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IEEE Guide for Performing Arc-Flash Hazard Calculations

Amendment 2: Changes to Clause 4

IEEE Industry Applications Society

Sponsored by the
Petroleum and Chemical Industry Committee

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USA

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(Amendment to
IEEE Std 1584™-2002)

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Approved 31 March 2011

IEEE-SA Standards Board

Abstract: Techniques for designers and facility operators to apply in determining the arc-flash hazard distance and the incident energy to which employees could be exposed during their work on or near electrical equipment are provided in IEEE Std 1584-2002 and IEEE Std 1584a-2004. Changes in Clause 4 (the analysis process), based on the experience of persons who have conducted many of these studies, are provided in this amendment.
Keywords: arc fault currents, arc-flash hazard, arc-flash hazard analysis, arc-flash hazard marking, arc-flash protection boundary, arc in enclosures, arc in open air, bolted fault currents, electrical hazard, IEEE 1584b, incident energy, personal protective equipment, protective device coordination study, short-circuit study, working distances

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Introduction

This introduction is not part of IEEE Std 1584b-2011, IEEE Guide for Performing Arc-Flash Hazard Calculations—Amendment 2: Changes to Clause 4.

It is hoped that the changes to Clause 4 will help improve the quality of the arc-flash studies being prepared for owners and other users by clarifying the wording to allow users to better understand the process.

This amendment revises Clause 4 dealing with the process of performing an arc-flash hazard calculations study. The revisions are based on the experiences of users of the guide with extensive experience in performing these studies since IEEE Std 1584-2002 was published in 2002.

When the guide was written, there was little experience in performing these studies. Now the Working Group members have more experience applying the guide and can enable more accurate studies by others by incorporating their knowledge into the guide.

Some of the existing wording in the guide has been found to be vague or open to interpretation. It is the intent of this amendment that the changes will improve the wording and make the standard easier to follow.

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IEEE Guide for Performing Arc-Flash Hazard Calculations

Amendment 2: Changes to Clause 4

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NOTE—The editing instructions contained in this amendment define how to merge the material contained therein into the existing base standard and its amendments to form the comprehensive standard.

The editing instructions are shown in ***bold italic***. Four editing instructions are used: change, delete, insert, and replace. ***Change*** is used to make corrections in existing text or tables. The editing instruction specifies the location of the change and describes what is being changed by using ~~strikethrough~~ (to remove old material) and <u>underscore</u> (to add new material). ***Delete*** removes existing material. ***Insert*** adds new material without disturbing the existing material. Insertions may require renumbering. If so, renumbering instructions are given in the editing instruction. ***Replace*** is used to make changes in figures or equations by removing the existing figure or equation and replacing it with a new one. Editing instructions, change markings, and this NOTE will not be carried over into future editions because the changes will be incorporated into the base standard. The editing instructions contained in this amendment define how to merge the material contained therein into the existing base standard and its amendments to form the comprehensive standard.

2. Normative r~~R~~eferences

Change the Clause 2 title as shown above.

Delete the following reference:

IEEE Std 141™-1993, IEEE Recommended Practice for Electric Power Distribution for Industrial Plants (*IEEE Red Book*™)

Insert the following reference alphabetically as it should appear in Clause 2:

IEEE Std 551™-2006, IEEE Recommended Practice for Calculating Short-Circuit Currents in Industrial and Commercial Power Systems (*IEEE Violet Book*™)

4. Analysis process

Change Clause 4 as follows:

An arc-flash hazard analysis should be performed in association with or as a continuation of the short-circuit study and protective-device coordination study.

The process and methodology of calculating short-circuit currents and performing protective-device coordination is covered in IEEE Std 551™-2006 (*IEEE Violet Book*™)~~141-1993 (*IEEE Red Book*™)~~ and IEEE Std 242-2001 (*IEEE Buff Book*™), respectively. Although it is possible to perform a short-circuit study manually, using the rationale presented in these references, electrical system analysis software may be used to simplify the calculations for complex distribution systems. Programs provide for much more of the necessary information and may be accurate as long as network details are specifically modeled. They usually improve calculation accuracy, consistency of results, and facilitate the simulation of multiple configuration iterations.

Results of the short-circuit study enable calculation of the arc-flash currents at potential fault points and in overcurrent protective devices. ~~are used to determine the fault current momentary duty, interrupting rating, and short-circuit (withstand) rating of electrical equipment.~~

Results of the protective-device coordination study are used to determine the time required for electrical circuit protective devices to isolate overload or short-circuit conditions. Results of both short-circuit and protective-device coordination studies provide information needed to perform an arc-flash hazard analysis.

Results of the arc-flash hazard analysis calculation are ~~used to identify~~ the arc-flash ~~flash~~ protection boundary and the arc-flash incident energy at defined ~~assigned~~ working distances at the location specified in the electrical power system. ~~throughout any position or level in the overall electrical generation, transmission, distribution, or utilization system.~~

4.1 Cautions and disclaimers

As an IEEE guide, this document suggests approaches for conducting an arc-flash hazard analysis but does not have mandatory requirements. Following the suggestions in this guide does not guarantee safety, and users should take all reasonable, independent steps necessary to minimize risks from arc flashes.

Users should be aware that the models in this guide are based upon measured arc current incident energy under a specific set of test conditions and on theoretical work. Distances, which are the basis for equations, are based on the measured distance of the test instrument from the arc-flash point source. These models will enable users to calculate the estimated maximum incident energy and the estimated arc-flash boundary distance. Real arc exposures may be more or less severe than indicated by these models.

This document is intended to provide guidance for the calculation of incident energy and arc-flash protection boundaries. Once calculated, this information can be used as a basis to develop strategies that have the goal of minimizing burn injuries. Strategies include specifying the rating of personal protective equipment (PPE), working deenergized, applying arc-resistant switchgear, and following other engineering techniques and work practices.

This guide is based upon testing and analysis of the burn hazard presented by incident energy. Other ~~The~~ potentially hazardous effects of molten metal splatter, projectiles, pressure impulses, and toxic arc by-products have not been considered in these methods. It is expected that future work will provide guidance for these other electrical hazards.

Available bolted fault currents should be determined at the point of each potential fault. Do not use overly conservative bolted fault current values. A conservatively high value may result in lower calculated incident energy than may actually be possible depending on the protective device's time-current response. ~~The l~~ Lower results would be obtained ~~caused~~ by using a faster time-current response value from the protective device's time-current curve.

~~Where used, PPE for the arc flash hazard is the last line of defense. The protection is not intended to prevent all injuries but to mitigate the impact of an arc flash upon the individual, should one occur. In many cases, the use of PPE has saved lives or prevented injury. The calculations in this guide will lead to selection of a level of PPE that is a balance between the calculated estimated incident energy exposure and the work activity being performed while meeting the following concerns:~~

a) ~~The desire to provide enough protection to prevent a second degree burn in all cases.~~

b) ~~The desire to avoid providing more protection than is needed. Hazards may be introduced by the garments such as heat stress, poor visibility, and limited body movement.~~

~~Professional judgment must be used in the selection of adequate PPE.~~

~~While it is outside the scope of this document to mandate PPE, some examples of where PPE may be required are: during load interruption, during the visual inspection that verifies that all disconnecting devices are open, and during the lockout/tagout. Adequate PPE is required during the tests to verify the absence of voltage after the circuits are deenergized and properly locked out/tagged out.~~

This information is based on technical data believed by the IEEE Std 1584-2002 working group to be reliable. It is offered as a tool for conducting an arc-flash hazard analysis. It is intended for use only by those experienced in power system studies and is not intended to substitute for the users' judgment or review in such studies.

It is subject to revision as additional knowledge and experience is gained. IEEE, those companies that contributed test data, and those people who worked on development of this standard make no guarantee of results and assume no obligation or liability whatsoever in connection with this information.

This guide is not intended to imply that workers be allowed to perform work on exposed energized equipment or circuit parts. It must be emphasized that the industry-recommended way to minimize electrical injuries and fatalities is to deenergize the ~~ensure that~~ equipment to create a ~~is deenergized and in an electrically safe~~ work condition that minimizes electrical safety risks before the commencement of work on the equipment. ~~But even this act,~~ The process of creating such an electrically safe work condition may expose~~, subjects~~ the worker to potential hazards, which ~~if they occur,~~ require PPE for protection against arc-flash burns.

~~Work intentionally performed on or near energized equipment or circuits is limited by standards and regulations, such as those issued by OSHA. OSHA 29 CFR Subpart S.1910.333 severely limits the situations in which work is performed near or on equipment or circuits that are or may be energized.~~

> ~~"Live parts to which an employee may be exposed shall be deenergized before the employee works on or near them, unless the employer can demonstrate that deenergizing introduces additional or increased hazards or is infeasible due to equipment design or operational limitations."~~

~~Financial considerations are not an adequate reason to work on or near energized circuits.~~

~~For ready access to the specific needed flash-protection boundary, working distance, and incident energy, such calculated values should be prominently displayed on every piece of electrical equipment where an arc-flash hazard exists in a workplace or otherwise be made available to workers.~~

~~Safety by design measures should be actively considered during the design of electrical installation to improve personnel safety. For example, properly tested and installed arc resistant switchgear (see IEEE C37.20.7-2001) can provide safety for operating personnel, while the doors are secured. Remote control and remote racking are also examples of methods to improve safety by design. Similarly, providing suitable and readily accessible disconnecting means separate from equipment to be worked upon will enable isolation and deenergization. Engineering designs can also specify the appropriate system design, equipment, protection, etc., to minimize fault current magnitude and duration. Changing protection settings can reduce the fault current. It is also possible to consider alternate work practices that provide increased work distances.~~

4.2 Step 1: Collect the system and installation data

The largest effort in an arc-flash hazard study is collecting the field data. Even for a plant with nominally up-to-date single-line diagrams, time-current curves, and short-circuit study on a computer, the field part of the study will take about half of the effort. Even for new facilities, field verification of the one-line diagrams and protection setting are necessary to verify the integrity of the power system. Regular site employees who are familiar with the site and its safety practices may be able to do this part of the job best.

While the data required for this study is similar to data collected for typical short-circuit and protective-device coordination studies, it goes further in that all low-voltage distribution and control equipment plus its feeders and large branch circuits must be included.

Annex A contains a sample form for most of the equipment and system data needed to perform the electrical system studies. Similar forms may be prepared ~~in advance~~ for all electrical equipment before starting a study.

Begin by reviewing the single-line diagrams and electrical equipment site and layout arrangement with people who are familiar with the site. The diagrams may have to be updated to show the current system configuration and orientation before the arc-flash study can begin. The single-line diagrams must include all alternate feeds. If single-line diagrams are not available, create them.

It is very important for electrical safety to have up-to-date single-line diagrams available. Refer to IEEE Std 315-1975 and IEEE Std 315A-1986 plus IEEE Std C37.2-2008~~1996~~ for examples.

When the basic electrical system scheme is complete on the diagrams, add the data needed for the short-circuit study. The study must take into account all sources, including utilities, standby and power generators, and large motors—those 37 kW (50 hp) and larger that contribute energy to short circuits.~~[10]~~

~~[10] 37 kW = 50 HP~~

The diagrams must show all transformers, transmission lines, distribution circuits, electrical system grounding, current limiting reactors and other current limiting devices, voltage correction or stabilization capacitors, disconnect switches, switchgear, motor control centers (MCCs), panelboards/switchboards including protective devices, fused load interrupter switches including fuse types and sizes, feeders and branch circuits, as well as motors included above, ~~down to the 600 V or 400 V level, and~~ transformers supplying instrument power and protective devices. Collect data for all equipment listed in the purpose of this document (see 1.2) that is three-phase ac equipment operating 208 V and 15 kV. Equipment below 240 V need not be considered unless it involves at least one 125 kVA or larger ~~low-impedance~~ transformer in its immediate power supply.

~~Get~~ Obtain the minimum and maximum available fault MVA and power angle or *X/R* ratio from the utility supplying service or for the separately derived power system. Do not use overly conservative bolted fault current values. Most utilities will readily supply information on the available fault level and *X/R* ratio at point of service. ~~When information is not provided, public utility commissions can be requested to require utilities to furnish this information. Available fault data must be realistic; not conservatively high.~~

For transformers, generators, large motors, and switchgear, ~~note~~ collect all the nameplate data. Typically this would include voltage/voltage ranges or tap settings, ampacity, kilowatt or kilovolt amperes, momentary or interrupting current rating, impedance or transient/subtransient reactance data, etc.

Next, collect ~~note~~ conductor and cable data along with its installation (routing and support method, in magnetic raceway—steel conduit or nonmagnetic raceway—aluminum tray, etc.) for all electrical circuits between the ~~utility~~ power source and the distribution and control equipment. Typical data might be: 300 m (1000 ft) of 3 single conductor 500 kcmil copper in overhead magnetic duct; ~~500~~ 600 m (2000 ft) of 6 single conductor 4/0 AWG copper in underground nonmagnetic duct; ~~100~~ 150 m (500 ft) of ~~3/C~~ 3 single conductor 250 kcmil aluminum in overhead cable tray; or ~~1000~~ 1200 m (4000 ft) pole line with 3 single conductor 4 AWG hard drawn copper conductors in a delta configuration with 500 mm (20 in) spacing. This information is needed for calculation of impedances. Typical sources of cable/conductor impedance data are available in software package libraries, and tables located in IEEE Std ~~141-1993~~551-2006. See Annex A for a sample data collection form for cables.

Finally, transformers supplying instrument power (current transformer, voltage transformer, or control power transformer) and protective-device data must be collected. It should be available on nameplate or time-current curves. If not, it may be available in specifications or in recent maintenance test reports. In any case, the user should verify ~~old~~ data is still up-to-date by checking with the owner's representative and, if necessary, by checking in the field. In some cases a field inspection is required to determine the types and ratings of fuses actually installed, as well as the settings of circuit breaker trips and/or the settings of protective relays.

4.3 Step 2: Determine the system modes of operation

~~In a site with~~ An electrical installation may have several modes of operation. It may be a simple radial distribution system ~~there is only one mode of operation – normal – but a~~ or a more complex system with ~~can have~~ many modes of operation, including~~. Examples of modes include~~:

- One or more utility feeders in service.
- Utility interface substation secondary bus tie breaker open or closed.
- Unit substation with one or two primary feeders.
- Unit substation with two transformers with secondary tie opened or closed.
- MCC with one or two feeders, one or both energized.
- Generators running in parallel with the utility supply or in standby.

— Utility system normal switching set for maximum possible fault MVA.

— Utility system normal switching configured for minimum possible fault MVA.

— Separately derived sources (generators)—maximum capacity on line.

— Separately derived sources (generators)—minimum number on line.

It is important to determine the available short-circuit current for the mode ~~modes~~ of operation that provide both the maximum and the minimum available short-circuit currents.

4.4 Step 3: Determine the bolted fault currents

Input all data from the single-line diagrams and the data collection effort into a short-circuit program. Commercially available programs can run thousands of buses and allow easy switching between modes. The simplified calculator included with this standard can determine bolted fault currents for radial systems for up to 600 V (see Figure B.1). Find the symmetrical root-mean-square (RMS) bolted fault current and *X/R* ratio at each point of concern—all locations where people could be working—by making each of these points a bus. Not every bus needs to be run for every mode because some modes will not significantly impact bolted fault current at some buses. For example, connecting transformer secondaries together may not increase fault energy on the primary side.

It is important to include all cables because to err on the high side does not necessarily increase safety: it may reduce it. Lower fault currents often persist longer than higher currents as shown on protective-device time-current curves.

4.5 Step 4: Determine the arc fault currents

The total arc fault current at the point of concern and the portion of that current passing through the first upstream protective device must be found. The arcing current in the protective device gives the duration that is to be used in the incident energy calculation with the total bus arcing current. In the case of locations being energized by multiple feeders, it is necessary to determine the portion of the total arc current passing through each protective device to determine the clearing time for each device.

The arc fault current depends primarily on the bolted fault current. The bolted fault current in the protective device can be found from the short-circuit study by looking at ~~a~~ the one-bus-away level contributions ~~run~~. This observation will make a distinction between the ~~separate~~ fault contributions from normal feeder, alternate feeder, and downstream motors. The arc current passing through each feeder or downstream load is proportional to its calculated short-circuit contribution.

The arc fault currents can then be calculated using the equations shown in 5.2. The calculated arc fault current will be lower than the bolted fault current due to arc impedance, especially for applications under 1000 V. For medium voltage applications the arc current is still a bit lower than the bolted fault current, and it must be calculated. The equations shown in 5.2 are incorporated in the programs offered with this standard. At the same time, a second set of arc fault currents must be determined for the applications under 1000 V (see 9.10.4).

4.6 Step 5: Find the overcurrent protective device characteristics and the duration of the arcs

~~In~~ During the field survey, up-to-date ~~system~~ time-current curves of overcurrent protective devices may have been ~~found~~ obtained or developed as part of a coordination study. If not, it is best to create them—~~e~~ to assist determining the duration of the arc. Commercially available software makes this task easy because several packages have extensive overcurrent protective device libraries. When a manufacturer's time-current curve shows a band, or range, the longest time should be used. If the time is longer than 2 seconds, consider how long a person is likely to remain in the location of the arc flash. It is likely that a person exposed to an arc flash will move away quickly if it physically possible, and 2 seconds is usually a reasonable maximum time for calculations. ~~Alternatively, for a very simple study, it is possible to use protective device characteristics, which can be found in manufacturer's data.~~

a) *Fuses:* Some classes of one manufacturer's low-voltage current-limiting fuses were tested to determine the effect of current-limiting action on incident energy and those results have been included in the model. See 5.6 for a list of the fuse classes, the ratings tested, and the limitations of the application of these models. When analyzing equipment protected by these fuses, time-current curves are not required, and the equations in 5.6 should be used. This calculation method is more accurate when using these specific fuses.

   For fuses not included in the model, the manufacturer's time-current curve~~s~~ information should be used. These curves may include both melting and clearing time. ~~If so, u~~ Use the clearing time, which represents the worst case. If the curve has ~~they show~~ only the average melt time, add 10% plus 0.004 seconds to that time, ~~15%, up to 0.03 seconds, and 10% above 0.03 seconds~~ to determine total clearing time. If the total clearing time at the arcing fault current is less than 10 milliseconds ~~is above the total clearing time at the bottom of the curve (0.01 seconds)~~, use 0.01 seconds for the time.

b) *Circuit breakers:* For low-voltage circuit breakers with integral trip units, the manufacturer's time-current curves include both the device tripping time and clearing time.

   A calculation of arc energy with circuit breakers is more accurate when information from the manufacturer's time-current curves is used. However, when they are not available, a simple method to determine the incident energy with circuit breakers has been included in the model. This simple method (see 5.7) can be implemented only if the arc current is in the instantaneous or magnetic trip range, and only requires input of the available bolted fault current. Although time-current curves are not required, this simple method will calculate conservative values of arc energy.

   Note that some low-voltage power circuit breakers may be equipped with retrofit trip kits. The time-current curves included with the replacement trip unit may, or may not, include the breaker operating time. If the curves show only the trip unit's operating time, a breaker operating time of 0.05 seconds should be added.

c) *Relay operated circuit breakers:* For relay operated circuit breakers, the relay curves show only the relay operating time in the time-delay region. For relays operating in their instantaneous region, allow 16 milliseconds on 60 Hz systems for operation. The circuit breaker ~~opening~~ interrupting time must be added to the relay operating time. ~~Table 1 shows recommended~~ For low voltage (<1 kV) relay operated power circuit breakers (non-integral trip), the ~~operating~~ interrupting time~~s~~ is typically 0.05 seconds (three cycles). ANSI medium- and high-voltage circuit breakers rated interrupting times vary greatly between two and eight cycles depending on the year of manufacture. Breakers rated to C37.6-1945 through C37.6-1961 had rated interrupting times of eight cycles for voltages below 72.5 kV. For higher voltages, the rated interrupting time was five cycles. The 1968 version of C37.6 changed the rated interrupting time of the medium- and high-voltage breakers to five cycles and three cycles, respectively. IEEE Std C37.06-2009 accepts a medium-voltage breaker interrupting time between three and five cycles. The high-voltage interrupting time remained at three cycles. ~~Opening~~ Interrupting times for particular circuit breakers can be verified by consulting the manufacturer's literature or the breaker nameplate data.

~~Table 1—Power circuit breaker operating times~~[a]

~~Circuit breaker rating and type~~	~~Opening time at 60 Hz (cycles)~~	~~Opening time (seconds)~~
~~Low voltage (molded case) (< 1000 V) (integral trip)~~	~~1.5~~	~~0.025~~
~~Low voltage (insulated case) (< 1000 V) power circuit breaker (integral trip or relay operated)~~	~~3.0~~	~~0.050~~
~~Medium voltage (1–35 kV)~~	~~5.0~~	~~0.080~~
~~Some high voltage (> 35 kV)~~	~~8.0~~	~~0.130~~

[a]~~This table does not include the external relay trip times.~~

~~For a limited set of cases this information is incorporated into the model and time-current curves are not required. Some classes of current limiting fuses were tested to determine the effect of current limiting action on incident energy and results have been included in the model. See 5.6 for a list of the fuse classes and ratings tested. A generalized solution has been developed for some circuit breakers with integral trip units, and it is part of the model. It is implemented only if the arc current is in the instantaneous or highest level trip range for the circuit breaker. See 5.7 for the types of circuit breakers included in the model.~~

4.7 Step 6: Document the system voltages and classes of equipment

For each bus, document the system voltage and the class of equipment as shown in Table 1~~Table 2~~. This will allow application of equations based on standard classes of equipment and bus-to-bus gaps as shown in Table 1~~Table 2~~.

4.8 Step 7: Select the working distances

Arc-flash protection is always based on the incident energy level on the person's head and torso ~~face and body~~ at the working distance, not the incident energy on the hands or arms. The degree of injury in a burn depends on the percentage of a person's skin that is burned. The head and ~~body are~~ torso make up a large percentage of total skin surface area and injury to these areas is much more life threatening than burns on the extremities. Typical working distances are shown in Table 2~~Table 3~~.

4.9 Step 8: Determine the incident energy for all equipment

A ~~software program~~ means for calculating incident energy must be selected. The possibilities are: manual calculations, a spreadsheet, and commercially available software. Clause 6 identifies and discusses the two calculators included with this guide and possible ~~future~~ commercial products. In each case the equations in the models, which appear in Clause 5, are embedded in the program or worksheet. In some programs the problem is solved one bus at a time; with others, hundreds or thousands of buses can be solved simultaneously.

It is important to realize that in evaluating the incident energy at an arcing fault location in the system, the protective device upstream from the point of the fault must be considered. An integral "main" overcurrent protective device may be considered in the calculation if it is adequately isolated from the bus to prevent escalation to a line-side fault. When the integral main overcurrent protective device is not adequately isolated from the bus, the upstream protective device must be considered as protecting the main and bus.

When developing a model, a bus should always be inserted on the line side of the main protective device and used for incident energy calculation for the main protective device and where appropriate for downstream equipment sections.

Table 1~~Table 2~~—Classes of equipment and typical bus gaps

Classes of equipment	Typical bus gaps (mm)	Typical bus gaps (in)
15 kV switchgear	152	6
5 kV switchgear	104	4
Low-voltage switchgear	32	1.25
Low-voltage MCCs and panelboards	25	1
Cable	13	0.5
Other	Not required	Not required

Table 2~~Table 3~~—Classes of equipment and typical working distances

Classes of equipment	Typical working distance[a] (mm)	Typical working distance[a] (in)
15 kV switchgear	910	36
5 kV switchgear	910	36
Low-voltage switchgear	610	24
Low-voltage MCCs and panelboards	455	18
Cable	455	18
Other	To be determined in field	To be determined in field

[a]Typical working distance is the sum of the distance between the worker standing in front of the equipment, and from the front of the equipment to the potential arc source inside the equipment.

4.10 Step 9: Determine the flash-protection boundary for all equipment

To find the flash-protection boundary, the equations for finding incident energy can be solved for the distance from the arc source at which the onset of a second degree burn could occur. The incident energy must be set at the minimum energy beyond which a second degree burn could occur. The programs include the flash-protection boundary based on an incident energy of 5.0 J/cm^2 (1/2 cal/cm^2).~~[11]~~

~~[11] 5.0 J/cm^2 = 1.2 cal/cm^2~~

Annex F

(informative)

Bibliography

Insert the following bibliographic entry in alphanumeric order and renumber as necessary:

[BX] IEC 62271-111 Ed. 1 (2005-11) (IEEE C37.60-2003-Compilation), High-voltage switchgear and controlgear – Part 111: Overhead, pad-mounted, dry vault, and submersible automatic circuit reclosers and fault interrupters for alternating current systems up to 38 kV.