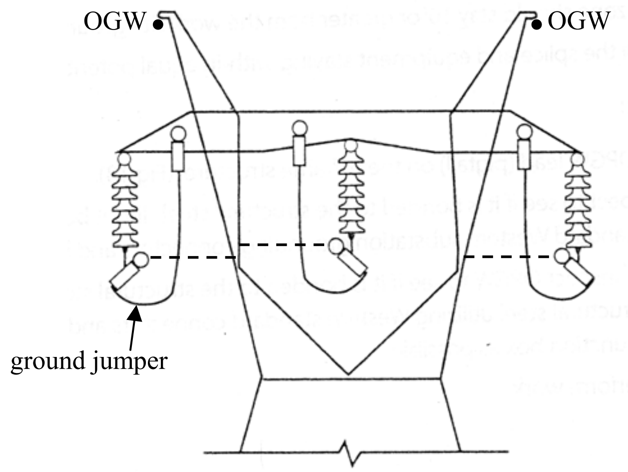


Figure 17. – Preferred method for grounding conductors on single-circuit high-voltage line steel structures. Dashed lines show alternate orientation for protective grounds on smaller (lower voltage) structures. OGW denotes overhead ground wire. OGWs must be bonded to worksite grounding system if within reach of linemen.

9.1.4 Painted Steel. Grounding is best accomplished by creating a ground attachment point similar as described in paragraph 9.1.3. Scraping the paint will seldom provide an adequate electrical connection, and will require repainting afterwards.

9.1.5 Overhead Ground Wires. Overhead ground wires must be bonded to the worksite grounding system (structure steel) with protective grounds if the work places lineworkers within their reach. The permanent structure hangers for overhead ground wires cannot be relied upon for good electrical bonding from a safety standpoint. Intentionally bonding overhead ground wires to the worksite structure also helps divert earth fault current away from the structure footings toward adjacent structures if the line is accidentally re-energized, reducing step and touch exposure voltages on the ground at the worksite. However, precaution must be taken to avoid exposure to possible hazardous step and touch potentials at adjacent structures.

When work is performed in the vicinity of insulated overhead ground wires, the specified working clearance for a 15-kilovolt circuit (Table 1, Section 3) must be maintained, or protective grounds shall be applied.

The importance of bonding overhead ground wires to the worksite structure for electrical safety cannot be overemphasized. Otherwise, a *lethal transferred touch voltage can appear between the structure steel and wire during an accidental energization of the grounded line, or in some cases due to coupling from a nearby energized line.*

9.1.6 Structure Footing Ground. Before installing protective grounds, permanent grounding for structure footings should be examined for damage, omission, or other indication of poor continuity between the structure and footing ground electrode. If in question, a temporary ground rod should be installed next to the footing and bonded to the worksite grounding system (steel).

9.2 Grounding on Wood Pole Transmission Structures

Preferred three-phase grounding applications on wood pole structures using grounding cluster bars are shown in figures 18 and 19. Grounding cluster bars must be positioned just below the lowest elevation of the lineman's feet for the work zone (approximately the elevation of the phase conductors) and shall be bonded to the pole structure ground leads if provided. The position of the cluster bar defines the lower boundary of the equipotential work zone on a pole. Figure 20 shows an example of an installed grounding cluster bar.

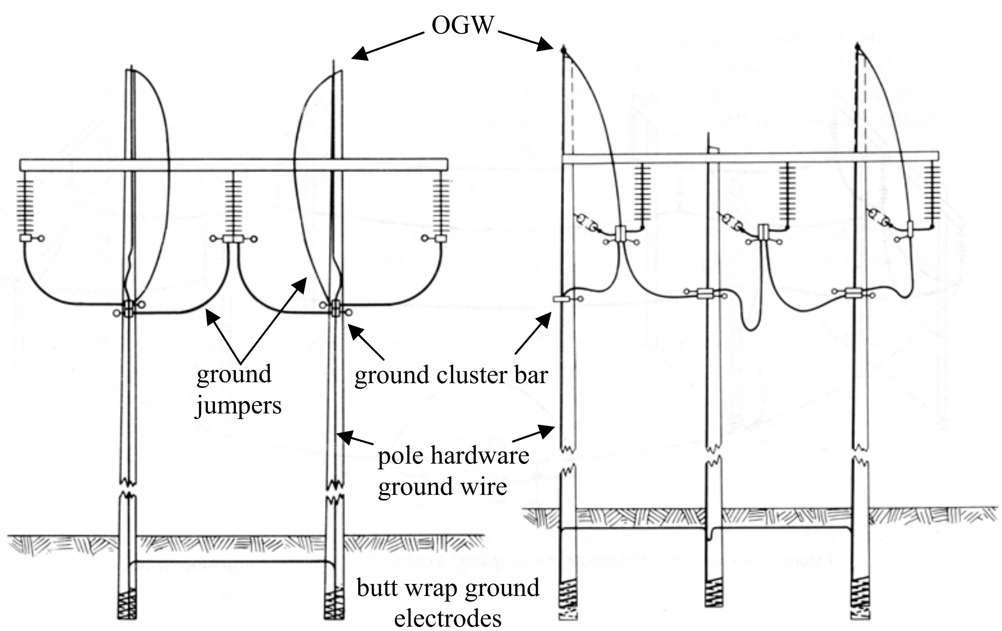


Figure 18. – Protective grounding jumper installation for two-pole and three-pole structures (grounded structures). OGW denotes overhead ground wire. OGWs must be bonded to the worksite grounding system if within reach of linemen. OGWs may be bonded to the cluster bars or to the grounded phase conductors with protective grounds.

Before installing protective grounds, permanent grounding for pole footings should be examined for damage, omission, or other indication of poor continuity between the structural hardware and pole ground electrode. If in question, a temporary ground rod should be installed next to the pole and bonded to the worksite site grounding system (figure 19).

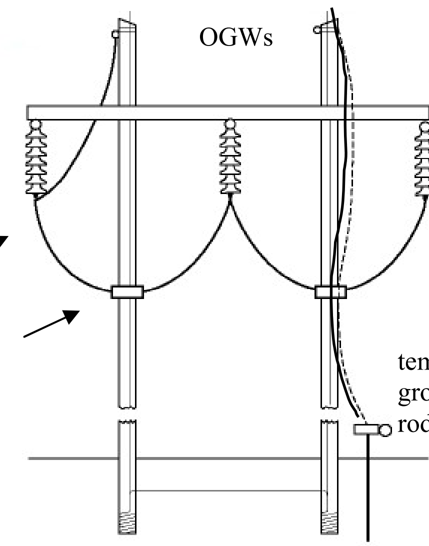


Figure 19. – Example protective grounding jumper installation showing use of ground rod for ungrounded structures or structures with questionable grounding integrity. OGW denotes overhead ground wire.

Refer to paragraph 9.1.5 for bonding overhead ground wires to the worksite grounding system. In addition, other conductive objects, such as guy wires, shall be bonded to the worksite grounding system if within reach of the linemen.

Figure 20. – Example ground cluster bar attached to wood pole. The bar provides convenient point of attachment for protective grounds and a bond to the pole structure ground wire, if provided.

9.3 Transmission Line Terminal Ground Switches

Transmission line terminal ground switches may be closed in parallel with personal protective grounds at the worksite. Closed line terminal ground switches can help ensure that the protective devices (relays, fuses) operate within the given time/current relationship to quickly isolate the source of accidental electrical energization. Also, in many cases closed terminal ground switches will reduce the fault current in protective grounds at the worksite, which lowers worker exposure voltages. However, depending on system configuration and loading conditions, closed terminal ground switches can increase induced circulating current in the line and multiple grounds due to coupling from nearby energized lines. This circulating current may be objectionable when installing or removing protective grounds, or create continuous hazardous levels of step and touch voltage at the grounded worksite. Therefore, use of line terminal ground switches is at the discretion of the crew and regional policy. *Line terminal ground switches cannot substitute for protective grounds at the worksite*.

Transmission interconnection is primarily with Western Area Power Administration and Bonneville Power Administration. An Interconnected System Clearance [2] may be required to address the use or omission of line terminal ground switches in the switching program.

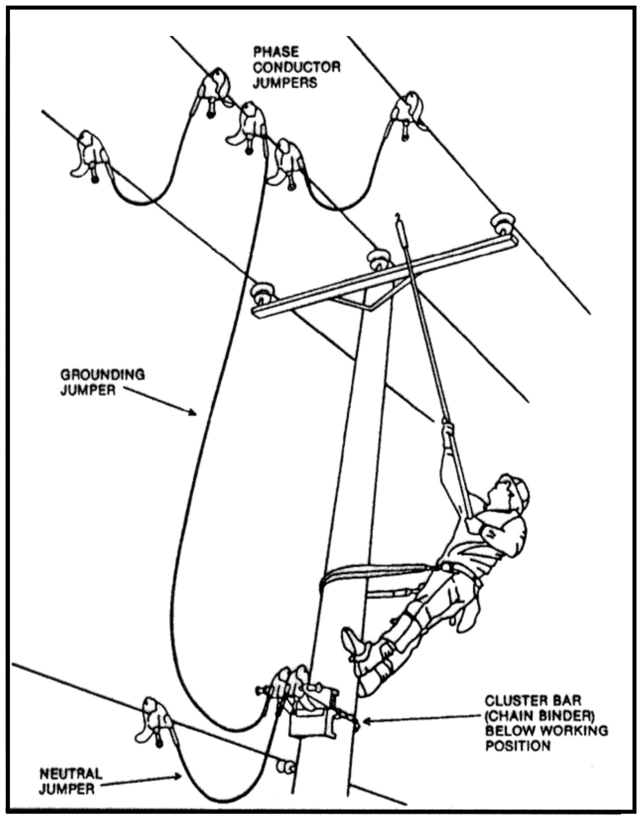


Figure 21. – Preferred method for protective grounding on lower voltage distribution lines.

9.4 Grounding on Distribution Lines

Protective grounding for distribution lines and aerial cable terminations should be accomplished as shown in figure 21. The grounding cluster bar (see photo, figure 20) must be positioned just below the lowest elevation of the lineman's feet for the work zone and shall be bonded to the neutral conductor and pole ground lead (not shown) if provided. The position of the cluster bar defines the lower boundary of the equipotential work zone on the pole. Connection of individual protective grounds from the cluster bar to each phase conductor is a permissible alternative, but may produce slightly higher exposure voltage.

Pole ground wires used for protective grounding shall be inspected before use to determine they have not been cut, damaged, or removed. If no pole ground exists, a temporary ground rod should be driven or screwed into the earth next to the pole and bonded to the cluster bar with a protective ground. Any guy wires within reach of the lineworker should be bonded to the worksite ground system (cluster bar). Ground crew should stay clear (at least 10 feet) of pole grounds, ground rods, and guy wires.

9.5 Surface Equipment and Vehicle Grounding

This paragraph applies to the grounding and bonding of equipment and vehicles involved in maintenance activities on or near power lines. Vehicles include, but are not limited to, aerial devices, passenger trucks, pole diggers, and cranes. The purpose of bonding equipment and vehicles to the worksite grounding system (during de-energized work) is to control and minimize transferred touch potentials between the structure, equipment, and vehicle during an accidental energization of the line. Vehicle and equipment grounds are to be used in conjunction with properly installed personal protective grounds. Ground cables used for equipment and vehicle grounding shall be no smaller than #1/0 copper and shall be tested in accordance with Section 10. In no instance shall vehicle and equipment grounds be used in place of personal protective grounds.

9.5.1 Aerial Devices. Aerial devices, whether with an insulated or uninsulated boom, and other maintenance vehicles or equipment that may contact a protective grounded worksite or allow a worker to contact the site, shall be bonded to the worksite grounding system. They shall be bonded (grounded) to the structure as the first step in establishing a grounding system. Multiple vehicles situated in a manner that allows a worker to contact two of them simultaneously shall be bonded together. Ground cables on reels or looped on the vehicle shall be completely unwound to allow thorough inspection of the cable prior to use as well as eliminate destructive forces resulting from induction in the event of a fault at the worksite.

9.5.2 Contact with Grounded Vehicles at Worksite. Vehicles and equipment that are bonded to the worksite grounding system can present a hazardous transferred touch voltage with the surrounding ground (earth) surface. Therefore, any vehicle or equipment bonded to the worksite grounding system (including conductive winch lines) and requiring sustained contact while standing on the ground, shall be equipped with an insulated platform or conductive mat bonded to the vehicle or equipment for the operator to stand on (figure 22).

Figure 22. – Application of conductive mat to provide safe working zone along side a maintenance vehicle. Matting and vehicle are bonded to the worksite grounding system, creating an equipotential zone between operator's hands (vehicle frame) and feet.

Figure 22.

9.6 Opening or Splicing Aerial Conductors

The following procedures shall be followed to create an equipotential work zone at the splice location (mid span or away from support structures).

9.6.1 Splicing at Ground Level

Prior to opening or splicing an electrically isolated line conductor or overhead ground wire, three-phase grounding shall be established at adjacent structures on both sides of the splice site or at the second set of structures as a matter of convenience (figure 23). Additional single-phase grounds shall be established for each conductor or overhead ground wire to be spliced, at both adjacent structures. Continuous grounding must be in place while lowering, splicing, and reinstalling the conductor or overhead ground wire.

A ground rod shall be located within 10 feet of the working area where conductors or overhead ground wires are to be spliced. The ground rod shall be bonded (jumpered) to both ends of the conductor or ground wire (using a hot stick) to maintain continuity prior to cutting. Splicing shall be carried out on a conductive mat which is bonded to the ground rod and conductor or ground wire to be worked. These jumpers shall maintain continuous bonding throughout the splicing activity. Workers shall remain on the mat while handling the conductor or ground wire.

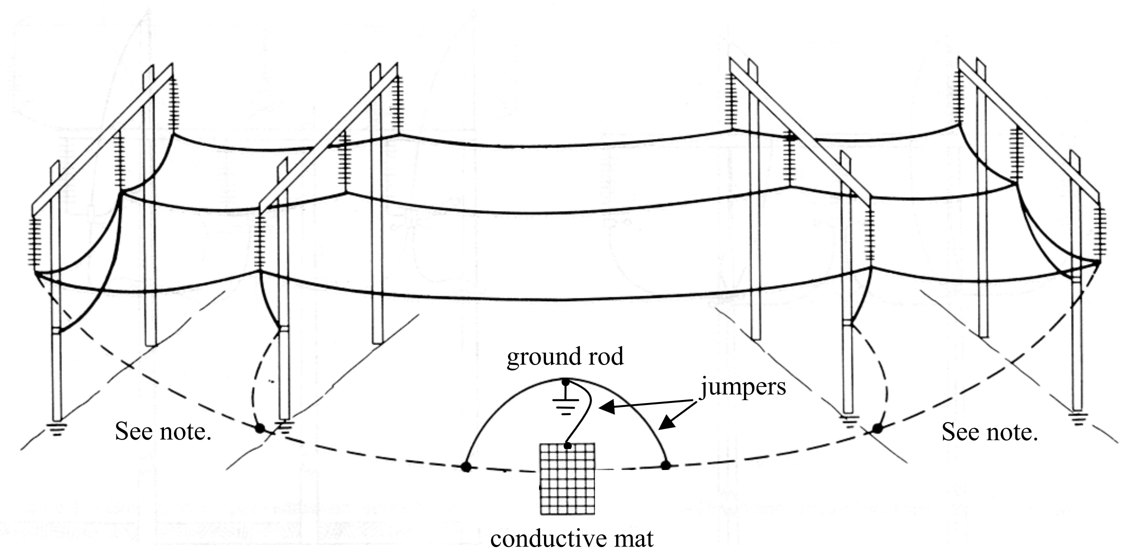


Figure 23. – Splicing line or ground wires at ground level on a conductive mat equipotential work zone. Jumpers are not to be disturbed or disconnected at any time during splicing activity. Note: Three-phase grounds on the structure should be located at the adjacent structure to the worksite if the work permits (shown here at 2nd structure as option to accommodate the work).

It is recommended that the mat be roped off and an insulated walkway provided for access to the mat, such as dry plank or fiberglass ladder at least 10 feet long. If a vehicle is involved in the splicing operation, it must be bonded to the common ground rod for the conductive mat and conductor or ground wire. If the splice is to be completed from a vehicle, the vehicle and conductor or overhead ground wire shall be grounded as stated for a conductive mat. Workers shall remain on the vehicle or take precaution against hazardous step and touch potentials.

An insulated platform may be used in lieu of a conductive mat. In this case, grounding and jumpering is performed similarly as is shown in figure 23, except that the jumper between ground rod and mat (platform) is omitted. Workers and equipment shall not extend over the insulated platform or come in contact with earth.

9.6.2 Splicing from Aerial Lift Equipment

Prior to opening or splicing an electrically isolated conductor or overhead ground wire, three-phase protective grounds shall be installed at both adjacent structures to the worksite, similar to that shown in figure 23. The aerial lift equipment shall be bonded to a driven ground rod installed midway and alongside the vehicle frame. This ground rod shall be bonded to the conductor or ground wire to be worked on with a protective ground of sufficient length to reach from the aerial worksite to ground level. In addition, conductive aerial platforms shall be bonded directly to the worksite conductor or ground wire with a second, shorter protective ground jumper. Any other conductors or ground wires that are within reach at the worksite also shall be bonded to the working conductor or ground wire at the worksite. Workers shall install a jumper cable or section of conductor to maintain the continuity of the conductor or overhead ground wire while accomplishing the splicing operation. The grounds and jumper shall be left in place until the splice is completed. Ground crew must take precaution to avoid hazardous step and touch potentials near the vehicle (paragraph 9.5.2).

The electrical bond between the vehicle ground rod and worksite conductor or ground wire to be spliced must be accomplished with a protective ground cable sized to carry the available fault current. In some situations this may call for substantial length of cable suspended from the aerial worksite to ground level. This ground cable shunts earth fault current which could otherwise flow in a conductive boom. Conductive booms of aerial lifts should not be used as the sole grounding conductor. The direct ground jumper from the aerial worksite to the platform controls touch potential.

9.7 Grounding Insulated Power Cable

Worksite protective grounding for insulated power cable terminations shall be accomplished similar to that required for grounding on power line structures. Cable phase terminals (terminators, potheads, etc.) and shield conductors shall be bonded to the worksite grounding system. The remote (ungrounded) end of the cable shall be treated as if energized. Refer to paragraph 8.4.3 for general cable testing procedure.

Although the cable phase conductors are ungrounded (isolated) at the remote (non-worksite) end of the cable, the cable shields are grounded there. Therefore, workers should take necessary precautions against hazardous step or touch potentials that could develop at the worksite due to a system ground fault at the remote end. Power line structure grounding described in Section 9 will provide adequate protection.

10. CARE, INSPECTION, AND TESTING PROTECTIVE GROUNDING EQUIPMENT

Like any other tool of the trade, grounding equipment must be maintained in good electrical and mechanical condition. This is ensured through proper handling, storage, inspection, and testing of equipment.

10.1 Care

Grounds shall be stored in suitable locations free from excessive moisture and mechanical disturbance. For outdoor use, grounds shall be placed in weatherproof padded boxes or canvas bags for transportation, or carefully coiled and hung on the inside of the truck. Grounds should not be thrown into the bottom of a truck with other equipment piled on top of them. Grounds with permanently connected hot sticks and separate hot sticks used to apply grounds shall be transported and stored in the same manner as live-line equipment, FIST 3-29. [3]

Figure 24. – Example of proper storage of protective grounds, coiled and hung on wall.

10.2 Inspection

10.2.1 Ground Cable Assemblies

Before each use, protective grounds shall be given a visual and mechanical inspection. Cables shall be carefully examined to detect broken strands, corrosion, and other physical damage to the cable, particularly near the ferrules due to frequent flexing. Connections between the cable and ferrules, and between ferrules and clamps should be checked for tightness. Ground clamps should be checked for damage (cracks, splits, etc.) and repaired if possible or discarded and replaced. Serrated jaws should be replaced when they become worn. Clamp tightening bolt threads should be checked for wear and smoothness of mechanical operation. If in doubt, electrical resistance tests may be performed to check electrical integrity of the cable, ferrules, and clamps (paragraph 10.3).

10.2.2 Live-Line Tools

Hot sticks and other live-line tools used to install protective grounds shall be visually inspected before each use. They shall be free from defect that could inhibit mechanical function or insulation value (dielectric withstand capability).

10.3 Testing

In addition to inspection before each use, protective grounds and associated live-line tools used for their installation shall be given initial and annual electrical tests as follows.

10.3.1 Ground Cable Assemblies

Electrical resistance of the various parts and joints of ground cable assemblies (figure 26) shall be measured by the direct-current millivolt drop test method. At a minimum, resistance of the cable (A-D), and cable-to-ferrule (A-B, D-E) and ferrule-to-clamp (B-C, E-F) connections shall be measured. Other joints or moving parts of clamps (depending on manufacture) can also be measured, for example, across the cone area of all-angle clamps (figure 25). Clamps should be firmly attached to a post if joints dependent on the force of clamping are to be measured.

Figure 25. – All-angle ground clamp.

Pins should be used to pierce the cable jacket and contact the conductor about one inch from the ferrule shoulders at each end of the cable (A & D) and length of cable between the pins carefully measured. Good testing practice calls for standardizing the locations of measurement points for consistency and data trending. A dc test current of approximately 20 amperes is passed through the ground cable assembly from tip to tip of the clamps (G). Do not use alternating-current as this will introduce error due to effects of induction. A good quality regulated dc power supply having minimal ac ripple and current control output, and a digital voltmeter is required. High ac ripple content, as is common in unfiltered supplies, is not suitable for this test because circuit inductance will affect the readings. The resistance, in ohms, of each part is determined by dividing the measured voltage drop (*V*), in volts, across each part by the power supply current (*I*), in amperes. Readings should be taken to within ±0.1mV and ±0.1A accuracy.

As an alternative, a good quality four-terminal type micro-ohmmeter may be used to make ground cable assembly resistance measurements. This type of test instrument has the advantage of reading directly in ohms. The instrument current and voltage test leads, commonly referred to as C and P, respectively, must be connected to the ground cable assembly under test in a similar manner as described above for the power supply test method; or the test instrument may provide built-in clamping posts for this purpose.

Ground Cable Components Maximum Recommended Measured Resistance:

Measurement	Resistance
Across each fixed or moving part and joint of ferrules and clamps:	50 micro-ohms (less than 20 typical)
Cable (points A to D):	Not to exceed resistance computed from Table 3 (paragraph 6.2.2) by more than 5%.

If any of the component resistances of clamps and ferrules exceed 50 micro-ohms, the clamp or ferrule should be examined for looseness or defect, and repaired or replaced as necessary. Any cable exceeding the five percent resistance tolerance should be carefully examined for deterioration or damage and replaced as necessary.

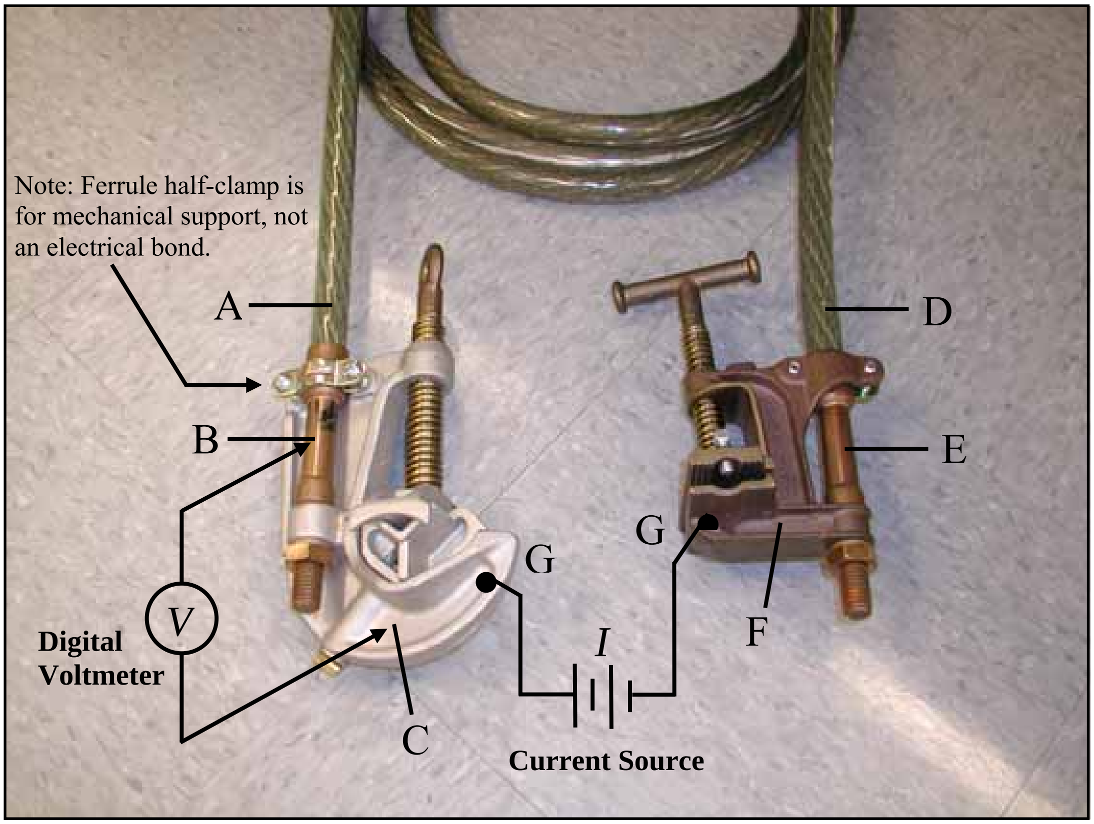


Figure 26. – Ground cable assembly connection points for dc millivolt drop resistance measurement. Test current (*I*) is passed through the tips of the clamps (G). Example volt drop (*V*) measurement is shown for ferrule-to-clamp (B-C) threaded-stud bolt connection. Note layout of cable has no effect on measurement results.

Test Applications Note:

The direct-current millivolt drop test is a sensitive test method that can detect loose or damaged parts of ground cable assemblies which might otherwise pass undetected by tests using alternating-current. Alternating-current tests can introduce inductive voltage drop errors which mask the small values of calculated resistance.

Ground cable assembly total resistance, which can be measured by the direct-current millivolt drop test, cannot be used by itself to predict in-service performance of protective grounds (exposure voltage) under fault conditions with alternating-currents. Neither will standardized testing with alternating-current provide accurate results. Rather, the *in-service worker exposure voltage must be predicted considering the installed layout of protective grounds at the worksite (paragraph 6.2.2).*

10.3.2 Live-Line Tools

Hot sticks and other live-line tools shall be tested for insulation value in accordance with FIST 3-29 [3] and IEEE Standard 978 [10] guidelines for shop testing procedure.

10.4 Records

Each protective ground cable shall be numbered or otherwise identified by means of a permanently attached tag, or the identification stamped on one of the clamps. A test record of the initial and annual resistance tests for each ground cable shall be maintained by the responsible office for as long as the ground cable remains in service. Records shall show the resistance of all measured parts of the ground cable assembly in order to track any change in condition with time and usage. Insulation test results for associated live-line tools shall also be logged.

11. REFERENCES

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[2.] Facilities Instructions, Standards, and Techniques (FIST) Volume 1-1, Hazardous Energy Control Program, U.S. Department of the Interior, Bureau of Reclamation Hydroelectric Research and Technical Service Group, D-8450, Denver Office, March 2002.

[3.] Facilities Instructions, Standards, and Techniques (FIST) Volume 3-29, Energized Facility Maintenance, U.S. Department of the Interior, Bureau of Reclamation Facilities Engineering Branch, Denver Office, May 1990.

[4.] ASTM F 855-97, Standard Specifications for Temporary Protective Grounds to Be Used on De-energized Electric Power Lines and Equipment, 1997.

[5.] IEEE 80-2000, IEEE Guide for Safety In AC Substation Grounding, 2000.

[6.] IEEE Document 94 SM 607-2 PWRD, Factors In Sizing Protective Grounds, IEEE Engineering in the Safety, Maintenance and Operations of Lines Subcommittee Report, June 1, 1994

[7.] IEEE 1246-2002, IEEE Guide for Temporary Protective Grounding Systems Used in Substations, April 2002

[8.] IEEE 1048-2003, IEEE Guide for Protective Grounding of Power Lines, 2003.

[9.] ASTM D120-02a, Standard Specification for Rubber Insulating Gloves, 2002.

[10.] IEEE 978-1984, IEEE Guide for In-Service Maintenance and Electrical Testing of Live-Line Tools, 1984.

[11.] Dalziel, Charles F., *Electric shock hazard*, IEEE Spectrum, February 1972.

[12.] Atwater, P. L. & DeHaan, J. M., *Staged Fault Evaluation of High-Voltage Equipment Maintenance Safety Grounding at a Large Hydro-Electric Powerplant*, 0-7803-5569-5/99 Energy Development and Power Generation Committee, 1999 IEEE Power Engineering Society Summer Meeting.

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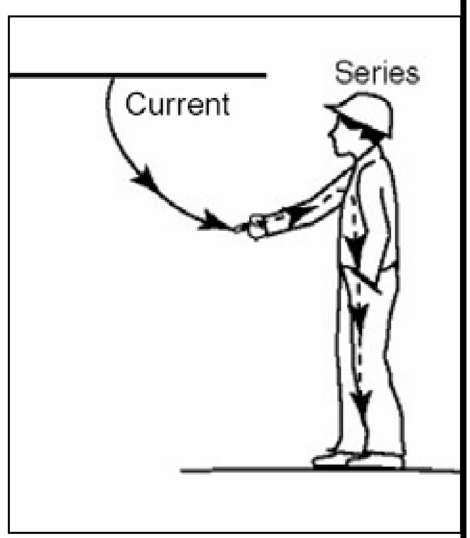
APPENDIX A

Qualitative Effects of Electric Current on the Human Body

60 Hz body current* (mA)	Effect
5000	tissue burning
250	fibrillation (probably fatal without resuscitation)
75	fibrillation threshold for heart (0.5% chance)
30	respiratory paralysis
25	breathing difficult
10	painful shock / let-go threshold
7	painful sensation
3	mild sensation
1	perception threshold

* Body currents for 68kg (150lb.) man. Current varies depending on body weight for male or female.



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APPENDIX B

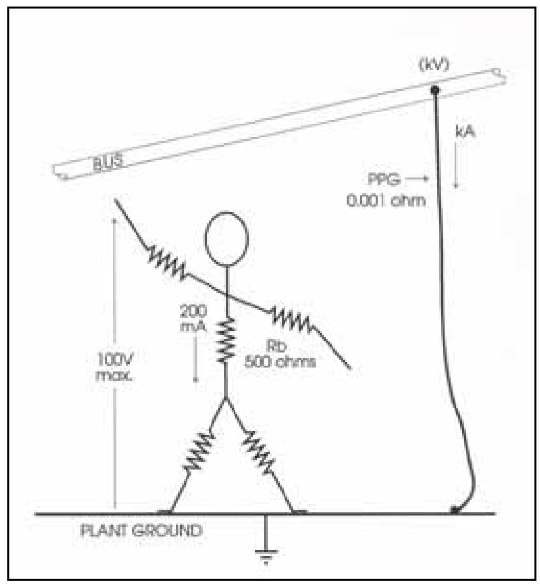
Derivation of Safe Exposure Voltage for Shock Survival

Extensive research on the effects of short duration shocks or current through the human body was conducted by C. F. Dalziel at the University of California, Berkeley in the 1960s. [11] From this research, an empirical equation was developed relating electric shock duration and body current to the condition of ventricular fibrillation of the heart. A high probability of death follows once fibrillation occurs without resuscitation.

A safe shock body current is one that, in all probability (99.5%), will not cause fibrillation. The Dalziel equation for a safe shock is:

$$I_k = K/\sqrt{t}$$

where I_k = max. safe body current (mA)
t = shock duration $0.0083<t<3$ s
K = factor for body weight
= 116 for 110lb. person
= 157 for 150lb. person
= 165 for 165lb. person.



Shock currents below the threshold determined by this equation, although not lethal, may be painful and cause involuntary movement.

Reclamation protective grounding safety criteria establishes safe body currents solving the above equation with K factor for a 110lb. person and fault clearing times of 0.5 s (30 cycles for transmission lines) and 0.25 s (15 cycles for plants & switchyards). Resulting safe body currents are 164 mA and 232 mA, respectively. To be conservative, these currents are rounded down to 150 mA (30 cycles) and 200 mA (15 cycles).

A 200 mA shock is depicted in the figure during the moment a personal protective ground (PPG) carries thousands of amperes fault current. An exposure voltage (ground cable impedance voltage drop) appears between the points of body contact with bus and plant ground (hand and feet). Body current will flow according to Ohm's law and in the worst case is equal to the exposure voltage divided by the body core resistance. Surface or skin resistances of the hands and feet (including gloves or shoes) which may be considerably higher than core resistance are neglected. As stated in Section 4, 500 ohms is assumed for core resistance and is conservatively low. This core resistance value is assumed for all current paths through the body (hand-to-hand, hand-to-feet, foot-to-foot). Therefore, maximum safe exposure voltages can be computed with Ohm's law for 15-cycle (200 mA) and 30-cycle (150 mA) fault clearing times:

Exposure voltage = safe body current I_k x core resistance R_b

= 0.2 x 500 = 100 volts (15 cycles)

= 0.15 x 500 = 75 volts (30 cycles)

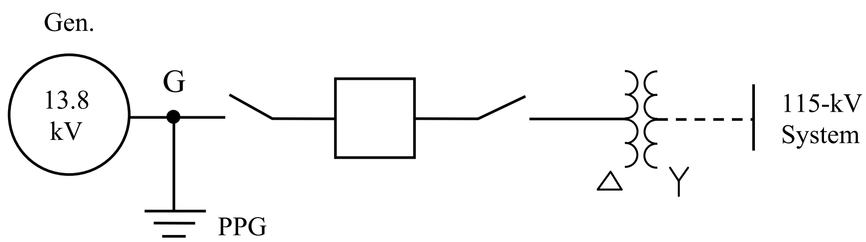
It is clear that the allowable safe body current (exposure voltage) decreases with increasing duration of shock. Any condition that might increase the fault clearing time beyond the15- and 30-cycle values assumed for protective grounding service should be evaluated. Factors such as slower protective relay operating time, delayed backup fault clearing, and reclosing may call for an adjustment in longer shock time and lower allowable exposure voltage. On the other hand, fault clearing times less than 15 cycles are not recommended for determining allowable exposure voltage.

Additional reference information on this subject may be found in IEEE Std. 80. [5]

APPENDIX C

Example Protective Ground Cable Sizing

A 13.8-kV generator and step-up power transformer are connected to a 115-kV power system in the figure below. Specific detail for the 115-kV connection between power system and transformer is omitted for simplicity. Personal protective grounds (PPG) are to be connected at point (G) for hands-on work on the generator bus and stator winding. The generator is on an electrical and mechanical clearance that permits workers around and on the rotating parts of the generator. The generator circuit breaker and associated disconnect switches are open. The transformer is energized from the 115-kV system. The available three-phase fault current at (G) from the 115-kV power system is 20,000 amperes symmetrical with an impedance X/R ratio of 20. The generator fault current contribution at (G), if it could rotate, is 15,000 amperes with an X/R ratio greater than 20. What is the minimum conductor size permitted for the protective grounds?



First determine the maximum available fault current at the worksite (G) where protective grounds are to be installed. Since the generator is on clearance and cannot rotate, the only source of available fault current at the worksite is from the 115-kV power system (20,000 amperes). Next, select a cable ampacity table from paragraph 5.1.1 to determine cable size. Since the power system fault impedance X/R ratio is greater than 10, use Table 2B. The grounds are to be installed in a powerplant, therefore the fault clearing time is assumed to be 15 cycles as given in paragraph 4.1. From Table 2B, the minimum cable size with an ampacity equal to or greater than 20,000 amperes for 15 cycles is #2/0 AWG copper (23,000 amperes). From ASTM F855, a grade 3 clamp and ferrule is compatible with #2/0 conductor. Note that if the cable size had been incorrectly selected from table 2A, a #1/0 conductor (21,000 amperes) would appear adequate. However, for this grounding application the smaller conductor would be undersized due to the additional heating effect of the dc offset component of fault current (refer to figure 3, Section 5).

A #2/0 copper cable has adequate ampacity (thermal capacity) for this grounding application. However, having adequate ampacity alone does not ensure the cable is suitable for installation at the worksite. Worker exposure voltage which is dependent on cable length must also be determined. Appendix D continues this grounding example with exposure voltage calculation.

APPENDIX D

Example Powerplant Grounding Worker Exposure Voltage Calculation

A set of three-phase protective grounds consists of 15 feet of #2/0 AWG copper cable per phase. The grounds are installed on a 13.8-kV generator bus which is connected to a single generator and step-up power transformer. The maximum available three-phase fault current is 20,000 amperes from the power system (generator on clearance and cannot rotate).

Case 1: Workers may range up to up to 10 feet away from the point of attachment of the grounds on the bus towards the generator where they may come in contact with the bus or generator winding and other grounded objects. What is the exposure voltage 10 feet from the grounds?

From paragraph 6.2.2, first calculate the ground cable resistance (IR) voltage drop. Using Table 3 the resistance per foot of #2/0 conductor at 20ºC is 0.0829 milliohms. The voltage drop is then:

Cable resistance volt drop = milliohms/ft. x length (ft.) x fault current (kA)

= 0.0829 x 15 x 20 = 24.9 volts.

Figure 7(A) applies to this grounding situation with the grounds located between the worker and source of fault current (power system). To find the predicted exposure voltage, adjusted for ground loop induction effect, multiply the cable resistance volt drop by K_{m1} = 2.2 from Table 4A (reprinted below) for D = 10 (10-foot loop depth), or:

Exposure voltage = ground cable resistance volt drop x K_{m1} (K_{m2} = 1)

= 24.9 x 2.2 = 54.8 volts.

The predicted worker exposure voltage including ground loop induction effect is about twice the value based only on ground cable resistance voltage drop. However, the predicted exposure voltage meets the 100-volt criteria from Section 4. Therefore, the 15-foot, #2/0 grounds are satisfactory for the job.

Case 2: What is the exposure voltage if workers can also move along the bus toward the power system, up to 10 feet from the point of attachment of the grounds?

In this case figure 7(B) from paragraph 6.2.2 applies because the workers can position themselves between the grounds and source of fault current (power system), which will produce a higher predicted exposure voltage. Previous values of cable resistance voltage drop and K_{m1} multiplier apply here because the ground cable length (L = 15) and ground loop depth (D = 10) are the same. The exposure voltage is found by multiplying the ground cable resistance voltage drop (24.9 V) by K_{m1} = 2.2 and by K_{m2} = 1.5 from Table 4B (reprinted below) for ratio D/L = 0.5 (choose closest D/L ratio in table for this case with D/L = 0.67), or:

$$\text{Exposure voltage} = \text{cable resistance volt drop} \times K_{m1} \times K_{m2}$$

$$= 24.9 \times 2.2 \times 1.5 = 82.2 \text{ volts.}$$

The predicted worker exposure voltage including ground loop induction effect is about three times the value based only on ground cable resistance voltage drop. However, the predicted exposure voltage meets the 100-volt criteria from Section 4. Therefore, the 15-foot, #2/0 grounds are still satisfactory for the job.

Table 4A
Ground Cable Reactance Multiplier K_{m1} for use with figure 7(A and B)

<table>
<tr><th rowspan="2">Ground cable size,
AWG or kcmil</th><th colspan="5">Depth of ground loop - D(ft.)</th></tr>
<tr><th>1</th><th>5</th><th>10</th><th>15</th><th>20 30</th></tr>
<tr><td>2</td><td>1.3</td><td colspan="3">1.5</td><td>1.6</td></tr>
<tr><td>1</td><td>1.4</td><td colspan="3">1.7</td><td>1.8</td></tr>
<tr><td>1/0</td><td>1.6</td><td colspan="3">1.9</td><td>2.1</td></tr>
<tr><td>2/0</td><td colspan="2">1.8</td><td colspan="2">2.2</td><td>2.4</td></tr>
<tr><td>3/0</td><td>2.0</td><td>2.4</td><td>2.6</td><td>2.7</td><td>2.9</td></tr>
<tr><td>4/0</td><td>2.3</td><td>2.9</td><td>3.1</td><td>3.3</td><td>3.5</td></tr>
<tr><td>250</td><td>2.6</td><td>3.3</td><td>3.6</td><td>3.8</td><td>4.0</td></tr>
<tr><td>350</td><td>3.3</td><td>4.2</td><td>4.7</td><td>5.0</td><td>5.3</td></tr>
</table>

Reprinted from paragraph 6.2.2.

Table 4B
Ground Cable Reactance Multiplier K_{m2} for use with figure 7(B)

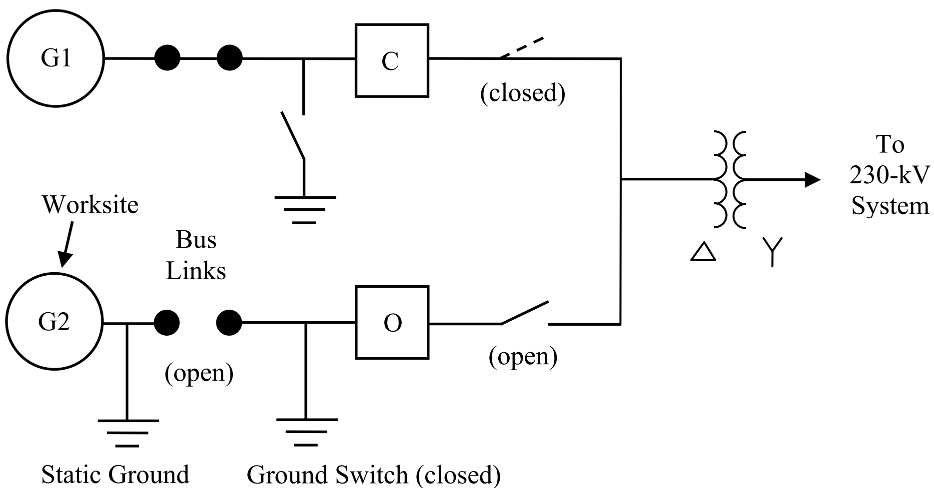
<table>
<tr><th rowspan="2">Ground cable size,
AWG or kcmil</th><th colspan="6">Ratio D/L</th></tr>
<tr><th>0.5</th><th>1</th><th>1.5</th><th>2</th><th>2.5</th><th>3</th></tr>
<tr><td>2</td><td rowspan="3">1.2</td><td rowspan="3">1.5</td><td rowspan="3">1.8</td><td rowspan="3">2.1</td><td rowspan="3">2.4</td><td rowspan="3">2.7</td></tr>
<tr><td>1</td></tr>
<tr><td>1/0</td></tr>
<tr><td>2/0</td><td rowspan="5">1.5</td><td rowspan="5">1.8</td><td rowspan="5">2.2</td><td rowspan="5">2.6</td><td rowspan="5">3.0</td><td rowspan="5">3.4</td></tr>
<tr><td>3/0</td></tr>
<tr><td>4/0</td></tr>
<tr><td>250</td></tr>
<tr><td>350</td></tr>
</table>

Reprinted from paragraph 6.2.2.

APPENDIX E

Double-Isolation Grounding for Generators Connected to a Common Step-Up Power Transformer

Two 13.8-kV generators are bussed to a common power transformer as shown in the figure. Unit G2 is on a clearance for maintenance which requires protective grounding. Unit G1 must remain on-line. Both generators are equipped with a ground switch on the generator side of the unit circuit breaker. These ground switches have a short-time current rating of 120,000 amperes for one second. Both generators also have removable bus links at their stator air housing as shown. The maximum available fault current at G2 is 80,000 amperes with X/R>20 from the combined power system and G1 current contributions (G2 contribution omitted).



Conventional protective grounding might be attempted at G2. Adequate ground cable ampacity for the available fault current (80,000 amperes) could *almost* be achieved using two parallel 250 kcmil conductors per phase. From table 2B, paragraph 5.1 for 15-cycle clearing, two parallel 250 kcmil conductors would have a combined ampacity of 79,200 amperes (including 1.8 multiplier for parallel cables). However, at this current magnitude the cables are likely to fail mechanically due to severe magnetic separation forces between phases. In addition, the worker exposure voltage is likely to exceed 100 volts for any practical working distance from the point of attachment of the ground cables to the generator bus.

Double-isolation grounding (shown for G2 in figure) avoids the problems with conventional grounding because: 1) the closed ground switch has ample capacity to carry the available fault current and trip upstream protection devices, and 2) no fault current or exposure voltage appears at the worksite due to the open bus links. Static grounds are installed at G2 to ensure the stator winding is at ground potential. G2 must be on the equivalent of an electrical/mechanical clearance that allows workers around and on the rotating parts of the machine (cannot rotate).

APPENDIX F

F1. TECHNICAL CONSIDERATIONS IN PROTECTIVE GROUNDING ON TRANSMISSION LINES.

A. **Connection to True Earth.** Electrically speaking, true earth can be considered as a conductor deep in the earth which has little or no resistance to electrical current. With this understanding, the resistance of a connection to true earth can be measured. Tower footing resistance means the resistance between the tower footing and true earth. This also is the meaning of ground mat resistance. Each tower and structure has its own resistance to true earth, and these values can vary quite widely.

The top surface of the earth then, is not true earth. Current can, and will, exist along the top surface of the earth, but not very far, since it tends to go deep into the earth rather than horizontally along the top of the ground. The resistance at the surface of the ground can be very high depending on its condition - rocky, sandy, wet, dry, etc. Thus, when current flows across the surface of the ground and to a ground rod or a steel tower footing, a voltage can be developed that is hazardous to groundmen.

Regarding power lines the ground fault current path is down the steel tower legs, or the personal protective ground cable to a ground rod, and then it spreads out at the ground surface around the tower legs or ground rod, and finally towards true earth. The closer a person is to the ground rod or the tower leg or the down guy, the greater the concentration of the current and the higher the voltage. The wider apart a person's legs are, or the greater the distance from the legs on the ground to the hands on the steel, the larger the voltage difference across the body. For this reason groundmen are cautioned to stay clear of structures at the ground surface level.

B. **Step Potential.** Step potential is caused by fault current through the earth. The current creates a voltage drop at the earth's surface. A person standing with feet apart bridges a portion of this drop. This places a potential difference from foot to foot. A test program was conducted to define the characteristics of this voltage drop across the earth. A rod was driven at a remote location. Voltage was measured at varying distances from the energized rod. A plot of the voltage distribution showed it decreases with distance from the rod, but in a nonlinear manner. A curve of resistance versus distance as developed by the James C. Biddle Co. is redrawn in Figure l.

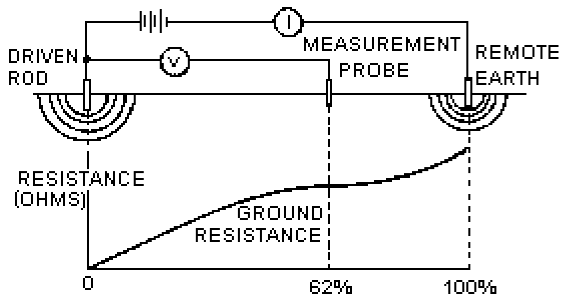


Figure 1
Distance from Driven Rod
Resistance vs. Distance

This nonlinearity can be explained by considering the ground electrode as a system, consisting of concentric cylinders of earth, rather than just the rod itself, see Figure 2.

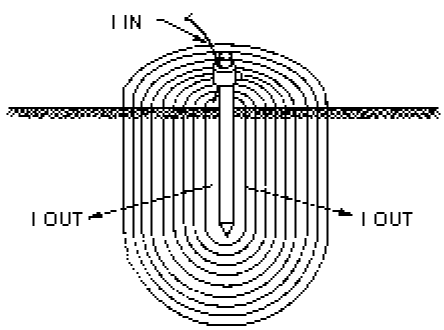


Figure 2
Earth Electrode System

Recall the basic equation for resistance of a conductor.

$$R = \frac{pl}{A}$$

Where R equals the resistance between two points, p=conductor resistivity, A is the cross sectional area of the conductive path and l the length of the conductive path. Current into the rod is radiated in all directions from the rod and subsequently from each concentric cylinder. Each concentric cylinder has a larger surface area than the preceding one. Therefore, resistance increases with each incremental increase in distance but by smaller amounts. Eventually, a point is reached where the outer shell has such a large surface area that any further increase adds little to the total resistance. At this point the resistance can be considered constant. It rises rapidly again as the measuring electrode intercepts the shells associated with the remote ground. The value of resistance finally attained is dependent upon the soil resistivity (p). Resistivity varies with the amount of soil moisture, salts present, temperature, and type. Resistance is further complicated by the rod diameter, length, number of rods used, and spacings. The actual current distribution in the earth is quite complicated because of levels or pockets of differing resistivities. It is similar to a series-parallel impedance electric circuit.

For the step potential problem this means that a person standing near the point where fault current enters the earth may have a large potential difference from foot to foot. It also means that the potential difference over the same span will be less and less as the span is moved away from the fault current entry point. Figure 3 illustrates this.

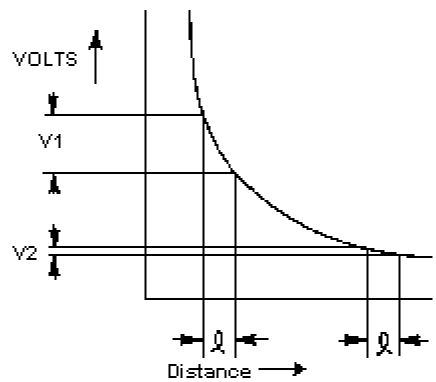


Figure 3
Variation of Step Potential
With Distance

C. **Use of Protective Mats.** The use of a local mat will provide adequate protection for a worker. The mat may be either insulating, to isolate the person and interrupt a circuit path, or conducting, which maintains constant potential over the worksite walk area. The use of a conducting mat moves the problem area. The maximum voltage gradient now starts at the mat's edge. Therefore, a worker must remain on the mat to stay in a safe zone. An insulating or conductive mat should contain an insulated approach, providing a means of entering or leaving the work area safely.

D. **Touch Potential.** Touch potential is a problem similar to step potential. It involves a fault current in the earth establishing a potential difference between the earth contact point and some remote hardware. Figure 4 illustrates touch potential.

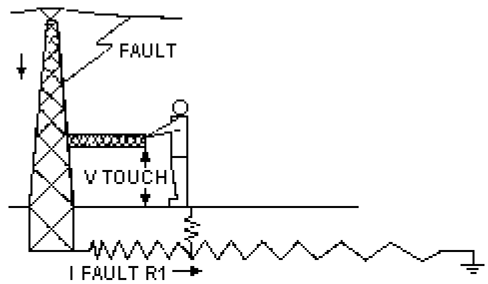


Figure 4
Touch Potential

Protection for touch potential is the same as for step potential, and this is the objective of Reclamation's and Western's use of switch operating platforms. Again, the worker must remain upon a local conductive mat as the highest voltage gradient has been moved to the mat's edge. Maximum step potential exists at the edge.

E. **Single-Point vs. Double-Point Grounding.** Another problem area created by fault current in the earth is the question of single-point versus double-point grounding. Single point is the placement of safety grounds or jumpers on the work tower only. Double point is the placement of jumpers on the adjacent tower on either side of the work tower. The work tower may or may not also have jumpers applied.

In the case of double-point grounding with no jumpers at the worksite, there will be no step-potential hazard. There is no current into the earth at the worksite to create the hazard. The high-voltage gradients associated with the current are present at the two adjacent structures only, unless the line has overhead ground wires. In that case ground fault current will exist from the grounded structures to the worksite structure on the overhead ground wires, causing hazardous voltage gradients there.

However, a worker on the work structure in contact with energized hardware is in the worst possible position. The structure is at zero volts and with the hardware energized, the full voltage rise (from grounded adjacent structures) is transferred across the worker. The use of the third jumper set to develop a safe work zone eliminates this problem. The use of three safety jumper sets provides little additional protection above the use of a single set, properly placed, at the worksite. If adequate safety can be maintained with a single-jumper set, then the use of one versus three sets becomes a matter of economics not safety.

F2. TECHNICAL CONSIDERATIONS IN PROTECTIVE GROUNDING IN SUBSTATIONS AND SWITCHYARDS.

A. **Substation Grounding System.** In principle, a safe substation grounding design has two objectives:

(1) Provides means to carry and dissipate electric currents into the ground under normal and fault conditions without exceeding any operating and equipment limits or adversely affecting continuity of service.

(2) Assures such a degree of human safety that a person working or walking in the vicinity of grounded facilities is not exposed to the danger of a critical electric shock.

Some 3 to 4 decades ago, a great many people assumed that any object grounded, however crudely, could be safely touched. This misconception probably contributed to many tragic accidents in the past.

A low station ground resistance is not, in itself, a guarantee of safety. Since there is no simple relation between the resistance of the ground system as a whole and the maximum shock current to which a person might be exposed, a station of relatively low ground resistance may be dangerous under some circumstances*, while another station with very high resistance may still be safe or can be made safe by careful design.

For instance, if a substation is supplied from an overhead line, a low ground mat resistance is important because a substantial part of the total ground fault current enters the earth, causing an often steep rise of the local ground potential; Figure B5.

If a gas-insulated bus or an underground cable feeder is used, a major part of the fault current returns through the enclosure or cable sheaths directly to the source. Since this metal link provides a low-impedance parallel path to the ground return, the rise of local ground potential is ultimately of lesser magnitude; Figure B6.

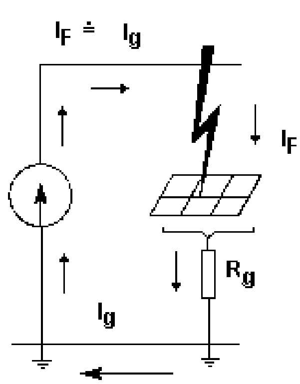


Figure B5.
Fault return circuit for overhead line.

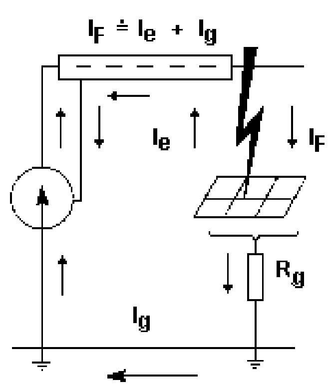


Figure B6.
Fault return circuit for cable or gas-insulated bus.

*The sole exception is the case where IR, the product of the maximum short-circuit current flowing in the ground system and the resistance of the latter, represents a voltage low enough to be contacted safely.

Nonetheless, in either case, the effect of that particular portion of fault current which enters and saturates the earth within the station area has to be further analyzed. If the geometry, location of ground electrodes, local soil characteristics, and other factors contribute to an excessive potential gradient field at the earth's surface, the grounding system thus might be inadequate despite its capacity to sustain the fault current in magnitude and duration, as permitted by protective relays.

Today there is much better understanding of the complex nature of this problem and more awareness of the multitude of factors which have to be taken into account, if the objectives of safe grounding are to be met.

Therefore, a practical approach to safe grounding always concerns and strives for balancing the interaction of two grounding systems:

(1) The permanent one, consisting of ground electrodes buried at some depth below the earth's surface; and

(2) The accidental one, temporarily established by a person touching a grounded object when standing or walking in the exposed area.

B. **Conditions of Danger.** Under typical ground fault conditions, the earth current will produce gradients within and around a substation. Figure 7 shows this effect for a station with a simple rectangular ground grid in homogenous soil, equipped with a number of ground rods along the perimeter.

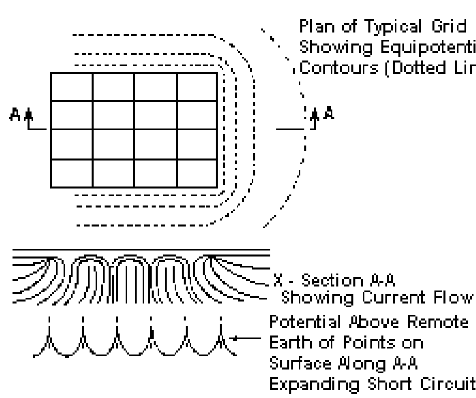


Figure 7.
Current and equipotential contours of a ground grid.

Unless proper precautions are taken in design, the maximum voltage gradients along the earth's surface may be so great (under very adverse conditions) as to endanger a worker walking there. Moreover, dangerous potential differences may sometimes develop between structures or equipment frames which are "grounded" to the nearby earth.

A logical approach to solving this problem is first to determine the circumstances which make electric shock accidents possible. Typical of the type we are considering are:

(1) Relatively high-fault current to ground in relation to the size of ground system and its resistance to remote earth.

(2) Soil resistivity and distribution of ground current such that high-voltage gradients occur at one or more points on the earth's surface.

(3) Presence of the individual at such a point, at such a time, and in such a position that his body is bridging two points of high-potential difference.

(4) Absence of a sufficient contact resistance or other series resistance, to limit current through the body to a safe value, under the above circumstances.

(5) Duration of the fault and body contact, and hence the current through a human body, for a sufficient time to cause harm at the given current intensity.

(6) Coincidence of all the unfavorable factors above.

On one hand, a small study would show that it is absolutely impossible (short of abandoning entirely the distribution and transmission of electric power) to prevent at all times, in all places, and under all conditions, the presence of voltages which might be potentially dangerous.

On the other hand, a relative infrequency of accidents of this type in real life, compared to accidents of other kinds, is without doubt due to the low probability of coincidence of all the unfavorable conditions required.

However, neither fact relieves the engineer of the responsibility of seeking to lower this probability as much as he or she reasonably can, since fatalities due to voltage gradients have occurred. Fortunately, in most cases, such gradients can be reduced to a sufficiently low value by cautious, intelligent design.

C. **Typical Shock Situations.** Figure 8 shows four basic situations involving a person and grounded facilities during a fault.

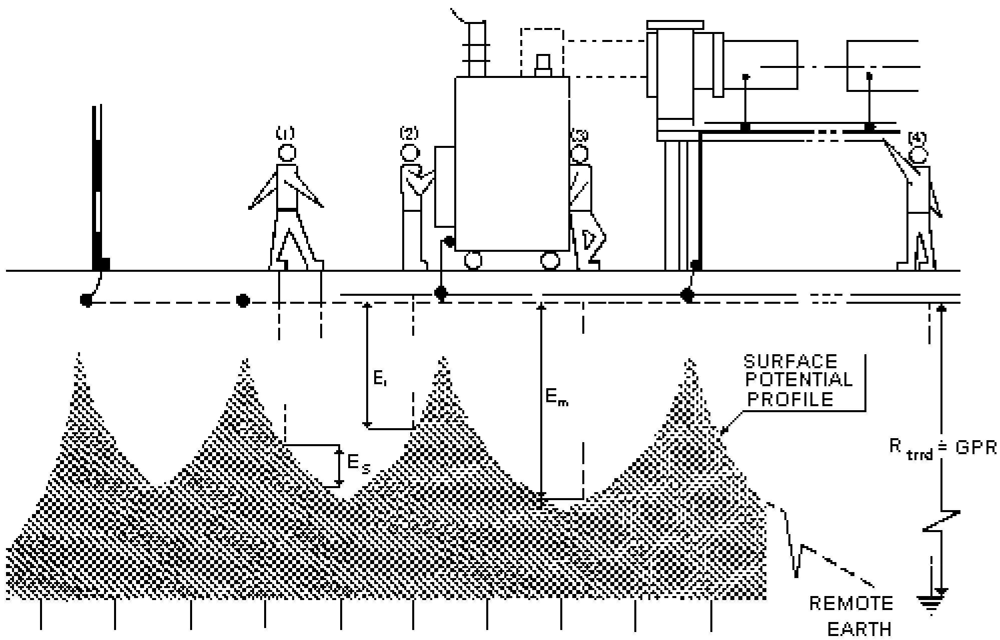


Figure 8.
Basic Shock Situations

(1) Step voltage is caused by fault current through the earth (resistance). It is defined as the difference in surface potential of two points at one pace (1 meter) distance experienced by a person bridging this distance with his feet without contacting anything else.

(2) Touch voltage is caused by a fault current in the earth establishing a potential difference between the feet on the earth contact point and the hand(s) in contact with substation equipment.

(3) Mesh voltage is the worst possible value of a touch voltage to be found within a mesh of a ground grid, if standing at or near the center of the mesh.

(4) Transferred voltage is a special case of the touch voltage in a remote area, where the shock voltage may be approaching (or equal to) the full ground potential rise of a ground electrode.

Typically, the case of transferred voltage occurs when a person standing within the station area touches a conductor grounded at a remote point or a person standing at a remote point touches a conductor connected to the station grounding grid. In both cases during fault conditions, the resulting potential to ground may equal the full voltage rise of a grounding grid discharging the fault current, and not the fraction of this total voltage encountered in the "ordinary" touch contact situations.

D. **Example and Discussion of a Structure Touch Voltage.** Probably the most common example of a related touch voltage is the worker operating a disconnect switch with the remote possibility of the switch faulting to the structure. This condition is shown in Figures 9 and 10. The structure is bonded to the station ground mat with two conductors having a combined resistance R_t.

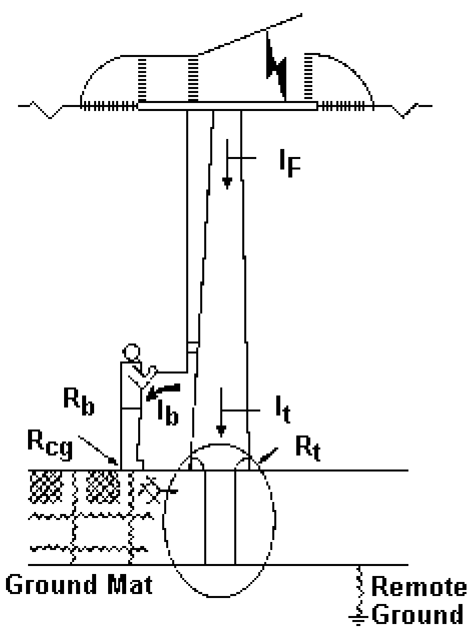


Figure 9.
Switching without switch operating platform.

In Figure 9, the operator places his body in parallel with the tower, and a portion of the fault current (I_F) will be shunted through his body. The current through his body is inversely proportional to the parallel resistance. The circuit is shown in Figure 11.

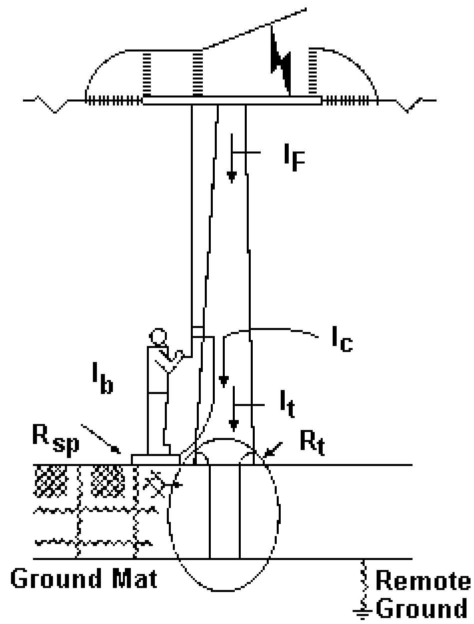


Figure 10.
Switching with switch operating platform.

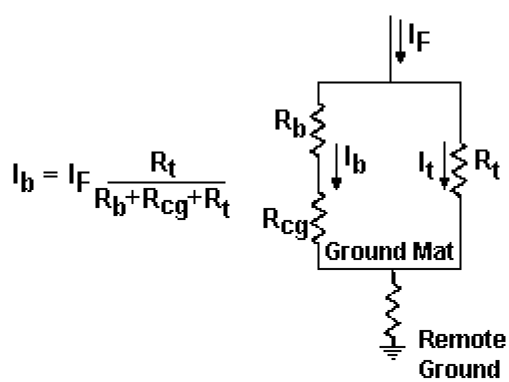


Figure 11.
Electric circuit for switch operator in Figure 9.

With good ground connections, the tower-to-ground mat resistance (R_t) should not exceed 0.0005 ohm. Resistance of the operator's contact to ground (R_{cg}) is a minimal value of 50 ohms based on a ground resistivity of 35 ohm-meters. Resistance of the operator's body (R_b) is assumed to be 500 ohms. We will assume a fault current of 50,000 amperes.

With these assumptions, the current through the operator's body (I_b) is 50,000 X 0.0005/550 or 45 mA, a safe value for 500 milliseconds (30 cycles).

The critical component in this system is R_t. A bad connection to the ground mat with an overall resistance of only 0.005 ohm would endanger the operator (450 mA body current).

Figure 10 shows a method to reduce the touch voltage hazard to the operator. The operator stands on a small metal platform that is connected by a low resistance cable (R_c, 4/0 copper) to the operating handle. This reduces the potential between the operator's hand and feet to nearly zero.

Current to ground through the operating platform is now divided between the operator's body and the short (4-foot) 4/0 copper shunt connection. Four feet of 4/0 copper has a resistance of 0.0002 ohm (Section 6, Table 3). Assume each connector has a resistance of 0.00015 ohm for a total resistance of 0.0005 ohm. These connections are visible for inspection. This circuit is shown in Figure 12.

$$I_{sp} = I_F \frac{R_t}{R_{sp} + \frac{R_b \times R_c}{R_b + R_c} + R_t}$$

$$I_b = I_{sp} \frac{R_c}{R_b + R_c}$$

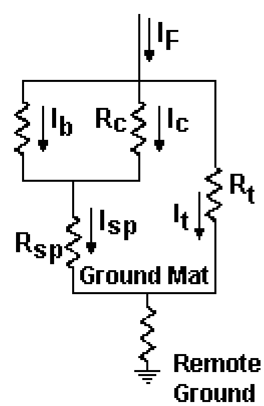


Figure 12.
Electrical circuit for switch operator in Figure 10.

Assuming a switching operating platform resistance to the ground mat (R_{sp}) of 1 ohm, then:

I_{sp} = 50,000 (0.0005/1.0010) = 25 amperes

I_B = 25 (0.0005/500) = 25 microamperes

The current through the operator's body is now only 25 microamperes, and thus the addition of the switch operator's platform has reduced the current through the operator's body by a factor of nearly 2,000!

The magnitude of R_t, R_c, and R_{sp} affect I_b. I_b increases when R_t increases or R_c increases or R_{sp} decreases. The worst conditions being when R_c increases to infinity (broken connection), R_t becomes high due to broken or bad connections to the ground mat, or R_{sp} approaches zero (low resistance to ground mat).

For any one of the above three worst conditions, the current through the operator's body is limited to a safe value. In addition, any damage to the switch platform cable can be easily and visually detected. Maintenance inspections of switch operator platforms should include two important points: 1) bonding cable R_c should be securely connected to the platform steel and operator handle or mechanism as practical (minimize R_c), with no other electrical contact to the structure steel along the way, and 2) the steel platform should be supported completely off the ground surface (maximize R_{sp}).

E. **Sources of Hazardous Current on De-energized Equipment.**

(1) Re-energization. Lethal current will appear on de-energized equipment if it is accidentally reenergized due to switching error or equipment failure. If the de-energized equipment has been properly grounded, the substation relaying should interrupt the current in 15 cycles (250 milliseconds) or less.

(2) Stored energy in capacitors.

(3) Voltage gradients induced by fault currents.

(4) Capacitor-coupled and electromagnetic-coupled voltages. Because of the small lengths and areas involved in substations, these voltages are normally more nuisance than hazard. Note this is not necessarily true for transmission lines.

F. **Grounding/Jumpering Requirements.** Our goal is to create and maintain conditions which limit the current through a worker's body to a safe value. To limit the current to a safe value, the voltage across the worker's body must not exceed 100 volts for 15 cycles

(250 milliseconds) or 75 volts for 30 cycles (500 milliseconds) during an accidental energization of the grounded worksite. See appendix B.

In practice, all points in the protective grounded work area are maintained, as nearly as practical, at the same potential. This is accomplished by connecting (jumpering) all potential sources of electrical energy and conducting components with low resistance grounding jumpers to create a three-phase-to-ground short-circuit. Grounding jumpers must connected between the points of likely body contact, usually from the circuit phase conductors to grounded objects (ground grid), in a short and direct manner. The frame of the equipment is (and must be) permanently connected to the ground grid.

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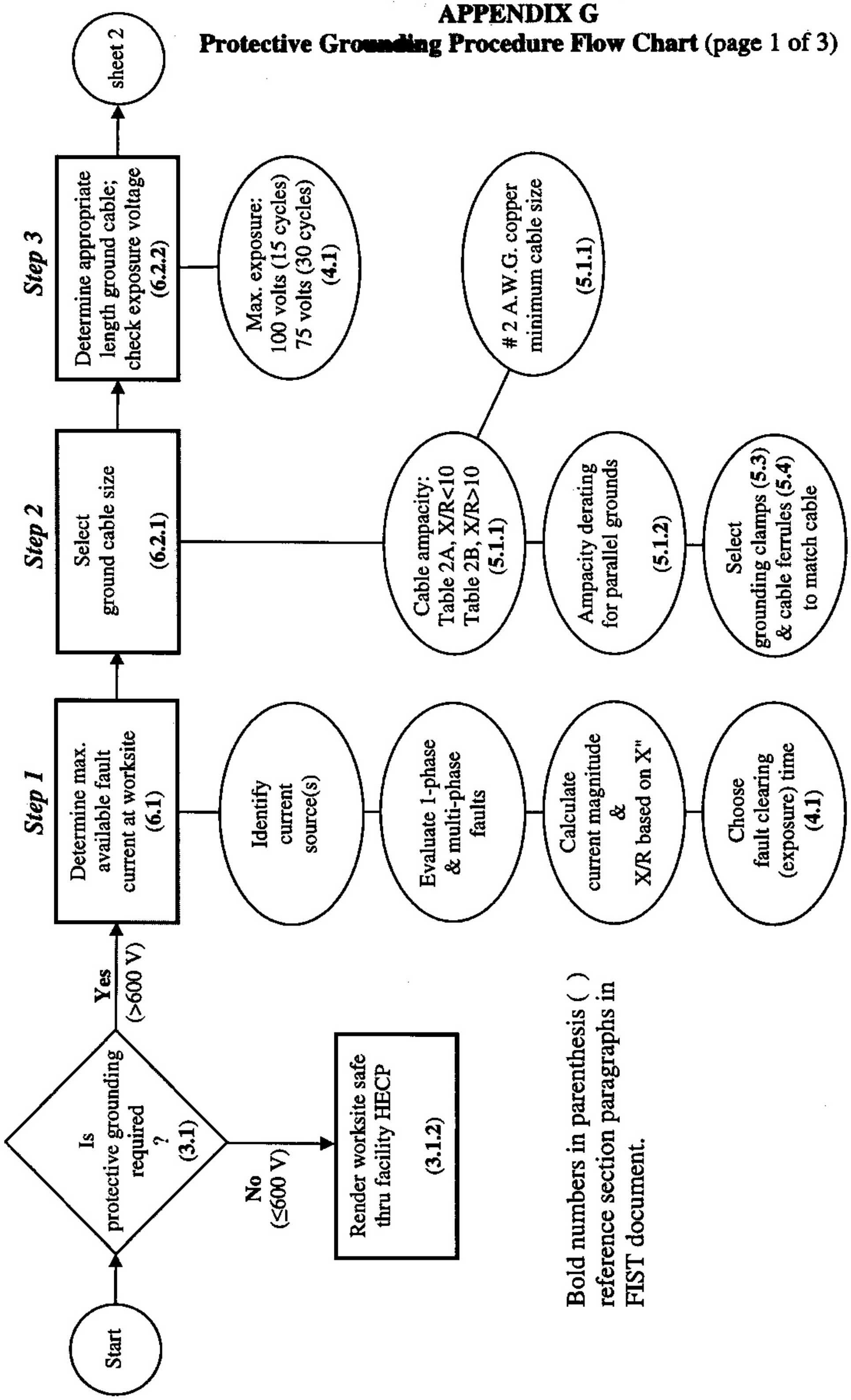
APPENDIX G

Protective Grounding Procedure Flow Chart (page 1 of 3)



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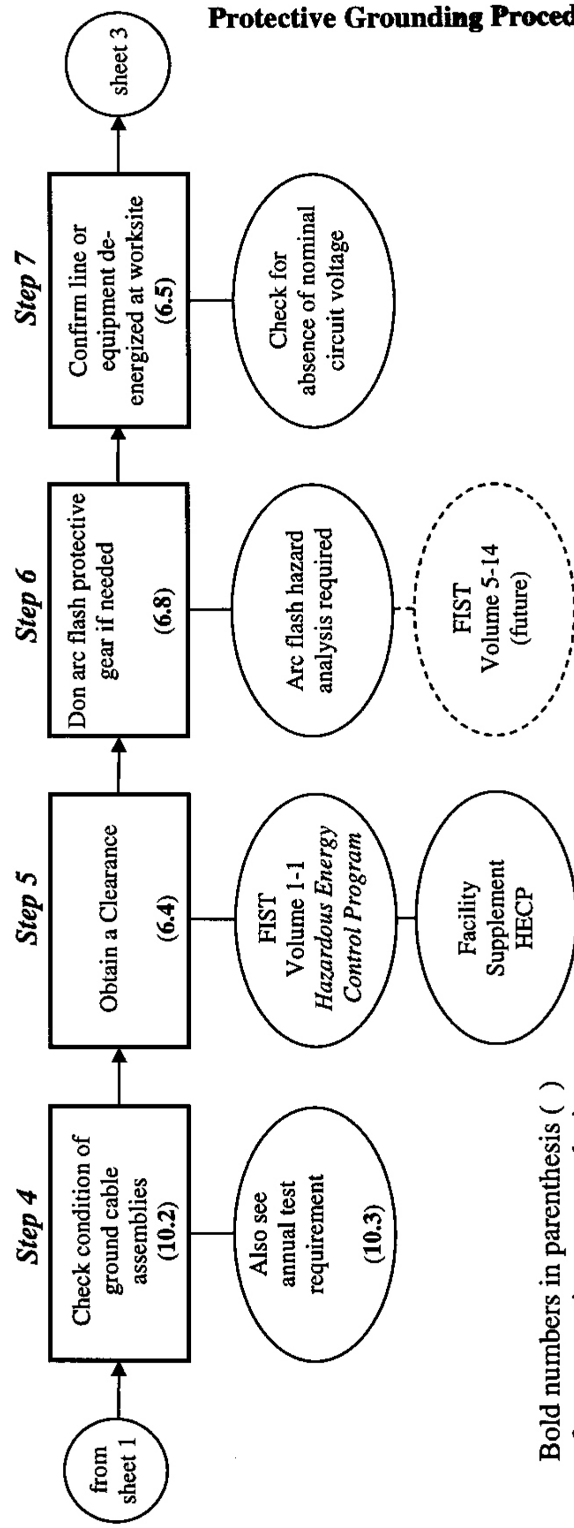
APPENDIX G
Protective Grounding Procedure Flow Chart (page 2 of 3)



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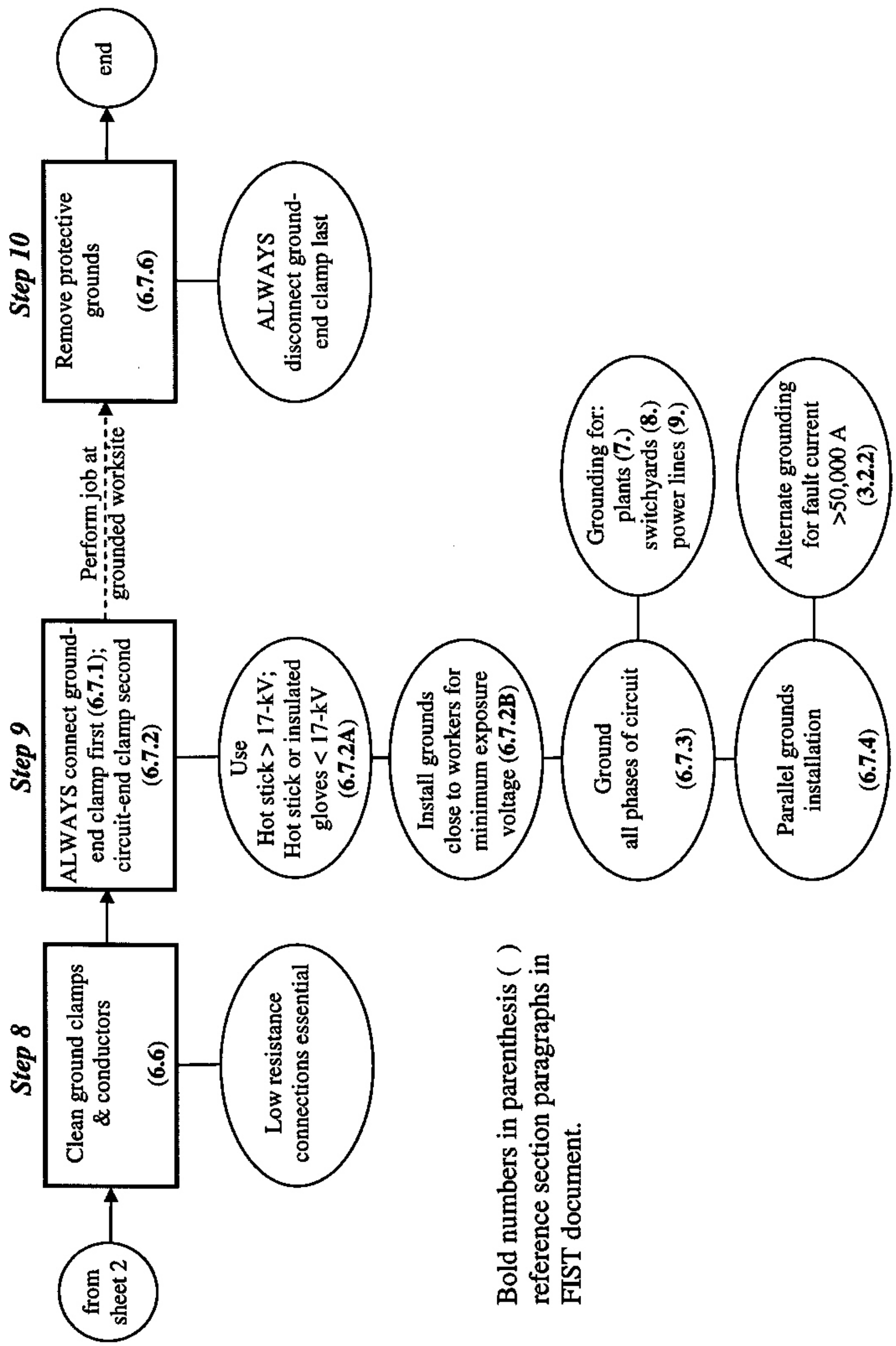
APPENDIX G
Protective Grounding Procedure Flow Chart (page 3 of 3)



MISSION STATEMENTS

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian tribes and our commitments to island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.