IEEE Guide for Temporary Protective Grounding Systems Used in Substations

Sponsor

Substations Committee

of the

IEEE Power & Energy Society

Approved 31 October 2011

IEEE-SA Standards Board
Abstract: The design, performance, use, testing, and installation of temporary protective grounding systems, including the connection points, as used in permanent and mobile substations, are covered in this guide.

Keywords: grounding, IEEE 1246, personnel safety, protective grounding, safety, temporary grounding, ultimate rating, withstand rating
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Introduction

This introduction is not part of IEEE Std 1246-2011, IEEE Guide for Temporary Protective Grounding Systems Used in Substations.

Practices for applying temporary protective grounds (TPGs) in substations vary from company to company. These practices have come from a number of documents such as ASTM F855, IEC 61230, and IEEE Std 1048-1990 [B15], as well as from field experience derived from line maintenance practices. This guide was developed to consolidate into one document all the necessary information for the company to develop sound personnel safety grounding practices in substations. The guide provides information on the physical construction, application, and testing of TPGs as they are used in substations.

This revision emphasizes the electromechanical forces present with high short-circuit currents and with high current offset (asymmetry). In recent tests, these forces were found to have significant impact on the ability of a complete TPG assembly, including attachment points, to successfully handle these high short-circuit currents. It also introduces a new method for determining the TPG impedance (length and cable size) for use in determining the current through the worker for an accidental energization.

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David Lane Garrett, Chair
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S. Aggarwal  Gary Housto  John Randolph
Stan Arnot  Raymond Hill  Joseph Renowden
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Ron Greenthaler  Robert Nowell  Teddy Olsen
Charles Grose  Kenneth White
Randall Groves  Carl Orde  James Wilson
Ajit Gwal  Lorraine Padden  Alexander Wong
David Harris  Bansi Patel  Larry Young
Martin Havelka  Christopher Petrola  Roland Youngberg

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IEEE Guide for Temporary Protective Grounding Systems Used in Substations

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1. Overview

1.1 Scope

This guide covers the design, performance, use, testing, and installation of temporary protective grounding (TPG) systems, including the connection points, as used in permanent and mobile substations. This guide does not address series-capacitor compensated systems.

1.2 Purpose

This guide suggests good practices, technical information, and safety criteria to assist in the selection and application of temporary protective grounding systems, including the connection points, as used in permanent and mobile substations.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.
3. Definitions

For the purposes of this document, the following terms and definitions apply. The IEEE Standards Dictionary: Glossary of Terms & Definitions should be referenced for terms not defined in this clause.

**bracket grounding:** The location of temporary protective grounds (TPGs) on all sides of a worksite. The location of the TPGs can be immediately adjacent to or some distance from the worksite.

**cluster ground assembly:** A preassembled set of four cable or bar assemblies, with three phase connections and one ground connection, all terminating at a common (cluster) point.

**continuity:** A continuous, unbroken electrical circuit. For the purposes of temporary protective grounding, any device capable of transforming voltage or producing a significant voltage drop cannot be considered as maintaining continuity. Examples include transformers, fuses, reactors, resistors, circuit breakers, and line traps.

**equipotential zone (equipotential grounding):** A general term used to describe the application of temporary protective grounds to limit the potential across the worker’s body. It is often associated with worksite or single-point grounding but also includes other applications of temporary grounding.

**ground potential rise (GPR):** The maximum voltage that a station-grounding grid can attain relative to a distant grounding point assumed to be at the potential of remote earth.

**multipoint grounding:** The application of temporary protective grounds (TPGs) on either side of the worksite, plus TPGs at the worksite. See also: bracket grounding, worksite (single-point) grounding.

**phase-to-ground (parallel) grounding:** The installation of temporary protective grounds from each phase to ground. The ground attachment point can be a common point for all three temporary protective ground (TPG) ground connections or can be a different point for one or more TPG ground connections, but a low-resistance connection between any separated TPG ground connection points is required.
### IEEE Std 1246-2011
IEEE Guide for Temporary Protective Grounding Systems Used in Substations

#### 3. Considerations for temporary protective grounding systems

**Phase-to-phase (chain) grounding:** The installation of temporary protective grounds from phase to phase with an additional temporary protective ground (TPG) connecting from one of the three phases to ground.

**Source grounding:** The location of temporary protective grounds (TPGs) so that a set of temporary protective grounds is between the worksite and all possible sources of current.

**Temporary protective ground (TPG) equipment:** Devices to limit the voltage difference between any two accessible points at the worksite to an appropriate value for safety, and with sufficient current withstand rating. These typically consist of cable assemblies, grounding switches, or temporarily installed bars.

**Ultimate rating (capacity):** A calculated maximum symmetrical current that a temporary protective ground cable is capable of carrying for a specified time without fusing or melting. When temporary protective ground (TPG) assemblies are exposed to currents that are close to the ultimate rating of the cable, they might be damaged. Some companies replace TPGs subjected to any known current from an accidental energization.

**Worksite (single-point) grounding:** The application of temporary protective grounds only in the immediate vicinity of an electrically continuous worksite. The location of the temporary protective grounds (TPGs) must be close enough to the worksite to prevent a hazardous difference in potential across a worker at the worksite.

#### 4. Considerations for temporary protective grounding systems

**4.1 General TPG**

Temporary protective ground equipment is used when grounding a substation power bus and equipment to protect personnel from high voltages that can be induced or applied because of equipment failure or operating error. The TPGs can be properly sized and assembled to protect personnel from injury during a steady state or abnormal power system operation. This is accomplished by creating a short circuit (using the TPGs) to deenergize the circuit as soon as possible while minimizing the exposure voltage at the worker.

**4.2 Permanent or mobile substation**

TPG assemblies are applicable for both mobile and permanent substations.

**4.3 Current magnitude and duration**

The current magnitude and duration of the short-circuit current are critical factors in sizing TPGs. The protective ground is sized to conduct the maximum available short-circuit current at the short-circuit location without failure for the duration of the short circuit.

**4.3.1 Current magnitude including direct current (dc) offset**

The current magnitude is one of the critical factors to be considered when sizing temporary protective grounding systems. The short-circuit current consists of a root-mean-square (rms) alternating current (ac) component and a dc offset current component. The rms ac component is determined by the subtransient impedances of the rotating machinery, the impedance of transformers, and the impedance of lines. The dc
offset component is determined by the $X/R$ ratio at the short-circuit location looking back into the power system and the time of short-circuit initiation on the voltage waveform.

Analytical studies indicate that when full dc offsets occur in the locations with high $X/R$ ratios (such as close to a generating plant or a large transmission substation), the short duration (6 to 60 cycles) fusing current ratings of grounding cables calculated using Onderdonk’s equation as considered in ASTM F855 might not be conservative. The additional heating from the dc current component reduces the cable current-carrying capability. The cable symmetrical current-carrying capability for the six-cycle rating is reduced approximately 28% when the $X/R$ ratio is changed from $X/R = 40$ to $X/R = 0$ as shown in Table 2 and Table 5, respectively.

At or near large generating plants and transmission substations, a large $X/R$ ratio is likely because the impedance of generators and transformers contains very little resistance. Whereas in extreme cases the $X/R$ ratio can be as high as 50, under most circumstances, the $X/R$ ratio does not exceed 40 within the substations. Several miles away from the substation, the $X/R$ ratio is dominated by the impedance of the line. The overall $X/R$ ratio can be determined by the line’s $X/R$ ratio. The typical range of $X/R$ ratios for lines is from 2 to 20 depending on the conductor configuration. A single, small conductor line will have a low $X/R$ ratio, whereas a bundled large conductor line will have a higher $X/R$ ratio.

In addition to the effects on fusing current, the $X/R$ ratio and dc offset can produce extremely high current peaks in the first few cycles relative to the rms current. Whereas the current peaks are proportional to the $X/R$ ratio, the rate of decay is inversely proportional to the $X/R$ ratio. The slowly decaying high current peaks, corresponding to higher $X/R$ ratios, create the most severe electromechanical forces, which can destroy the TPG assembly long before it fails thermally. In such a case, the worker would be without protection for a longer duration before the short circuit clears. IEC 61230 requires temporary grounding (earthing) devices to withstand a peak asymmetrical current of 2.6 times the rms current value for 60 Hz systems above 1 kV.

### 4.3.2 Short-circuit duration including primary and backup relaying

The short-circuit duration is another critical factor to consider when sizing protective grounds. The short-circuit duration is the time required to clear the short circuit by primary or backup relaying. The short-circuit clearing time is the sum of relay and breaker operation times. Primary relaying is the first line of defense to clear a short circuit at high speed. Utilizing the primary relay short-circuit clearing time minimizes the grounding cable size; however, before relying on the primary relay operation to size the protective grounds, consider the reliability of the relays. Many circuits are protected by slower clearing fuses that can take many cycles or even seconds to interrupt the current.

Backup protection is provided for possible failure in the primary protection system or for possible failure of the circuit breaker or other protective device. Remote backup and local backup are two forms of backup protection in common use on power systems. In remote backup protection, short circuits are cleared from the system, one substation away from where the short circuit has occurred. In local backup protection, short circuits are cleared locally in the same substation where the short circuit has occurred. Local backup protection will clear the short circuit from the system in less time than that provided by remote backup protection. Utilizing the backup protection, short-circuit clearing time provides a conservatively sized protective ground. If more than one relay operates to clear a short circuit on the system, the total time required for the last relay to operate determines the backup clearing time. For example, local breaker failure can add from 8 to 12 cycles to the primary clearing time. Zone 2 or remote backup relaying can add from 12 to 24 cycles to the primary clearing time. Backup protection from fuses can add seconds to the primary clearing time. Table 1 gives example ranges of clearing times for different protection schemes. Each company evaluates the primary and backup relay short-circuit clearing times on their power system and determines the short-circuit clearing time to use for sizing the protective ground.
Table 1—Typical fault clearing times for various substation bus protection schemes

<table>
<thead>
<tr>
<th>Bus protection scheme type</th>
<th>Typical clearing time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Busses with differential protection</td>
<td>2–8</td>
</tr>
<tr>
<td>Busses without differential protection</td>
<td>12–60</td>
</tr>
<tr>
<td>Busses cleared remotely</td>
<td>20–90</td>
</tr>
<tr>
<td>Busses with fused primary protection</td>
<td>60–300</td>
</tr>
</tbody>
</table>

4.3.3 Circuit breaker reclosure considerations

Tests (EPRI EL-5258 [1987] [B4]) have indicated that the cooling of TPGs between reclosures is insignificant. If the reclosing scheme is not disabled, then the additional short-circuit duration after reclosure(s) can be included in the total time used to size the TPG.

4.4 Special areas of concern

4.4.1 General

Any device capable of transforming voltage or producing a voltage drop is not to be considered as maintaining continuity for the purpose of personnel safety. Such devices include transformers, fuses, reactors, resistors, circuit breakers, disconnect switches, and line traps.

Subclauses 4.4.2 through 4.4.6 are used when planning installation of TPGs on major equipment in substations.

4.4.2 Main power transformers

The following should be considered when applying TPGs:

a) The turn ratio of many transformers makes them capable of transforming low voltages to high voltages, even when they are not connected to the normal power source. These normally low voltages can come from continuity checking instruments, insulation checking apparatus, and electric arc welders.

b) Shorting of current transformer (CT) secondary leads, and opening of disconnect switches or removal of fuses located in voltage transformer (VT) secondary leads.

c) During oil handling, the oil storage tank, hose, filtering equipment, and pumping equipment can be bonded together with the transformer tank being filled to minimize electric potentials on the equipment. Not only can the hose pick up an induced current, but also the oil flowing in the hose can build up a static charge, unless prevented.

d) Ground all terminals (windings).

4.4.3 Circuit breakers and circuit switchers

The TPG assemblies are applied on both sides of the device when maintaining circuit breakers, circuit switchers, or other devices that can have a circuit disconnection not visible to the worker. Consider the following:

a) Shorting of circuit breaker bushing CT secondary leads.

b) Applying a TPG assembly between the breaker and its free-standing CTs to prevent creation of an electrical loop that can cause circulating current and spurious operation of protective devices.
4.4.4 Instrument and substation service transformer

The voltage and substation service transformers, because of their very high turns ratio, are extremely hazardous if they are hooked up to electrical equipment in such a way as to allow the applied voltages to be backfed. Backfeeding could cause a severe electric shock to personnel who come in contact with any of the connected circuits anywhere in the substation yard. Opening secondary disconnect switches and removing fuses minimizes the hazards from secondary backfeed.

4.4.5 Capacitor banks

Substation capacitor banks retain stored charge even if the power source has been disconnected. After allowing for self-discharge (typically 5 min), the de-energized capacitor bank can be fully discharged by the application of a grounded short circuit across its terminal. In a capacitor bank comprising two or more parallel groups of series strings of units, each series group that is within reach can have a TPG connected across the entire string, and each individual unit of a series string that is within reach can be shorted by temporarily touching a wire across the unit terminals to provide full discharge. Similarly, in a capacitor bank composed of two or more series groups of parallel units, each parallel group that is within reach can have a TPG installed across the parallel group, and each unit that is within reach can be shorted by temporarily touching a wire across the unit terminals or from a single terminal to ground to provide full discharge.

4.4.6 Power cables and terminations

Before cutting the power cable, apply TPGs at each end of the power cable to dissipate capacitive energy.

4.5 TPG cable assemblies

The TPG cable assemblies typically consist of a combination of cable and ground clamps configured for connecting the phase conductors or equipment to a substation grounding system. TPG cable assemblies are appropriately sized and configured to survive the available short-circuit current exposure. Refer to Table 1 and Table 2 in ASTM F855 (2009 or later) for selecting the appropriate TPG cable assemblies based on the short-circuit clearing time, available short-circuit current, and $X/R$ ratio for thermal and electromechanical considerations.

A TPG cable assembly consists of the following:

a) Ground end. The ground end consists of a clamp (to be connected to a grounded structure or to a ground grid riser, a cable termination, and possibly heat-shrinkable tubing to seal exposed cable strands. T-handled clamps can have difficulty achieving the required torque for certain types of clamps (especially flat-faced clamps).

b) Flexible conductor with a suitable jacket.

c) Source end. The source end consists of a clamp (typically with an "eye" for handling and tightening) to be connected with the insulating stick to a de-energized conductor, a bus, an attachment stud, a cable termination, and (possibly) heat-shrinkable tubing to seal exposed cable strands.

Multiple manufacturers make specific TPG assemblies and components. For more details, refer to the manufacturer’s literature and 4.7.1.
4.6 TPG cable

4.6.1 Conductor material

Fine-stranded copper conductors are used for temporary protective ground cables. (See 4.6.4.) The diameters of the strands are generally specified by the manufacturer or by the appropriate standard. Inspection and testing ensures compliance with the cable material requirements. Check the electrical resistance of the conductors at 20 °C by the test given in IEC 60227-2 [B8] and IEC 60245-2-1997 [B9].

4.6.2 Sizing protective ground cables

The rating of the cable is a key component of sizing the TPG cable assembly. For cables rated for low current asymmetry, ASTM F855 defines grades 1 –7 based on a withstand rating that is 70% to 80% of the ultimate capacity. ASTM F855 defines ratings for grades 1H to 7H for high current asymmetry applications based on a percentage of the cable’s ultimate capacity. IEC 61230 only describes test procedures, with the test assembly being rated at the tested current value (i.e., it does not refer to either the ultimate or the withstand rating of the cable).

When selecting a cable for high current asymmetry, the dc offset current should be considered as it considerably reduces the capacity of cables for short durations. For added safety, some companies use the ultimate capacity and replace the assembly after exposure to an accidental energization. Table 2 through Table 5 list the ultimate equivalent symmetrical current-carrying capability of cables for a worst-case dc offset for X/R ratios of 40, 20, 10, and 0, respectively. Sizing TPG cable assemblies based on cable ampacity alone may result in unexpected failures. Refer to 4.5 for a discussion of proper TPG assembly sizing.

### Table 2—Ultimate equivalent symmetrical current-carrying capabilities of copper grounding cables (currents are rms values, for frequency of 60 Hz; X/R = 40; current in kA)

<table>
<thead>
<tr>
<th>Cable size (AWG or kcmil)</th>
<th>Nominal cross section (mm²)</th>
<th>6 cycles (100 ms)</th>
<th>15 cycles (250 ms)</th>
<th>30 cycles (500 ms)</th>
<th>45 cycles (750 ms)</th>
<th>60 cycles (1 s)</th>
<th>180 cycles (3 s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#2</td>
<td>33.63</td>
<td>22</td>
<td>16</td>
<td>12</td>
<td>10</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>#1</td>
<td>42.41</td>
<td>28</td>
<td>21</td>
<td>16</td>
<td>13</td>
<td>11</td>
<td>7</td>
</tr>
<tr>
<td>1/0</td>
<td>53.48</td>
<td>36</td>
<td>26</td>
<td>20</td>
<td>17</td>
<td>14</td>
<td>8</td>
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<td>2/0</td>
<td>67.42</td>
<td>45</td>
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<td>4/0</td>
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<td>126.65</td>
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<td>350</td>
<td>177.36</td>
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<td>87</td>
<td>67</td>
<td>56</td>
<td>49</td>
<td>29</td>
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</table>
Table 3—Ultimate equivalent symmetrical current-carrying capabilities of copper grounding cables (currents are rms values, for frequency of 60 Hz; $X/R = 20$; current in kA)

<table>
<thead>
<tr>
<th>Cable size (AWG or kcmil)</th>
<th>Nominal cross section (mm$^2$)</th>
<th>6 cycles (100 ms)</th>
<th>15 cycles (250 ms)</th>
<th>30 cycles (500 ms)</th>
<th>45 cycles (750 ms)</th>
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<td>13</td>
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<td>5</td>
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Table 4—Ultimate equivalent symmetrical current-carrying capabilities of copper grounding cables (currents are rms values, for frequency of 60 Hz; $X/R = 10$; current in kA)

<table>
<thead>
<tr>
<th>Cable size (AWG or kcmil)</th>
<th>Nominal cross section (mm$^2$)</th>
<th>6 cycles (100 ms)</th>
<th>15 cycles (250 ms)</th>
<th>30 cycles (500 ms)</th>
<th>45 cycles (750 ms)</th>
<th>60 cycles (1 s)</th>
<th>180 cycles (3 s)</th>
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Table 5—Ultimate equivalent symmetrical current-carrying capabilities of copper grounding cables (currents are rms values, for frequency of 60 Hz; $X/R = 0$; current in kA)

<table>
<thead>
<tr>
<th>Cable size (AWG or kcmil)</th>
<th>Nominal cross section (mm$^2$)</th>
<th>6 cycles (100 ms)</th>
<th>15 cycles (250 ms)</th>
<th>30 cycles (500 ms)</th>
<th>45 cycles (750 ms)</th>
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<td>30</td>
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</table>

NOTE 1—The current values in Table 2 through Table 5 were calculated from the computer program RTGC (Reichman et al. [B19]). This computer program can be used directly to determine the grounding cable size requirements for a known $X/R$ ratio and short-circuit clearing time.

NOTE 2—Angle of current initiation = 90° (maximum dc offset). Initial conductor temperature = 40 °C; final conductor temperature = 1083 °C.

NOTE 3—These current values consider the cable thermal limits only and do not consider the severe electromechanical forces present during the first few cycles of a fully offset wave, which can mechanically damage the TPG cable assembly or cause complete failure.

NOTE 4—For derating of multiple cables, refer to 4.8.3.

NOTE 5—Metric values are soft conversions. Soft conversion is a direct area calculation in metric units from the AWG size.
4.6.3 Jacket

The following types of jacketing materials are generally used in cable designs, primarily for the protection of the conductor:

a) A jacket based on a compound of vulcanized ethylene propylene rubber (EPR) or ethylene propylene diene monomer.

b) A general-purpose jacket based on a compound of thermoplastic polyvinylchloride (PVC), copolymers, or silicone rubber compounds.

c) A cold-resistant jacket based on a compound of thermoplastic PVC or one of its copolymers or silicone rubber compounds.

A separating tape made of suitable material might be placed between the conductor and the jacket. Consider the fire-retardant characteristics of the jacket material. Because some jacketing materials produce toxic fumes if overheated, their use might be limited to outdoor applications. An indoor application could be permissible with forced-air ventilation.

The jacket should have adequate mechanical strength and elasticity within the temperature limits to which it can be exposed in normal use. Compliance with the following references verifies the mechanical strength and elasticity of each type of jacketing material:

- IEC 60502-1994 [B12] for EPR or a similar compound. Additionally, the cables covered by this type of compound are subject to a bending or elongation test at 50 °C.


The applicable test methods and the results to be obtained for each type of jacketing material are also specified in these standards.

The jacket is normally applied closely to the conductor with a separator, if any. It should be possible to remove the jacket without damaging the strands. This may be checked by visual inspection. The jackets are available in several colors. The typical colors available include orange, yellow, black, and green. There is no preferred color for the jacket. The PVC (thermoplastic) jackets are usually made transparent. Some users prefer transparent jackets because it allows for the visual inspection of the conductor. PVC (thermoplastic) jackets can become opaque and brittle over time.

4.6.4 Cable stranding configuration

Cable stranding is specified in ASTM F855. TPG cables are typically furnished in three types. The type depends on both the cable and the protective jacket. The major characteristics of these ground cables are as follows:

a) Type I

1) Conductor—Stranded soft drawn copper conductor with 665 strands or more of #30 or #34 AWG.

2) Jacket—Elastomer jacket, as rated by the manufacturer, flexible for installation and serviceable for continuous use within the temperature range –40 °C to +90 °C.

b) Type II

1) Conductor—Stranded soft drawn copper conductor with 133 strands or more for #2, or 259 strands or more for 1/0 AWG, and greater.

2) Jacket—Elastomer jacket, as rated by the manufacturer, flexible for installation and serviceable for continuous use within the temperature range –25 °C to +90 °C.
c) Type III
   1) Conductor—Stranded soft drawn copper conductor with 665 strands or more of #30 AWG.
   2) Jacket—Thermoplastic jacket, as rated by the manufacturer, flexible for installation and serviceable for continuous use within the temperature range –10 °C to +60 °C. The use of type III cables is sometimes restricted to open areas or spaces with adequate ventilation so that any fumes produced by overheating can be dispersed.

4.7 Clamps

Clamps are rated for the maximum available short-circuit current, including asymmetry and duration, to which they can be subjected without exceeding service requirements. The clamp and conductor assembly should be capable of carrying the available short-circuit current for the specific time without damage or separation from the phase conductor or ground point.

Clamps for grounding applications are characterized by their time versus current ratings, overall general shape, and clamping configuration. The clamp configuration should accept the main and tap conductor sizes and have the appropriate jaw configuration.

If inadequately rated, electromechanical forces from a short circuit can break the connection of the clamp from the phase conductor, or even break the clamp, or the clamped connection can loosen and fail. ASTM F855 provides information on clamp material and strength specifications.

4.7.1 Clamp types

A large variety of clamps is available in the industry, each suitable for either a specific or multiple applications. Clamps are designed to fit various shapes of bus work, stranded or solid conductors, and steel tower structures. For more information, refer to the manufacturer’s literature.

A clamp can have either smooth or serrated jaws. The smooth jaw clamp is designed to minimize conductor damage and generally is used on cleaned conductors to provide a reliable connection. The serrated jaw clamps are designed to break through the buildup of corrosion or oxide film on the conductor. If a clamp with serrated jaws is used improperly, then the conductor surface could be damaged.

4.7.2 Clamp material

Clamps are typically made from an aluminum or copper alloy. Copper cables should not be fitted directly into aluminum alloy clamps because of corrosion and resulting loss of both electrical contact and mechanical strength. To minimize corrosion, consider using tinned cable terminations or a suitable corrosion inhibitor. Even with these precautions, a corrosive atmosphere or excessive moisture might damage the TPG cable assembly.

4.7.3 Mechanical considerations

For high short-circuit currents, the clamps and the terminations are subjected to very high electromechanical forces during short-circuit conditions, especially when long cables are left unsecured. Under such conditions, large magnetic forces can accelerate the cables to high velocities and the clamps are called on to absorb much of this kinetic energy. Also, if a TPG were to fail mechanically, the failure would most likely be within the first three cycles, and the worker would be without any protection for the remainder of the short-circuit duration.
Violent cable whipping can be reduced by restraining the cable using a rope. If used, the restraint should not create a rigid binding point, but it should absorb shock and prevent the violent cable movement produced by the magnetic forces. If the cables are twisted or wrapped around the structure, then a transformer effect is created, inductive reactance increases, and the cable could overheat and fail. The increase in reactance also increases the worker exposure voltage. In addition, when there is a large dc offset with full asymmetry, the peak current can be up to twice the value of the symmetrical peak current. The magnetic forces can be up to four times as high in such cases. ASTM F855 now includes ratings for both low and high asymmetrical currents. The ratings for the lower asymmetry are based on maximum peak current of 20% over the symmetrical peak current (1.75 times the rms current). The lower asymmetries are classified grades 1 to 7. The ratings for high asymmetries are based on maximum peak current of 90% over the symmetrical peak current (2.69 times the rms current). The higher asymmetries are classified grades 1H to 7H. IEC 61230 requires rating at 84% peak over the symmetrical peak current (2.6 times the rms current).

The mechanical adequacy of a given design and construction of a clamp, for a given short-circuit current, depends on the combination of cable type and length and on the type of cable-to-clamp attachment with which it is to be used. For a given short-circuit current magnitude and duration, a certain clamp can be entirely adequate mechanically for one application but inadequate for another. Only full-scale, short-circuit current tests on the most adverse application of a clamp would allow one to determine its mechanical ruggedness and acceptability for the specific application.

Most substation applications involve three-phase TPGs, and high electromechanical forces can be produced between the individual TPGs when subjected to high short-circuit currents. A TPG assembly that would otherwise pass a single-phase test might not survive a three-phase test. Examples would include the chain grounding configuration (with two or three TPGs installed in close proximity on one of the phase conductors) and parallel grounding (with all three TPG ground ends attached to a common ground). Therefore, consider interphase forces when applying TPGs and test as needed.

4.7.4 Cable-to-clamp termination

The most critical component of the TPG cable assembly for withstanding the extreme electromechanical forces is probably the cable termination and how it is attached to the clamp. The cable can be terminated at the clamp in several ways. Typical cable terminations are compression type, but other types exist. For compression ferrules, follow the manufacturer’s specifications closely, including compression die type, size, pressure, and compression pattern (i.e., overlap versus nonoverlap, how many compressions, etc.).

Cable terminations are available in a threaded and nonthreaded form. Terminations using solder are generally not used because the low melting temperature of solder is likely to fail for high currents. Terminations can provide a low-resistance connection at the cable-to-clamp interface. Because of the high mechanical forces, one of the most important requirements of the cable-to-clamp termination is the provision for strain relief for the cable.

Adhesive-lined heat-shrinkable tubing or cold-shrink tubing minimizes corrosion between the cable strands and enhances strain relief.

4.8 Multiple assemblies

Multiple assemblies terminated at the same point provide multiple paths for the available short-circuit current. This can reduce the size requirement for any individual path (cable). However, unless the current paths have equal impedance, the short-circuit current will not divide equally.

Extreme electromechanical forces present under high short-circuit current conditions can break the clamp or cable termination, leaving a worker without protection. Unlike thermal energy, electromechanical forces on individual TPGs do not reduce in the same proportion as the current. More likely, the electromechanical
forces on multiple assemblies would be similar to that developed by the total short-circuit current. This is because the various loops consisting of phase conductors, TPGs, and current-return circuits primarily determine the electromechanical forces on a TPG regardless of its multiplicity. Also, using multiple assemblies introduces additional forces between the multiple cables.

Even if properly sized for available short-circuit current (including any derating factors for multiple assemblies), the manner in which the TPGs are physically located and arranged on the phase conductor can have a significant impact on the ability of the multiple assemblies to handle successfully the high short-circuit current. The best arrangement will be one that minimizes cable movement or allows cable movement only in a direction that the strain relief is intended to allow.

More than two parallel TPGs will have uncertain short-circuit current distribution and high electromechanical forces, and generally, only one or two are used. It is possible to reduce the number of the TPG assemblies by increasing the conductor size, reducing the required protection time, reconfiguring the system to reduce the available short-circuit current, or any combination of these methods. If more than two TPGs are necessary, the use of custom-designed assemblies with special installation techniques is required.

4.8.1 Path impedance

When it is necessary to use multiple temporary grounds in parallel per phase, it is very important to provide equal impedance of each TPG. To be sure that balanced current flows through each TPG, the following items can be made equal:

a) Size and type of stirrups
b) Size and type of clamp
c) Length and ampacity of each conductor
d) Similar connection of each conductor in the clamp
e) Cleanliness of conductors, stirrups, and mating surfaces of clamps
f) Torque applied to each clamp
g) Size and location of ground riser to which the TPGs are attached, if applicable

The cleanliness of each connection and the torque applied to the clamps are of major importance. Dirty surfaces or insufficient torque can result in overheating and failure.

Inductive reactance is often more important than resistance in terms of the total impedance of the grounding cable. However, differences in resistance where the cable is connected to the clamp and where the clamp is connected to the phase conductor can be very significant in determining current sharing.

Inevitably, because some unbalance will cause a potential difference between cables, 600 V insulated cables are used to minimize arcing.

4.8.2 Positioning

If two TPGs in parallel are used, attach the clamps as close together as possible to minimize unequal currents in each TPG. Butting the clamps together will reduce the possibility of the clamps slipping off due to the large attractive force between them during the short circuit. It is an industry practice to connect the TPGs as close to each other as possible on the phase conductor, which further improves equal current distribution. Install the parallel clamps no intentional delay to limit the exposure of a single cable to a short circuit.
4.8.3 Derating of multiple TPGs

To account for unequal current division, reduce the thermal current rating (4.6.2) by at least 10% of each TPG used in the multiple assembly set. In addition to thermal current rating, worker exposure voltage must be considered. The magnetic coupling between the multiple cables reduces the paralleling effect of impedance reduction (i.e., the total impedance of two closely spaced identical TPGs is much higher than half the impedance of a single TPG). Refer to 5.3.6.

4.9 Attachment points

Fixed-point protective grounding terminals attached to the bus conductors, equipment terminals, or structures have been gaining acceptance in the utility industry. These terminals provide an attachment point for protective grounds that lends itself to the adaptability of standard clamps. This avoids forcing these clamps to conform to a wide range of conductor sizes and configurations. These fixed attachments (studs and stirrups) need to be able to withstand, mechanically and electrically, the available short-circuit current. The corona protection of the attachment points needs to be considered.

ASTM F855 does not include specific testing of attachment hardware similar to testing a TPG cable or bar assembly. IEC 61230 does address the testing of attachment hardware. To address the thermal and electromechanical capabilities for the available short-circuit current, this hardware can be tested as suggested in 4.5 and 8.1, or as in IEC 61230.

4.9.1 Bus conductors

A substation can include a wide range of conductor sizes and shapes. If a 125 mm or larger diameter tubular bus is used, then special attachment points (stirrups) are usually provided for the installation of TPGs. Regardless of the type of attachment point, it has to be compatible with the thermal and electromechanical capabilities of the TPGs with which it will be used.

4.9.2 Stirrups

Stirrups of various sizes and shapes can be manufactured from material compatible with the conductor material to which the stirrup is attached.

4.9.3 Studs

Studs can be designed such that the clamps are prevented from sliding off during a short circuit. The studs can be bolted, welded, or compressed on to the conductor, and they can be manufactured from material compatible with the conductor to which they are attached.

4.10 Cable extensions

Dangerous voltage levels can develop across extremely small resistances during high-current short circuits. The TPGs with center splices to extend their length can increase the overall TPG resistance. This is not intended to prohibit the use of cluster devices on a worksite, but to point out matters to be considered.
5. Application

5.1 General

It is suggested that TPGs be installed, used, and serviced only by competent personnel using good work and safety practices. This clause is intended to provide the user with information and guidance in the proper selection and installation of TPGs.

5.1.1 Single phase

When maintenance is required on single-phase circuits, use a single-phase TPG assembly to connect the phase conductor to a grounding electrode.

5.1.2 Three phase

When maintenance is required on three-phase circuits, use one of the following methods:

a) Three single-phase TPGs connecting each phase (phase-to-ground or parallel grounding) to ground.

b) TPGs connecting phase-to-phase-to-phase—with one of the three phases connecting to ground (phase-to-phase or chain grounding).

c) One prefabricated three-phase TPG (cluster ground) connecting each phase to a common point, and then connecting that common point to ground.

The type of three-phase configuration used will influence the available short-circuit current distribution among the individual TPGs and the worker, as illustrated in Figure 1, for both three-phase and single-phase energizations.

NOTE—For illustration purposes only, the circuits are simplified to illustrate all relative body currents for the TPG configurations.

*Figure 1*—Variation of current flows for various TPG configurations
In the parallel configuration (Figure 1(a)), a TPG is in parallel with the worker between the phase and the ground, resulting in the minimum possible current through the worker. In the chain configuration, with one of the outer phases connected through a TPG to the ground, the current is either the minimum (Figure 1(b)) or the maximum (Figure 1(c)) possible current, depending on the worker location relative to the phase with the TPG to ground. This is because of the additional TPG conductor length from the contacted phase to the grounded phase. Grounding the middle phase (Figure 1(d)) would reduce the current through the worker compared with grounding one of the outer phases. In contrast, if the worker simultaneously contacts two phases, then chain grounding provides the minimum possible current through the worker as a TPG is directly in parallel with the worker contact points. Cluster TPGs provide some of the advantages of both parallel and chain grounding.

5.2 Location of the TPGs

5.2.1 Source (bracket) grounding

Source grounding uses TPGs placed between the worksite and any possible energy source. The energy sources include transformers, transmission lines, and generating units, and they include backfeed to the bus from networked distribution lines, energized secondaries of VTs, and bus crossings (possible energized bus dropping on to a deenergized bus, or vice versa). The TPGs connect the deenergized bus or equipment to the substation ground. The TPGs might be located an appreciable distance from the worksite in large substations.

A variation of source grounding, generally involving two sources—one source on each side of the worksite—is often referred to as bracket grounding. This term is more appropriate in transmission or distribution line grounding, where the worksite can be energized from either end of the line. In a substation, improper application of bracket grounding can result in energy sources connected to the deenergized bus between the worksite and the TPG location(s). Although many applications of bracket grounding are electrically the same as source grounding (such as TPGs applied on either side of a circuit breaker), some applications meet the visual requirements of a bracket (or working between grounds) but are electrically quite different. An example would be TPGs located at the ends of a straight bus, with one or more transmission line terminations between the TPG locations. Personnel working on the straight bus would be between grounds (bracketed by grounds), but the TPGs would not be between the worksite and all sources of energy. Figure 2(a) and Figure 2(b) use a simplified circuit to illustrate the difference in body current for improper and proper bracket (source) grounding. A 1000 Ω body resistance is assumed for each worksite for these calculations. The distances represent the separation between the worksite and the TPG or between the worksite and the source (entry point) of current to the deenergized bus.
5.2.2 Worksite (single-point) grounding

In worksite grounding, the TPGs are placed as close as possible to the worksite. They are used to connect the deenergized bus or equipment to the substation ground or local ground. They are designed to carry the maximum available short-circuit current, both symmetrical and asymmetrical, that can occur at the worksite, in the event of accidental reenergization. A perceived disadvantage is that the worker is not working between two visible grounds on a circuit that can be energized from either of two directions, resulting in a sense of a lack of safety at the work location. Typically, the current through the worker will be greater if energization occurs from the side opposite the TPG location. To be considered a worksite ground, the TPGs must be located very close to the actual worksite to minimize worker exposure voltage. A good rule of thumb is to place the TPGs within a distance reachable from the worksite using a live-line tool. Mechanical whipping of TPGs placed too close to the worker presents a safety concern. In this situation, restrain the TPGs. An advantage of this method is that the worker makes fewer connections. See 4.7.3.
5.2.3 Multipoint grounds

Multipoint grounding is a combination of both worksite and bracket or source grounds. An advantage of multipoint grounding follows from the principle of current division between all paths. Multipoint grounding significantly reduces the current through the worker compared with either worksite or bracket grounding. Because of the redundancy of TPGs, the worker would be better protected even if one of the bracket TPGs were to fail mechanically or thermally.

5.3 Ratings and selections

5.3.1 TPG conductor size

The size and maximum length of a TPG is based on the application and available short-circuit current, using the sizing criteria of 4.6.2 and, where applicable, the worker exposure (touch) voltage evaluation procedure in 5.3.2. When TPGs are located at two or more locations (electrically in parallel), the TPGs will not share the available short-circuit current equally. The majority of the current is carried by the TPG closest to the source of energy. For example, with two TPGs placed 16 m apart on the same bus (e.g., bracket grounding), the current division between the TPGs is on the order of 3 to 1 (75% to 25%). Size all TPGs as though they are the only TPG installed. See also 5.3.6.

5.3.2 Worker exposure (touch) voltage evaluation

Worker exposure voltages present during an accidental energization of a grounded worksite in an alternating-current substation are dependent on the magnitude of available short-circuit current, size and length of TPGs, grounding configuration (i.e., bracket, single point, etc.), and location of the touch point in relation to the attachment of TPGs to grounded conductors or equipment. The latter consideration involves an induction ground loop formed by the closed circuit with the TPG, bus, worker, and ground return path to the TPG. The TPG ground return path is an intentional conductor (not earth) of various forms, which includes the substation ground grid, equipment ground conductor, conductive structure, and/or grounded enclosures.

The exposure voltage at the worker touch point with TPG grounded bus or equipment is the total or phasor summation of both resistive $I_R$ and reactive $I_X$ voltage drops created by short-circuit current in the TPGs, connective bus, and in some cases, ground return path. The reactive or induction ground loop $I_X$ voltage drop component can be significant; generally, it increases with the distance between the worker and the point of attachment of TPGs and increases with bus phase spacing. The net result of both effects makes the worst-case worker exposure voltage a single-phase energization with the worker more than 15.24 m (50 ft) away from his TPG. In this scenario, the worker exposure voltage is proportional to the total impedance of the TPG path to the ground grid, both resistive and reactive (self-impedance) components. This includes the total TPG length plus any steel that is between the TPG and the grounding pigtail plus the length of the ground grid pigtail that connects to the ground grid mesh. In some cases, the actual exposure voltage, accounting for induction can exceed the resistive $I_R$ voltage drop of the TPG alone by a factor of four or more. Therefore, the effectiveness of TPGs in controlling the worksite exposure voltage depends on the effects of induction ground loops with the worker and on the self-impedance of the parallel path.

The following method of calculating touch voltage with TPG impedance $K$ factors may be used to approximate the total TPG-worker ground loop voltage drop for the three grounded worksite configurations in 5.3.3 through 5.3.5. It is emphasized that the method of $K$ factors is sensitive to the actual physical layout and connection of TPGs at a worksite, and to modeling assumptions. Therefore, other worksite grounding layouts require different TPG $K$ factor values.

Comment [SI15]: OK to replace the center dots with multiplication signs throughout this paragraph? IEEE Standards prefers the × over the center dot.
5.3.3 TPG impedance K factors for single-point grounded worksite with TPGs between worker and source of energy

The TPG impedance K factors in Table C.1 may be used to approximate the total worker touch voltage at a single-point grounded worksite during an accidental single or three-phase energization. The K factors adjust the TPG cable resistance to an approximate effective impedance value based on stated specific ground loop assumptions about the grounded worksite layout for the TPG and worker. The TPGs are assumed to hang vertically from their point of attachment to bus or equipment to the ground-end connection in a rectangular configuration with the worker location, as shown in Figure C.1.

Worker touch voltage for a phase-to-ground contact may be approximated by the equation:

\[ V_t = I_f \times R_c \times K \]

(1)

where

- \( V_t \) is the touch voltage, \( \text{V rms} \)
- \( I_f \) is the available short-circuit current, \( \text{kA rms sym} \)
- \( R_c \) is the TPG cable dc resistance (excluding clamps and ferrules), \( \text{mohms} \)
- \( K \) is the TPG impedance K factor (Table C.1)

Refer to C.2 for step-by-step instructions for using Equation (1).

Example

A 69 kV circuit breaker is connected to disconnect switches on either side via 5 m sections of a horizontal overhead bus. To maintain the breaker, the breaker is opened, along with the disconnect switches. Both switches are single-point, single-phase or three-phase grounded with 4.57 m (15 ft), number 4/0 AWG copper TPG(s). One TPG is connected from each switch terminal(s) (on the breaker side of switch) to the station ground stub-ups for the switch. The worker position is assumed at the terminals of the breaker. The likely energization would come from closing one of the disconnect switches, which means the worker is 5 m away from the source side of the TPG (i.e., TPG between worker and source). The available three-phase short-circuit current at the breaker is 25 kA rms sym. The touch voltage shall be determined at the circuit breaker (worker touches overhead bus near breaker and grounded breaker enclosure).

Refer to Figure C.3. In this example, the length \( L \) of the TPGs is 4.57 m (15 ft) and the distance \( D \) from TPG to worker touch point is 5 m. From Table C.1, the value of \( K \) for 4/0 AWG TPG is 3.26. The TPG conductor resistance \( R_c \) is calculated from Table C.2 using the value 0.175 m\( \Omega \)-m for a 4/0 AWG conductor. \( R_c \) is then 0.175 * 4.57 = 0.80 m\( \Omega \). Using Equation (1), the calculated worker touch voltage at the disconnect switch structure is:

\[ V_t = 25 \times 0.80 \times 3.26 \]

Field Code Changed

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5.3.4 TPG impedance $K$ factors for single-point grounded worksite with worker between TPGs and source of energy

The situation of a worker positioned between the TPGs and source of energy presents a greater exposure voltage than described in 5.3.3 for the same distance between worker and TPG. This is because of the additional voltage drop of the section of short-circuit current carrying grounded bus and station ground return conductor (ground grid or structure), which form the induction ground loop with the TPG and worker. In this case, no single value $K$ factor is adequate for a given size TPG as in 5.3.3. Rather, the $K$ factors increase significantly in proportion to the distance from worker to TPG. The touch voltage calculation procedure is similar as in 5.3.3, but the appropriate value of $K$ must be chosen from the families of $K$ curves in C.3.2. However, to minimize worker exposure voltage with single-point worksite grounding, it is better to position the TPGs between the energy source and worker(s) when practical (see discussion in 5.2.2).

**Example**

Same grounding scenario as in the example of 5.3.3 except TPGs are located at the terminals of the circuit breaker and the worker is near (at) the switch end of the 5 m bus section from switch to breaker (worker between TPGs and source of energy). Determine the touch voltage at the disconnect switch (worker touches overhead bus disconnect switch and grounded switch structure).

In this example, a single-value $K$ factor for TPG conductor size is not applicable. Use the $K$ factor family of curves in Figure C.19 for TPG length of 4.57 m. Reading the curve for 4/0 AWG conductor at ground loop depth $D = 5$ m, the value of $K$ is approximately 9.5. Using Equation (1), the calculated worker touch voltage at the disconnect switch structure is

$$V_t = 25 \times 0.80 \times 9.5 = 190 \text{ V}$$

5.3.5 TPG impedance $K$ factors for bracket grounded worksite

For single or three-phase bracket grounded worksites (two TPGs per phase, Figure C.2) involving one or more short-circuit current sources, the TPG impedance $K$ factor curves in Figure C.6 may be used to approximate the maximum exposure voltage that can develop on the bus between the TPGs. The touch voltage calculation procedure is similar as in 5.3.3, however, note that the total bracket TPGs or available short-circuit current must be used for $I_s$ as discussed in C.2.

**Example**

An insulator is to be replaced atop a metal pedestal, which supports the horizontal bus in a substation. Six 250 kcmil copper TPGs, 6m (19.7 ft) long, are connected to the bus on both sides of the pedestal in a three-phase bracket-grounding configuration (one TPG per phase at each bracket location, six TPGs total). The bracket grounds are spaced 10 m apart with the pedestal somewhere between them. A source of short-circuit current exists on either side of the bracket grounded worksite, with available single-phase short-circuit currents of 36 kA rms sym and 40 kA rms sym, respectively. Determine the touch voltage at the bus support pedestal (worker touches grounded overhead bus and pedestal).
Refer to Figure C.2. The bus support pedestal is located at the worker touch point in the figure, and short-circuit current sources exist from both right and left ends of the bus. It is reasonable to assume that the grounded worksite could become accidentally energized by either, but not both, energy sources at one time. Therefore, choose the higher available short-circuit current value (40 kA) to determine the worst-case touch voltage. Use the $K$ factor family of curves in Figure C.23 and Figure C.24 and linear interpolation to determine the $K$ factor for a 6 m long, 250 kcmil copper TPG. The values of $K$ for a 4.57 m and 10 m length, 250 kcmil TPG for $B = 10$ m are approximately 2.15 and 1.85, respectively. By interpolation, a 6 m, 250 kcmil TPG has a $K$ factor of approximately 2.1. TPG conductor resistance $R_c$ is calculated from Table C.2 using the value 0.148 m $\Omega$/m for the 250 kcmil conductor. $R_c$ is then $0.148 \times 6 = 0.89$ m $\Omega$. Using Equation (1), the calculated worker touch voltage at the bus support pedestal is:

$$V_t = 40 \times 0.89 \times 2.1 = 75 \text{ V}$$

This calculated touch voltage represents the maximum voltage that would appear somewhere on the bus between the bracket grounds, at an unspecified distance $D$ from the TPG in Figure C.2. The available short-circuit current (combined TPG phase currents $I_1 + I_2$ in Figure C.2) and not an individual bracket TPG current is used to calculate touch voltage in Equation (1). Refer to C.1.3.3 for further explanation of $K$ factor modeling for bracket grounding.

### 5.3.6 Multiple assemblies (parallel TPGs)

In some grounding situations, the calculated worksite touch voltage from the preceding equation might exceed the company safety criteria. It is then logical to question whether installing a second, equally sized, adjacent parallel TPG at each grounding point (not the same as bracket grounding) would significantly lower the touch voltage. The effective impedance of two adjacent parallel TPGs is significantly greater than half the impedance of a single TPG (parallel TPG resistance is one half, and reactance is greater than one half). Therefore, the user should understand how to predict the effect of paralleling TPGs for the purpose of reducing the touch voltage. Other means to lower the touch voltage or shock exposure are discussed in 5.2.

Generally, the exposure voltage at a grounded worksite can be minimized by using the shortest TPGs practical for the application with the TPGs installed in parallel with and in close proximity to the worker (5.1.2), between the worker and energy source; or bracket grounding can be used as conditions allow. However, among typically used grounding methods, the multipoint grounding (5.2.3) would provide the most effective protection.

### 5.4 Methods

#### 5.4.1 TPG cable or bar assemblies

The TPG cable or bar assemblies connect the phase conductors or equipment to a substation grounding system or a local ground.

#### 5.4.2 Grounding switches

Grounding switches are permanently installed switches kept in the open position until required. Grounding switches are used for connecting the bus (deenergized, i.e., for maintenance) to the substation grounding system. They are often used to connect the phase conductors to a ground electrode when the phase conductors are too large in diameter or too high to accommodate a TPG effectively. They are also used extensively in global information systems equipment.
The advantages of grounding switches are their operational convenience when frequent grounding is required and the capability of including mechanical interlocks to prevent inadvertently opening the switch or even to restrict access to an area. Ground switches designed to withstand the maximum asymmetrical current anticipated at the substation have another advantage in that they facilitate multipoint grounds in the substation. A disadvantage is that ground switches require maintenance and might not easily operate when called upon because of the long periods between operations. If air insulated grounding switches are used, then TPGs provide worker protection at the worksite. For example, ground switches are located at the ends of a long section of bus, with TPGs located at one or more worksites between the ground switches.

### 5.4.3 Ground and test devices

A ground and test device is a device used in metal-clad switchgear for accessing the primary bus (either "main" bus or "outgoing" bus) and ground bus within an individual cell or cubicle. It provides visible, protective grounding in the work area.

As a grounding device, it makes available the accessed primary bus and ground bus for interconnecting by an equipment operator. This interconnecting is done either manually, using standard TPGs, or through an integral "grounding" switch.

As a testing device, it makes the primary bus and ground bus accessible for voltage and phase relation checks. These devices are installed in place of the standard circuit breakers. See IEEE Std C37.20.6™-2007 [B18] for more information concerning ground and test devices.

### 6. Installation and removal

#### 6.1 General procedures

The exact procedures for applying TPGs can differ, depending on the type, rating, configuration of the equipment being isolated and grounded, and specific policies of the organization. Consider the possible arc flash hazard involved with installing and removing TPGs and choose the appropriate personnel protective equipment to minimize burn hazards. (For more relevant information on arc-flash hazards, refer to IEEE Std 1584™-2002 [B16].) The TPG is applied between the ground electrode and the deenergized bus or line. The ground electrode consists of the substation grounding system, which includes system neutrals, ground grids, ground rods, overhead ground wires, and structures. Ensure that the ground electrode is capable of carrying the maximum available short-circuit current at the point of application. General procedures are listed as follows:

a) Check grounding assembly to verify that it is in good operating condition.

b) Isolate the section of bus, line, or equipment, including secondary circuits, if appropriate.

c) Install barrier, if required (rope off area).

d) Test for voltage on the deenergized bus, line, or equipment.

e) Clean areas on bus and ground electrodes following approved safety procedures.

f) Install assembly on ground electrode.

g) Install assembly on deenergized bus, line, or equipment.

h) Remove assembly from deenergized bus, line, or equipment.

i) Remove assembly from ground electrode.
6.2 Tools

Live-line tools are protective operating devices made from suitable insulating materials. See IEEE Std 516™-2009 [B14]. Ground clamps, cleaning tools, and measuring instruments may be attached to live-line tools for working on energized or statically charged conductors. Live-line tools are available in various shapes, sizes, and lengths.

6.2.1 Clamp stick

Clamp sticks are a class of the live-line tool used when more complex operations are required. These live-line tools have mechanical linkages to improve maneuverability and control of ground clamps, tools, measurement equipment, and other devices.

To increase the worker’s lifting capabilities, a hook lift stick (shepherd’s hook) with block and rope assembly reduces the effort required to raise and install large capacity clamps on an overhead bus.

6.2.2 Bucket and platform truck

Bucket and platform trucks are used to reach otherwise inaccessible equipment or bus conductors requiring grounding. Live-line tools might be used in conjunction with bucket and platform trucks for grounding applications. Before work begins, ground the truck frame to the substation grounding system (6.5.3).

Platforms are used to elevate the worker to the work area for better access. Platforms can be either insulating or noninsulating. Live-line tools may also be used in conjunction with platforms for grounding applications. Ground the temporary noninsulating platforms prior to beginning work. Ground the permanent platforms in accordance with IEEE Std 80™.

6.3 Testing for voltage

Before any grounding connections are made, test the bus or equipment to verify it is deenergized. The devices and methods discussed in 6.3.1 through 6.3.3 are used to detect the presence of voltage on the bus, equipment, and ground electrode.

6.3.1 Proximity voltage detectors

These devices detect the presence of voltages by being placed in the electric field near the bus, using the appropriate live-line tool.

6.3.2 Multirange voltage detectors

These devices are voltage detectors, which are attached to live-line tools and have probes that need to be placed directly on the bus to be tested.

6.3.3 Fuzzing (buzzing or teasing)

Fuzzing, which is also known as buzzing or teasing, is a method using a conductive tool on the end of a clamp stick and dragging the conductive device along the bus. A buzzing could indicate an energized bus. Because this technique is very subjective, it is not suggested.
6.4 Placing and removing of TPGs

The temporary protective grounding assembly may be placed at such locations and arranged in such a manner as to minimize the risk of employee exposure to hazardous differences in electrical potential and movement of the assembly under short-circuit conditions.

6.4.1 Cleaning of bus and electrodes

Prior to making any grounding connection, clean all contact connection surfaces to remove any buildup of dirt, oil, grease, or oxides. Remove protective coatings, such as paint, from steel surfaces prior to making connections. Clean nonplated contact surfaces using V-shaped wire brushes, standard wire brushes, sanders, or other similar tools. These cleaning tools are an attachment to live-line tools. In lieu of cleaning, use grounding clamps with serrated jaws to penetrate the corrosion on a tubular bus or use clamps with piercing bolts to penetrate galvanized surfaces. Note that piercing bolts are sometimes found to be ineffective under high short-circuit current conditions, and clamps with serrated jaws sometimes deform conductor surfaces, causing corona at higher voltages.

6.4.2 Order of connections of TPGs

When a ground is to be attached to a bus, incoming line, or equipment, the ground-end connection is attached first, and then the other end is attached by means of a live-line tool.

6.4.3 Order of removing TPGs

When a TPG is to be removed, the TPG assembly is removed from the bus, line, or equipment using a live-line tool before the ground-end connection is removed.

6.5 Equipment grounding

6.5.1 General

Work in substations does not permit universal applications of grounding. Evaluate each job with regard to the live equipment installed at the substation, other work activities, switching in the vicinity, and the type of work being done. Additional rigging and physical barriers might be necessary to prevent contact with live equipment.

Induction current can be a serious problem in a substation. A single ground will allow steady-state charging current to flow for a deenergized bus section that is parallel to an energized bus section. Applying two grounds to a bus section can provide a loop for current from the magnetic field to flow. Some equipment can develop voltage caused by capacitive coupling with nearby live conductors, if the equipment is isolated from the ground. Refer to Annex A for more information.

Temporary grounds are used to extend the permanent grounded work zone to include bus, lines, cables, and equipment, which are normally energized.
6.5.2 Electrical bonding for static and capacitive coupled voltage

While working on a circuit that is properly grounded, a person is protected by proper bonding techniques. Bonding is the electrical connection between metallic parts or conductors. The purpose of bonding is to connect solidly every metallic part in the work area to minimize any potential differences.

6.5.3 Transport and work equipment

Ground all vehicles utilizing any type of aerial equipment in a substation. The vehicle ground is connected to the vehicle first and the grounding system last to minimize sparks near the vehicle’s fuel or combustible materials on the vehicle.

Grounding the vehicle provides for quick clearing of the circuit if the vehicle becomes energized, thus reducing the time of exposure of persons in the work area to the electrical hazard.

External to the substation, protection to personnel is provided by avoiding contact between people on the ground and the vehicle or equipment when it is being used in the vicinity of energized conductors or apparatus. If, however, the vehicle is within the substation grid and the grid is properly designed, then touching the vehicle is no worse than touching any other grounded structure or equipment during a short-circuit current, although the probability of an inadvertent energization of the vehicle would be higher.

For persons standing on the ground, avoiding contact with a vehicle or an attached trailer while the boom aerial device is being moved in the vicinity of energized conductors or apparatus minimizes the possibility of hazards in the event the device comes in contact with the energized conductor. When it is necessary to operate the controls at the ground or vehicle level, protect the operator by one of the following methods:

a) Stand on a metal operator’s platform installed for this specific purpose.

b) Stand on the deck of the vehicle.

c) Stand on a portable conductive mat electrically attached to the grounded vehicle.

6.5.4 Arc welders

If the arc welder ground lead is placed to include a transformer or CT winding in the weld circuit, then a backfeed source is created that can produce a hazardous voltage in another winding. The fact that some welding equipment operates on dc does not eliminate the hazard because the voltage is induced when the electrode makes or breaks the circuit. Attaching leads near capacitor banks can also charge the capacitors to a hazardous voltage.

7. Minimizing static and capacitively coupled voltage on personnel

This clause serves as a guide to help alleviate the adverse effects caused by static voltage and electric field induction in substations when a worker becomes isolated from the ground (i.e., working aloft, or wearing rubber soled or insulating footwear).

The purpose of protective equipment against static voltage and electric field induction is to bring the worker and work surface to the same electrical potential and to keep them at the same potential throughout the job.

This clause does not constitute a recommendation but suggests a method to alleviate the adverse effects of discharges from static voltage and electric field induction. Many substation bus and equipment arrangements reduce levels of electric field below the perceptible range.
7.1 Protective garments

Protective garments can include conductive jackets, undershirts, shirts, trousers, boots, and gloves worn separately or in any combination as deemed necessary to mitigate the adverse affects of voltage discharges.

7.2 Attachments

Attachments to a grounded steel structure or other grounded devices can be made with conductive straps using magnets or clamps for attaching to the grounded structure. The other end of the conductive strap is connected to the worker’s conductive garments. A 2 m (6.56 ft) long conductive strap is suggested as an optimum manageable length.

8. Testing

8.1 New TPG component and assembly testing

Test the TPG assemblies and components in accordance with ASTM F855 or IEC 61230. ASTM F855 allows testing with currents with either low (grades 1–7) or high (grades 1H–7H) asymmetry. Choose the appropriate grade level for the application. IEC 61230 requires testing with 1.15 times the rated current and having an asymmetry factor of 2.6 times the rms value.

8.2 In-service inspection, maintenance, and testing TPGs

Inspect and test the TPG assemblies and components in accordance with ASTM F2249.

8.2.1 Visual inspection

a) Check for the presence of broken strands, especially near the cable termination. If any defects are found, then either repair or replace the assembly (remove from service), as appropriate.

b) Check for damaged or burned jacket material, for cable material discoloration and corrosion.

c) Check for damaged cable terminations. Check the clamps for sharp edges, cracks, splits, or other defects.

8.2.2 Operation check

Examine the individual components as follows:

a) Verify that the clamps operate smoothly and are free of excessive looseness. If any defects are found, then either repair or remove from service, as appropriate.

b) Clean the clamp jaws, eye-screws, and T-handle screws of dirt, oil, grease, and/or any corrosion.

c) Verify that the interface connection between the cable termination and the clamp is clean.

d) Verify that the cable termination to the clamp is tight.
8.2.3 Periodic testing of TPGs

Experience has shown that TPGs can be damaged by rough usage or corrosion. A visual inspection and electrical tests can be performed.

8.2.3.1 Visual test

The ability of the welded or compression cable termination to sustain electromechanical force has been well demonstrated. The direct clamping of a conductor to the ground clamp is likely satisfactory when new, but mechanical stresses on the conductor during its service life degrade it substantially. A thorough visual inspection is essential in the review of a TPG quality. Evidence of broken strands or corrosion within the cable termination or the cable is a sign of this degradation and requires further investigation.

8.2.3.2 Electrical test

An electrical test provides a means of monitoring continuity and changes in the electrical properties of a TPG. However, electrical tests alone do not adequately allow the user to predict the in-service performance of the TPG (exposure voltage drop) when carrying short-circuit current at the grounded worksite (5.1). Perform the electrical test on a TPG when it is new and at intervals thereafter. Differences in the electrical properties of the TPG would be an indication of the changing condition of the TPG. The tests are performed with dc or ac. Equipment is commercially available to perform an electrical test on a TPG cable assembly. ASTM F2249 gives specific guidelines to test the assemblies.

8.2.3.2.1 Direct current test

A direct current of at least 10 A, but not exceeding the continuous current rating, is passed through the complete TPG cable assembly. The direct current resistance of the TPG cable assembly is the voltage across the assembly divided by the current. The dc test is not sensitive to placement or surroundings of the TPG cable assembly being tested and, therefore, tends to be more repeatable than the ac test. Individual components of the cable assembly (cable, ferrules, and clamps) are tested and tracked for change (increase) in resistance, which can indicate wear, looseness, or corrosion.

8.2.3.2.2 Alternating current test

An ac current of at least 10 A, but not exceeding the continuous current rating, is applied to the TPG cable assembly. The impedance of the cable assembly is calculated by dividing the measured voltage across the TPG by the test current.

8.2.4 Testing and maintenance intervals

Testing and maintenance intervals are dependent on applicable codes, exposure, manner of use, individual company policy, and operating procedures.
Annex A

(informative)

Bibliography

Bibliographical references are resources that provide additional or helpful material but do not need to be understood or used to implement this standard. Reference to these resources is made for informational use only.

[B1] ASTM B172-2010, Standard Specification for Rope-Lay-Stranded Copper Conductors Having Bunch-Stranded Members for Electrical Conductors.6


[B12] IEC 60502-1994, Extruded Solid Dielectric Insulated Power Cable for Rated Voltages from 1 kV Up To 30 kV.


Comment [S122]: The references in the Bibliography have been set according to the style put forth in the 2009 IEEE Standards Style Manual. Also, this new opening paragraph was added to the Bibliography per IEEE Standards Style.

The numbering was changed in the Bibliography to [B#] because B stands for “Bibliography” regardless of which annex it falls under.

6 ASTM publications are available from the American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, USA (http://www.astm.org/).

7 EPRI publications are available from the Electric Research and Power Institute, 3420 Hillview Avenue, Palo Alto, CA 94304, USA (www.epri.com).

8 ICEA publications are available from ICEA, P.O. Box 20048, Minneapolis, MN 55420, USA (http://www.icea.org/).

9 IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3 rue de Varembe, CH-1211, Genève 20, Switzerland/Suisse (http://www.iec.ch/). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

10 The IEEE standards or products referred to in this annex are trademarks owned by the Institute of Electrical and Electronics Engineers, Incorporated.

11 IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, Piscataway, NJ 08854-4141, USA (http://standards.ieee.org/).


Annex B

(normative)

Terminology

B.1 Voltage and currents at the worksite

B.1.1 System voltage

System voltage refers to the bus or phase voltage and is generally specified in kilovolts (kV), phase-to-phase.

B.1.2 Static voltage

Static voltage can be built up on floating metallic objects (steel structures, bus conductors, etc.) by wind friction, dry conduction, or dust. Static voltage can also exist on a deenergized section of bus as a result of the capacitive nature of the bus at de-energization (trapped charge). Generally, static voltage buildup or trapped charge is less severe than the other worksite voltages that can exist. Once these static voltages are removed by proper grounding, they do not immediately return. However, applying the first set of grounds creates a new steady-state problem resulting from electric field induction.

B.1.3 Electric field induction (capacitive coupled)

Capacitive coupled voltages typically exist on a floating object in an electric field created by an energized circuit as shown in Figure B.1. The floating object can be a de-energized bus, a metallic structure, a transmission line, part of equipment, or a person on an insulating platform.

![Figure B.1—Equivalent circuit for capacitive-coupled voltage; conductor a is energized and conductor b is floating](image-url)

When an object in contact with the earth or a grounded object comes into contact with the de-energized conductor, the circuit is as shown in Figure B.2. Before contact is made with the floating conductor, the voltage on the conductor will be elevated because of the electric field of the energized conductor. This voltage is a function of the operating voltage of the energized conductor and the distance between the energized and de-energized conductors. Once the de-energized conductor is grounded, a significant potential difference no longer exists between the conductor and ground. However, unlike the case of the electrically floating conductor, there is now a path for charging current to flow through the grounded object to ground. The resulting charging current is not transient in nature; i.e., the resulting charge cannot be discharged or “bled off.” It is sinusoidal and continuous. This charging current is a function of the operating voltage of the energized conductor, the distance between the energized and de-energized conductors, and the length...
that the conductors are paralleled. The charging current is independent of all reasonable values of grid resistance, tower footing resistances, and series worker impedance of 1000 \( \Omega \) or less. It is believed that many fatalities and injuries attributed to induction are the result of a worker inadvertently becoming in series with this charging current. The worker can do nothing to reduce the charging current associated with installing the first set of TPGs or removing the last set of TPGs at a given location. The charging current can only be avoided.

**Figure B.2**—Case of contact with deenergized conductor

B.1.4 Magnetically coupled voltage

Magnetically induced voltage is similar to the action that occurs in a transformer. When the primary winding is energized, the resulting current flow induces a voltage in the secondary winding. The same phenomenon occurs when an energized conductor (primary winding) carrying current is adjacent to a deenergized (switched out) conductor (secondary winding). In this case, the transformer has an air core instead of an iron core. A voltage is thus developed at point B. This circuit is illustrated in Figure B.3. Grounding both ends of the deenergized conductor will minimize the potential difference across the worker in contact with the deenergized conductor, even though this provides a closed loop (i.e., shorted secondary) and allows current to flow in the deenergized conductor.

**Figure B.3**
B.1.5 Currents

Under normal circumstances, only the rated load current is present at an energized worksite. During deenergized maintenance operations, with TPGs in place, consider available short-circuit currents. This short-circuit current will be substantially larger than the steady-state current. In addition, consider the current asymmetry and duration.

The asymmetry is a function of the reactance divided by the resistance ($X/R$ ratio) of the circuit. The result is a nonperiodic, exponentially decaying dc component combined with the ac symmetrical component, as illustrated in Figure B.4 (top graph). The peak current value can be increased to almost twice the symmetrical peak value. The asymmetry causes an increase in electromechanical forces and in the heating of the protective equipment components. The bottom graph of Figure B.4 shows the typical current waveform from an oscillograph.

Figure B.3—Magnetically coupled voltage
B.2 Safety criteria

B.2.1 Body current safety

Humans are highly sensitive to electrical current, primarily because their body’s nervous system is electrically stimulated. The magnitude of current that a body can tolerate depends on the frequency, duration, and physical condition of the body. It is the consensus of researchers, however, that generally for frequencies above 25 Hz and for a duration of a few seconds, the threshold of perception is 1 mA. A current of 9 mA to 25 mA makes it difficult for people to release their grip from a power circuit, and at 30 mA, muscular contractions can make breathing difficult. At higher currents, a person’s heart can cease to function (ventricular fibrillation). See IEEE Std 80 for more information concerning body currents.

As previously stated, the magnitude of current a body can tolerate depends to a great extent on the duration of the shock. Researchers have concluded that 99.5% of all persons could withstand, without ventricular fibrillation, currents with a magnitude determined by Equation (B.1) or Equation (B.2) for short durations:

\[ I_n = \frac{0.116}{\sqrt{t}} \quad \text{for a 50 kg (110 lb) body} \quad \text{(B.1)} \]

or
\[ I_B = \frac{0.157}{\sqrt{t_s}} \quad \text{for a 70 kg (155 lb) body} \quad (B.2) \]

where

- \( I_B \) is the rms magnitude of body current (A)
- \( t_s \) is the duration of current exposure (s)

Generally, Equation (B.1) is used for a more conservative approach. However, use Equation (B.2) provided that the average population weight is expected to be at least 70 kg (155 lb). Equation (B.1) and Equation (B.2) also indicate that much higher body currents are tolerated where fast operating protective devices are relied on to limit short-circuit current durations.

For capacitive-coupled voltage situations, where the conductor is energized continuously, the safety-related let-go current is more appropriate as the safety-related current limit.

**B.2.2 Shock hazard**

**B.2.2.1 Touch voltage**

*Touch voltage* is the potential difference between the ground potential rise (GPR) and the surface potential at the point where a person is standing, while at the same time having a hand in contact with a grounded structure. (See Figure B.5.)

**B.2.2.2 Step voltage**

*Step voltage* is the difference in surface potential experienced by a person bridging a distance of 1 m with the feet without contacting any grounded object. (See Figure B.5.)

![Figure B.5—Basic shock situation](image-url)
B.2.2.3 Transferred voltage

Transferred voltage is a special case of touch voltage where a voltage is transferred into or out of the substation from or to a remote point external to the substation site. (See Figure B.5.)

Deleted: A
Deleted: Figure B.5

B.2.2.4 Mesh voltage

Mesh voltage is the maximum touch voltage within a mesh of a ground grid.

Deleted: The

B.2.2.5 Metal-to-metal touch voltage

Metal-to-metal touch voltage is the difference in potential between metallic objects or structures within the substation site that could be bridged by direct hand-to-hand or hand-to-feet contact.

Deleted: The
C.1 Development of TPG impedance $K$ factor

Historically, most computations of worker exposure voltage for temporary protective grounding in ac substations have used only the resistance of the TPG cable in parallel with the assumed worker resistance to determine the current through the worker. This neglects any mutual induction between the TPG and the worker, the self-inductance of the TPG, any increase in TPG resistance as the TPG temperature increases from the high current, and any impedances of external circuit components (such as bus).

Impedance correction factors ($K$ factors) were developed to improve the TPG resistance $I\cdot R$ voltage drop method of approximating worker exposure voltage at a grounded worksite. The use of $K$ factors in this guide will provide more realistic values of exposure voltage by accounting for magnetic induction of the TPGs and in some cases the impedance of the short-circuit current carrying bus and ground return path at the substation worksite. It is emphasized that the method of $K$ factors is an approximation resulting from the variation in layout encountered at a grounded worksite and modeling assumptions. It may nonetheless be considered a tool for evaluation of exposure voltage.

C.1.1 Grounded worksite touch (exposure) voltage

During accidental energization of a grounded worksite, a voltage drop develops across the TPGs and any other segment of bus, which carries the short-circuit current. This voltage drop becomes an exposure voltage if contacted by a worker, by either phase-to-ground or phase-to-phase contact. For electrical shock evaluation, it is common practice to determine touch voltage by calculating the resistive $I\cdot R$ voltage drop of the TPGs using the worksite available short-circuit current. For this purpose, a TPG is assumed to be directly in parallel with the worker’s body. Both theoretical study and experimental test results indicate that using TPG cable resistance alone can be inaccurate (low) for determining exposure voltage. The formation of induction ground loops with the TPG and worker can introduce a significant reactive component of voltage drop.

C.1.2 Induction ground loop

As a result of the spatial layout of TPGs in relation to a worker at a grounded worksite, a ground loop is usually formed by a TPG, the grounded bus and equipment, worker’s body, and a ground return path to the TPG. In substations and switchyards, the worksite ground return path is conductor (ground grid, grounded equipment, etc.) and not earth. The ground loop circuit becomes closed when the worker simultaneously touches a conductor that has been grounded by a TPG and another grounded object in the station. See Figure C.1.

C.1.2.1 Induction ground loop for single-point grounded worksite

During an accidental energization of a single-point grounded worksite with TPGs connecting each phase to ground, a TPG conducts short-circuit current that forms a ground loop with the worker (A-phase in Figure C.1). The A-phase short-circuit current creates both a resistive $I\cdot R$ voltage drop and a reactive $I\cdot XL$ voltage drop across the TPG. The reactive voltage drop is created by magnetic induction from the short-circuit current, whereby an alternating magnetic flux passes through (links with) the area enclosed by the...
ground loop. For a three-phase energized grounded worksite as in Figure C.1, the currents in the B- and C-phase TPGs also produce magnetic flux linkages, which induce additional voltages in the A-phase ground loop with the worker. Therefore, both resistive and reactive components of potential are present at the worker touch point; the reactance components are out of phase with the resistive component.

A similar induction ground loop can form when a worker is positioned between the TPGs and the energy source. In this case, the voltage at the touch point includes additional resistive and reactive voltage drop components resulting from the current in the bus section between the TPGs and the worker.

C.1.2.2 Induction ground loop for bracket grounding worksite

A TPG induction ground loop is formed with the worker as shown in Figure C.2. For modeling purposes in this guide, the TPG closest to the energy source defines the depth of the ground loop (dimension D). Note that for any given position of the worker between TPGs, the same worker exposure voltage would be obtained if either TPG was chosen to define the ground loop (the sum of the voltages around either ground loop circuit must be the same at a common point on the bus).
C.1.3 TPG impedance (induction ground loop) modeling

A composite value of impedance (reactance and resistance) can be derived for a TPG forming an induction ground loop with the worker, for single or multiphase worksite grounding, which accounts for all of the induced (reactive) voltage drops in the ground loop. This composite impedance, if multiplied by the available short-circuit current, approximates the true TPG voltage drop or worker touch voltage for a specific grounded worksite layout. This composite impedance represents an equivalent lumped impedance of a single TPG directly in parallel with the worker. The resistance of the worker’s body and associated voltage drop in the ground loop circuit resulting from current through the body is negligible as the body resistance is always several orders of magnitude greater than the TPG equivalent impedance. Therefore, the entire IZ voltage drop produced by the TPG composite impedance would appear across the body.

TPG composite impedance equations were derived for single and three-phase, single-point grounding and single-phase bracket grounding. The derivations are complex, therefore only a basic derivation procedure, final equations, and graphed results are presented in this annex. Composite impedance was derived from circuit analysis using self and mutual reactances of the short-circuit current carrying conductors (TPGs, overhead bus, and ground return where appropriate) for the specified grounded worksite configurations. These conductors produce magnetic flux through the area enclosed by the TPG ground loop circuit with a worker.
The general electrical circuit model used to develop TPG composite impedance and $K$ factors for single-point worksite grounding is shown in Figure C.3. A similar circuit modeling method was used with Figure C.2 for bracket worksite grounding. In all cases, the mathematical derivations assume that the TPGs hang vertically and straight for their entire length $L$. The worker completes the ground loop circuit by touching the substation ground grid conductor, either directly or indirectly through a grounded conductive object such as a substation structure.

A similar circuit modeling approach was used with Figure C.2 as the basic diagram for derivation of $K$ factors for bracket worksite grounding.

### C.1.3.1 Derivation of TPG composite impedance for single-point grounded worksite, TPGs positioned between worker and energy source

The defined worker exposure or touch voltage in Figure C.3 is the potential between the A-phase bus and substation ground (ground grid conductor, grounded equipment or structure, etc.), at distance $D$ from A-phase TPG of length $L$. The lumped impedances $Z_{sa}, Z_{sb},$ and $Z_{sc}$ represent the TPG conductors resistance ($R_c$) and self and mutual reactances associated with the ground loop circuit formed by the A-phase TPG, grounded overhead bus, ground grid conductor, and worker’s body ($R_w$). Balanced three-phase short-circuit current flows in the TPGs from the source at left. No current is assumed in the ground grid conductor between the A-phase TPG and worker. The exposure (touch)
voltage \( V_{esg} \) on the A-phase bus is then determined by summing the voltages induced in the ground loop circuit with the worker from the current in each of the three TPGs as in Equation (C.1):

\[
V_{esg} = I_e \left( R_c + jX_a \right) + j(I_e \cdot X_{ab}) + j(I_e \cdot X_{ac})
\]  

(C.1)

where

- \( R_c \) is the TPG cable resistance (excluding clamps and ferrules), ohm
- \( X_a \) is the A-phase TPG self reactance out to touch point \( D \), ohm
- \( X_{ab} \) is the A-phase TPG coupled reactance out to touch point \( D \) from the current in B-phase TPG, ohm
- \( X_{ac} \) is the A-phase TPG coupled reactance out to touch point \( D \) from the current in C-phase TPG, ohm
- \( I_e \) is the \( f(1,0) \)
- \( I'_{ac} \) is the \( f(0.5+0.866) \)
- \( I'_{ab} \) is the \( f(0.5-0.866) \)

Note that only the A-phase TPG cable resistance produces an \( IR \) voltage drop that appears in the ground loop circuit with the worker.

Substituting the rectangular form of phase currents into Equation (C.1), collecting real and imaginary terms, and then dividing by the short-circuit current magnitude \( I_f \) provides the desired A-phase TPG composite impedance \( Z_g \) as in Equation (C.2):

\[
Z_g = \frac{\sqrt{R_c + 0.0003 + 0.866(X_{ab} - X_a)^2 + [X_a - 0.5(X_{ab} + X_{ac})]^2}}
\]  

(C.2)

where

- \( Z_g \) is the A-phase TPG composite impedance for three-phase single-point grounding

[TPGs between worker and energy source], ohm, and the constant 0.0003 represents a nominal resistance for the TPG clamps and ferrules. Expressions for the TPG self and coupled reactances are given in C.4.1.

Note that Equation (C.2) is derived specifically for the rectangular geometry depicted in Figure C.1 and Figure C.3 with TPGs hung vertically from the bus, between worker and energy source. Equation (C.2) is also valid for a worker touching the C-phase bus as a result of symmetry. A similar derivation of TPG composite impedance for the B-phase (middle) resulted in a slightly lower impedance and, therefore, is not presented in this guide. Because of the rectangular geometry, only the currents in the TPGs produce significant magnetic flux linkages with the TPG ground loop formed with the worker. Currents in the overhead bus and station ground grid (ground return current, if any, assumed to flow toward the source) do not produce flux that links with the worker ground loop.

Equation (C.2) is cumbersome and needs further refinement for ready use in this guide. To accomplish this, TPG impedance \( K \) factor curves were created with computer software. However, the reader may utilize Equation (C.2) by determining values for reactance terms \( X_a \), \( X_{ab} \), and \( X_{ac} \) from the formula in C.4.1.

TPG composite impedance \( Z_g \) from Equation (C.2) can be normalized to the TPG cable resistance by dividing by \( R_c \). This normalized value, defined impedance \( K \) factor, can be plotted as a family of curves for a given TPG conductor size and length, as shown in C.3.1. Impedance \( K \) factors were evaluated for 2 m, 6.56 ft, 4.57 m (15 ft), and 10 m (32.81 ft) length TPGs in conductor sizes #2 AWG through 350 kcmil (not all shown in C.3.1) to determine the worst-case (highest) values.

12 Refer to ASTM F-855 for an evaluation of clamp and ferrule resistance.
IEEE Std 1246-2011
IEEE Guide for Temporary Protective Grounding Systems Used in Substations

The single-value $K$ factors in Table C.1 may be used to determine worst-case touch voltage (see C.2) for the following conditions: rectangular grounding layout as shown in Figure C.1 and Figure C.3 and copper TPG lengths of 2 m through 10 m. Table C.1 may also be conservatively used for single-phase grounding, assuming there is insignificant current in the ground grid between the TPG and the worker. For this single-phase condition, it is noteworthy that the reactive component of the TPG composite (ground loop) impedance approaches the self-reactance of the TPG conductor when the loop depth $D$ and bus spacing $S$ become large. This effect can be observed in the flattening of the $K$ factor curves in Figure C.3 for $D$ greater than approximately 10 m and $S = 24$ m. For this reason, the values in Table C.1 were computed using only the self-impedance of the TPG conductor assuming length of 10 m.

### Table C.1—60 Hz TPG impedance $K$ factors ($Z/R_c$) for single- and three-phase, single-point grounded worksite with single copper cable TPG, 10 m or less connecting each phase-to-ground grid

<table>
<thead>
<tr>
<th>TPG cable size AWG or kcmil</th>
<th>$K$ factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.49</td>
</tr>
<tr>
<td>1</td>
<td>1.69</td>
</tr>
<tr>
<td>1/0</td>
<td>1.97</td>
</tr>
<tr>
<td>2/0</td>
<td>2.27</td>
</tr>
<tr>
<td>3/0</td>
<td>2.71</td>
</tr>
<tr>
<td>4/0</td>
<td>3.26</td>
</tr>
<tr>
<td>250</td>
<td>3.74</td>
</tr>
<tr>
<td>350</td>
<td>5.01</td>
</tr>
</tbody>
</table>

Note: The TPGs are positioned between the worker and the short-circuit current source.

C.1.3.2 Derivation of TPG composite impedance for single-point grounded worksite, worker positioned between TPGs and energy source

A worker positioned between the worksite TPGs and the energy source creates a higher worker exposure voltage situation than if the TPGs are positioned between the worker and the energy source. For this case (Figure C.1 with worker touch point at A-phase bus to left of TPGs at distance $D$), the short-circuit current related voltage drops across the station bus and ground grid return conductor, which form the ground loop with the worker, must be added to the exposure voltage in Equation (C.1). Equation (C.2) must then be modified to include the associated bus and ground grid conductor impedances, resulting in Equation (C.3) for single-phase grounding ($X_b = X_c = 0$). A single-phase grounding model was chosen for conservative (slightly higher exposure voltage) results, with the assumption that all of the return-to-source short-circuit current flows in a single ground conductor between the TPG and the worker.

$$Z_{gs} = \sqrt{\left(\frac{R_c}{R_c + 0.0003 + R_b + R_e}\right)^2 + \left(X_c + X_e + X_s\right)^2} \tag{C.3}$$

where

- $Z_{gs}$ is the TPG composite impedance for single-phase, single-point grounding with worker between TPG and energy source, ohm
- $R_c$ is the [see Equation (C.1)], ohm
- $R_b$ is the resistance of bus forming ground loop with worker, ohm
- $X_c$ is the self-reactance of bus forming ground loop with worker, ohm
- $X_e$ is the self-reactance of assumed 4/0 AWG ground grid conductor forming ground loop with worker, ohm
- $X_s$ is the self-reactance of assumed 4/0 AWG ground grid conductor forming ground loop with worker, ohm

40 Copyright © 2012 IEEE. All rights reserved.
Expressions for the resistance and self-reactance of bus and 4/0 AWG ground grid conductor are given in C.4.2.

The computer-generated factor curves ($Z_r/Z_g$) in C.3.2 show an ever-rising trend in value of $K$ with increasing distance between worker and TPG. Therefore, single-value $K$ factors as in Table C.1 cannot be applied to this situation.

Comparing the single-point grounding $K$ curves in C.3.1 and C.3.2 makes it apparent that touch voltage can be significantly higher when the worker is positioned between the TPGs and the energy source. Locating the TPGs between the worker and the energy source is the preferred method for single-point grounding wherever practical. If the energy source can be located on either side of the worksite, then locate the TPGs as close as possible to the worker to minimize the higher worker exposure voltage or consider using bracket grounding.

C.1.3.3 TPG impedance $K$ factor for bracket grounded worksite

TPG impedance $K$ factors can be developed for bracket grounding in a similar manner as for single-point grounding in C.1.3.2. However, in this case, short-circuit current division (mostly the result of magnetic coupling) in the bracket TPGs connected to the phase touched by the worker must be determined. Short-circuit current-related voltage drop in the connecting bus and station ground grid return conductor between the bracket TPGs forming the ground loop with the worker must also be determined (Figure C.2). This increases the complexity of deriving the TPG composite impedance equation $Z_g$.

Computer-generated $K$ factor data were created for single-phase bracket grounding and a portion of this data is plotted for the 4/0 AWG TPG conductor in C.3.3 for illustration of $K$ versus ground loop depth $D$ for a given bracket distance $B$ (Figure C.21). The maximum or peak value of $K$ in each curve is of interest for determining worst-case worker exposure voltage for a given TPG bracket spacing. Therefore, maximum values of $K$ are plotted in Figure C.22 and Figure C.23 as families of curves for all TPG cable sizes that were modeled. Examination of these peak $K$ factor curves indicate that bracket grounding can provide lower $K$ factor values (worker exposure voltage) than single-point grounding. Three-phase bracket grounding was not modeled, but it has a similar variation in $K$ curves with bus spacing $S$ shown for single-point grounding.

As shown in Figure C.22 through Figure C.24, there is considerably more variation in the $K$ factors for bracket grounding, with dependence on both TPG length and bracket separation distance. Although these figures can be used to determine the $K$ factor within the range of parameters modeled, a conservative approximation can also be obtained by using the same $K$ factors as for worksite grounding and shown in Table C.1. A single value of $K$ cannot be appropriately used for all applications without first examining and understanding the limitations of the curves.

C.2 Application of TPG impedance $K$ factors

The TPG impedance $K$ factors in this annex may be used to convert TPG conductor resistance to approximate equivalent impedance that represents a single TPG, connected directly in parallel with the worker’s body at a grounded worksite. This equivalent impedance accounts for the distributed resistance and inductance of the ground loop formed by the TPG and the worker. Magnetic coupling from short-circuit current in all three phase TPGs is included in the computation of $K$ values for three-phase grounding where specified.

Impedance $K$ factors are provided for three grounding scenarios:

a) Single-point grounded worksite with TPGs positioned between worker and energy source.
C.2.1 Calculation procedure for worker touch voltage

Worker touch voltage may be approximated by Equation (C.4):

\[
V_t = I_f \cdot R_c \cdot K
\]  

(C.4)

where

- \(V_t\) is the touch voltage, \(V_{rms}\)
- \(I_f\) is the available short-circuit current, kA rms sym
- \(R_c\) is the TPG cable resistance (excluding clamps and ferrules), milliohm
- \(K\) is the TPG impedance multiplier

Use the following steps to calculate worker touch voltage for a specific grounding application:

1. Determine the required TPG size based on the available short-circuit current (4.6.2).
2. Determine the required TPG conductor length \(L\) in meters.
3. Select the TPG \(K\) factor from:
   - Table C.1 for single-point grounding (TPG between worker and energy source). If desired, the reader may select a value directly from the \(K\) curves in C.3 for a specific application, or calculate \(K\) using the procedure in C.1.3.1.
   - Figure C.18 through Figure C.20 for single-point grounding (worker between TPG and energy source). The \(K\) curves in C.3.2 may be used for both single-phase and three-phase grounding, or the reader may calculate \(K\) using the procedure in C.1.3.2. No single value of \(K\) can be applied as for single-point grounding, as the \(K\) factors vary too much versus the ground loop path.
   - Figure C.21 through Figure C.24 for bracket grounding, or conservatively use \(K\) factor from Table C.1 (see NOTE). The maximum value \(K\) curves in Figure C.21 through Figure C.24 may be used for both single-phase and three-phase grounding, or Table C.1 may be used after reading C.1.3.3. No readily available \(K\) factor calculation procedure is provided for bracket grounding.
4. Calculate the TPG conductor resistance from Table C.2.
5. Calculate the touch voltage from Equation (C.4), noting \(I_f\) must be in kA if \(R_c\) is in m\(\Omega\) from Table C.2.

The \(K\) factor values given in the tables and curves of Annex C were calculated for the copper TPG conductor with radius and resistance \(R_c\) values based on Table C.2. The use of other conductor resistance values in Equation (C.4) will introduce error in \(V_t\) approximately in proportion to the ratio of the other-to-specified conductor resistances.

**NOTE:** To calculate the bracket grounding touch voltage, use the total available short-circuit current \((I_1 + I_2\) in Figure C.2) for \(I_f\) in Equation (C.4), not an individual TPG current. The derivation of \(Z_k\) for calculating \(K\) factor accounts for the current division.
Table C.2—DC resistance of copper welding cable, milliohms per meter at 25 °C

<table>
<thead>
<tr>
<th>Conductor size</th>
<th>Conductor radius (cm)</th>
<th>mΩ/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWG or kcmil</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.428</td>
<td>0.551</td>
</tr>
<tr>
<td>1</td>
<td>0.478</td>
<td>0.436</td>
</tr>
<tr>
<td>1/0</td>
<td>0.537</td>
<td>0.344</td>
</tr>
<tr>
<td>2/0</td>
<td>0.645</td>
<td>0.278</td>
</tr>
<tr>
<td>3/0</td>
<td>0.732</td>
<td>0.220</td>
</tr>
<tr>
<td>4/0</td>
<td>0.819</td>
<td>0.175</td>
</tr>
<tr>
<td>250</td>
<td>0.906</td>
<td>0.148</td>
</tr>
<tr>
<td>350</td>
<td>1.048</td>
<td>0.106</td>
</tr>
</tbody>
</table>

NOTE—Average value for Class K and M conductors.

C.3 TPG impedance $K$ factor curves

C.3.1 Single-point grounded worksite, TPGs positioned between worker and energy source

TPG impedance $K$ curves for three-phase, single-point grounding are shown in the following charts. Note that the three-phase, single-point grounding curves with bus spacing $S = 24$ m are also valid for single-phase grounding.

Fourteen of 24 charts created for the development of the method of $K$ curves for this guide are shown below for observation and use. These charts are sufficient to demonstrate the trends in $K$ values for various worksite conditions. Charts not shown are for 2 m and 10 m length TPGs for some conductor sizes.

NOTE—All of the following TPG impedance $K$ factor curves are plotted for a power system frequency of 60 Hz.

Figure C.4—#2 AWG copper TPG length = 2 m (6.56 ft)
Figure C.5—#2 AWG copper TPG length = 4.57 m (15 ft)

Figure C.6—#2 AWG copper TPG length = 10 m (32.81 ft)
Figure C.7—#1 AWG copper TPG length = 4.57 m (15 ft)

Figure C.8—1/0 AWG copper TPG length = 4.57 m (15 ft)
Figure C.9—2/0 AWG copper TPG Length = 4.57 m (15 ft)

Figure C.10—3/0 AWG copper TPG length = 4.57 m (15 ft)
Figure C.11—4/0 AWG copper TPG length = 2 m (6.56 ft)

Figure C.12—4/0 AWG copper TPG length = 4.57 m (15 ft)
Figure C.13—4/0 AWG copper TPG length 10 m (32.81 ft)

Figure C.14—250 kcmil copper TPG length = 4.57 m (15 ft)
Figure C.15—350 kcmil copper TPG length = 2 m (6.56 ft)

Figure C.16—350 kcmil copper TPG length = 4.57 m (15 ft)
C.3.2 Single–point grounded worksite, worker positioned between TPGs and energy source

Families of TPG impedance $K$ curves are shown for TPG lengths of 2 m (6.56 ft), 4.57 m (15 ft), and 10 m (32.81 ft) as depicted in Figure C.1, except the worker is now positioned to the left of the TPGs (between source and TPGs). The values of $K$ for other lengths of TPGs between 2 m (6.56 ft) and 10 m (32.81 ft) may be interpolated from the curves. Ground loop depth $D$ is the distance from TPG to worker (toward source). These $K$ curves account for impedance of the section of station bus of length $D$ and same length of an assumed 4/0 AWG station ground grid conductor that together form the ground loop with the worker and conduct the short-circuit current. These curves are derived for single-phase, single-point worksite grounding but are applicable to three-phase grounding as well. The observation here is that the value of $K$ and worker exposure voltage rises significantly as the distance between worker and TPG increase. Refer to C.1.3.2.

Figure C.18 through Figure C.20 show 60 Hz TPG impedance $K$ factor curves for single-phase, single-point grounding with the worker positioned between the TPG and the energy source.

---

1 The station bus is assumed to be a schedule 40 seamless bus pipe, 3 in nominal size, 3.5 in outer diameter, 3.06 in inner diameter, and resistance at 70°C: 8.126 μΩ/ft. Larger bus sizes should result in slightly lower $K$ factors.
Figure C.18—2 m (6.56 ft) length TPGs

Figure C.19—4.57 m (15 ft) length TPGs
C.3.3 Single-phase bracket grounded worksite

Refer to C.1.3.3 for a discussion of TPG impedance $K$ factors for bracket grounding. Figure C.21 illustrates the impedance $K$ factor model data curves for only one TPG cable size and length. These data and similar data for all other TPG model data are plotted in another form of curves showing maximum $K$ values versus TPG bracket spacing in Figure C.22 through Figure C.24. These curves may be used to approximate worst-case worker exposure voltage for a given TPG bracket spacing (see Figure C.2). These $K$ factor curves account for the impedance of the section of station bus (see footnote 11) and an assumed single 4/0 AWG station ground grid conductor that together form the ground loop with the worker and conduct the short-circuit current.

These single-phase, TPG bracket maximum-value $K$ curves are applicable for three-phase grounding for bus spacing $S$ (Figure C.1) greater than 1.5 m and become conservative (high $K$ values) for bus spacing less than 1.5 m.
NOTE—The curves include the effect of impedance for a single 4/0 AWG station ground grid conductor current return path below the overhead bus (Figure C.2). *B* = bracket separation distance between TPGs.

**Figure C.21**—Example 60 Hz TPG \( K \) factor curves for single-phase bracket grounding with 4/0 copper TPGs.

Figure C.22 through Figure C.24 show curves for 60 Hz TPG maximum impedance \( K \) factors for single-phase bracket grounding, as shown in Figure C.2. The curves represent the highest value of \( K \) obtained at an unspecified worker position between bracket TPGs.
Figure C.22—2 m (6.56 ft) TPGs

Figure C.23—4.57 m (15 ft) TPGs
C.4 TPG reactance terms for calculation of $Z_g$ and $K$ factor

C.4.1 Single-point grounded worksite (TPGs between worker and energy source)

The reader may calculate TPG composite impedance $Z_g$ (and $K$ factor) with Equation (C.2) in C.1.3.1 by determining values for reactance terms $X_a$, $X_{ab}$, and $X_{ac}$ with Equation (C.5) through Equation (C.7):

\[ X_a = 2\pi f (L_a - L_{tash}) \]  
\[ X_{ab} = 2\pi f (L_{tash} - L_{tahb}) \]  
\[ X_{ac} = 2\pi f (L_{tash} - L_{tacl}) \]

where

- $L_a$ is the A-phase TPG self-inductance, H
- $L_{tash}$ is the A-phase TPG mutual inductance with worker body at touch point D, H
- $L_{tahb}$ is the B-phase TPG mutual inductance with worker body at touch point D, H
- $L_{tacl}$ is the C-phase TPG mutual inductance with worker body at touch point D, H
- $L_{tash}$ is the mutual inductance of A- and B-phase TPGs, H
- $L_{tacl}$ is the mutual inductance of A- and C-phase TPGs, H
- $f$ is the frequency, Hz ($f = 60$ Hz for $K$ factor values given in this guide)
Equation (C.5) through Equation (C.7) were derived specifically for the TPG induction ground loop arrangement shown in Figure C.1 and Figure C.3. Formulas for determining the self ($L_s$) and mutual ($L_m$) inductances of finite length conductors from Grover [B5] are shown in Equation (C.8):

$$L_s = 2L \left[ \ln \left( \frac{2L}{r} \right) - 0.75 \right] \times 10^{-6} \text{ H}$$  \hspace{1cm} (C.8)

$$L_m = 2L \left[ \ln \left( \frac{L}{d} \right) + \sqrt{1 + \left( \frac{L}{d} \right)^2} - \sqrt{1 + \left( \frac{d}{L} \right)^2} - \frac{d}{L} \right] \times 10^{-6} \text{ H}$$  \hspace{1cm} (C.9)

where

- $L$ is the TPG length (Figure C.1 and Figure C.3), cm
- $r$ is the TPG conductor radius (excluding jacket), cm
- $d$ is the distance between center of conductors, cm

In determining the mutual inductances, the user must carefully select distance $d$ to be the horizontal length between the mutually coupled conductors of interest. For calculation of $L_{mb}$ and $L_{ma}$, distance $d$ is equal to $S$ and $2S$, respectively, in Figure C.1 and Figure C.3. For calculation of the mutual inductances of TPGs with the worker’s body, distance $d$ must be determined for the specific TPG to worker touch point on the bus; $d$ is dimension $D$ in Figure C.1 and Figure C.3 for $L_{mb}$, or $d$ is the diagonal length from respective TPG to worker touch point for $L_{ma}$ and $L_{mb}$.

C.4.2 Single-point grounded worksite (worker between TPGs and energy source)

The reader may calculate TPG composite impedance $Z_g$ (and $K$ factor) with Equation (C.3) in C.1.3.2 by determining the values for $R_b$, $R_g$, $X_b$, and $X_g$ with the following in Equation (C.10):

Self-inductance formula for bus and cable from Grover [B5]

Tubular conductor

$$L_g = 2D \left[ \ln \left( \frac{2D}{r} \right) + \ln \xi - 1 \right] \times 10^{-6}$$  \hspace{1cm} (C.10)

where

- $L_g$ is the self-inductance of short-circuit current carrying bus forming ground loop with TPG and worker, H
- $D$ is the distance between TPG and worker, cm
- $r$ is the pipe bus outer radius (1/2 outer diameter), cm
- $\ln \xi$ is the 0.0416 for pipe bus specified in footnote 11

Solid round conductor

$$L_g = 2D \left[ \ln \left( \frac{2D}{r} \right) - 0.75 \right] \times 10^{-6}$$  \hspace{1cm} (C.11)
where

\[ I_g \text{ is the self-inductance of short-circuit current carrying station ground grid conductor (single conductor) forming ground loop with TPG and worker, } H \]
\[ D \text{ is the distance between TPG and worker, cm} \]
\[ r \text{ is the radius of ground grid conductor, cm} \]

Based on the preceding inductance formula and published resistance data for bus and cable (see footnote 5 and Table C.2), the values for the resistance and self-reactance of the station bus and the single 4/0 AWG ground grid conductor used for the calculation of \( K \) values in C.3.2, with Equation (C.3) are as follows:

\[ R_b = 0.000\,026\,7 \text{ ohm/m and } X_b = 0.000\,46 \text{ ohm/m for bus} \]
\[ R_g = 0.000\,175 \text{ ohm/m and } X_g = 0.000\,6 \text{ ohm/m for 4/0 AWG copper conductor} \]