Practical Solution Guide to Arc Flash Hazards

Courtesy of ESA
Developers of EasyPower®
www.EasyPower.com

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Published by ESA, Inc.

Disclaimer

Warning - Disclaimer: The calculation methods listed in the book are based on theoretical equations derived from measured test results. The test results are a function of specific humidity, barometric pressure, temperature, arc distance, and many other variables. These parameters may not be the same in your facility or application. The results calculated from these equations may not produce conservative results when applied to your facility. PPE recommended by any calculation method will NOT provide complete protection for all arc hazards. Injury can be expected when wearing recommended PPE. The results should be applied only by engineers experienced in the application of arc flash hazards. The authors make no warranty concerning the accuracy of these results as applied to real world scenarios.

Arc flash as given in ***NFPA®-70E*** *and* ***IEEE® Std-1584-2002™*** *is concerned with personal injury when a worker is near or working on energized equipment. Working on energized conductors should only be done when it is impossible to shut down the equipment. This book does not condone working on energized equipment.*

Using the methods in NFPA 70E or IEEE Std-1584 does not insure that a worker will not be injured by burns from an arc-flash. Following the NFPA 70E and IEEE 1584 procedures and wearing the proper protective equipment will greatly reduce the possibility of burns. Using the incident energy equations developed from the arc flash tests, it is expected that the personal protective equipment (PPE) classification per the tables in NFPA 70E will be adequate for 95% of the classifications based on test results.

Forward

ESA is pleased to bring you the "**Practical Solution Guide to Arc Flash Hazards**" version 1.0. We believe this will be a valuable tool for electrical engineers, safety managers, or anyone responsible for implementing and maintaining an arc flash hazard safety program.

The guide was designed to walk you through the necessary steps of implementing an arc flash assessment as part of your overall safety program requirements. It will help you and your team make important decisions concerning the safety of your employees and how to manage the complex tasks of OSHA and NFPA-70E compliance for arc flash hazards.

Arc flash hazard analysis and safety program development to protect against arc flash hazards is in its infancy. Research into the arcing phenomena is ongoing as industry tries to better understand and model arcing faults. Standards and recommended practices are changing constantly in order to reflect the added understanding we are gaining and to better protect workers. Personal protective equipment (PPE) is also changing at a rapid pace as new and better technology is developed. ESA has created an Arc Flash Resource Center at the website www.easypower.com to keep you up to date as new information becomes available and industry advancements are made. Look for new versions of this guide as we continue to enhance and add new technology to the arc flash assessment process.

ESA is committed to providing industry with the most advanced state of the art technology in our EasyPower software product line. We believe EasyPower provides the self-documenting solution capabilities to keep your safety program current and in compliance with OSHA and NFPA-70E regulations. ESA can also provide detailed engineering studies and arc flash assessment programs to help your company get started.

We hope that the "**Practical Solution Guide to Arc Flash Hazards**" becomes a valued resource to your library.

Sincerely,

Chet E. Davis, PE

President, ESA

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1 Introduction

This chapter provides an overview of arc flash hazards and briefly describes the various causes, nature, results, standards and procedures associated with arc flash hazards. In order to deal with the hazard, it is first necessary to develop an understanding of the phenomena. Details are provided in the following chapters.

An electric arc or an arcing fault is a flashover of electric current through air in electrical equipment from one exposed live conductor to another or to ground. Arc flash hazard is the danger of excessive heat exposure and serious burn injury due to arcing faults in electrical power systems. Electric arcs produce intense heat, sound blast and pressure waves. They have extremely high temperatures, radiate intense heat, can ignite clothes and cause severe burns that can be fatal.

The demand for continuous supply of power has brought about the need for electrical workers to perform maintenance work on exposed live parts of electrical equipment. Besides the existence of electrical shock hazard that results from direct contact of live conductors with body parts, there also exists a possibility of electric arcs striking across live conductors. Although electrical safety programs have existed since the beginning of electricity, arc flash hazard has not been prominently addressed until recently.

1.1 Causes of Electric Arcs

Arcs can be initiated by the following:

- Glow to arc discharge:
    - Dust and impurities: Dust and impurities on insulating surfaces can provide a path for current, allowing it to flashover and create arc discharge across the surface. This can develop into greater arcs. Fumes or vapor of chemicals can reduce the breakdown voltage of air and cause arc flash.
    - Corrosion: Corrosion of equipment parts can provide impurities on insulating surfaces. Corrosion also weakens the contact between conductor terminals, increasing the contact resistance through oxidation or other corrosive contamination. Heat is generated on the contacts and sparks may be produced, this can lead to arcing faults with nearby exposed conductors of different phase or ground.
- Condensation of vapor and water dripping can cause tracking on the surface of insulating materials. This can create a flashover to ground and potential escalation to phase to phase arcing[1].
- Spark discharge:

  - Accidental touching: Accidental contact with live exposed parts can initiate arc faults.
  - Dropping tools: Accidental dropping of tools may cause momentary short circuit, produce sparks and initiate arcs.

- Over-voltages across narrow gaps: When air gap between conductors of different phases is very narrow (due to poor workmanship or damage of insulating materials), arcs may strike across during over-voltages.
- Failure of insulating materials.

Electric arcs are also caused by the following:

- Improperly designed or utilized equipment.
- Improper work procedures.

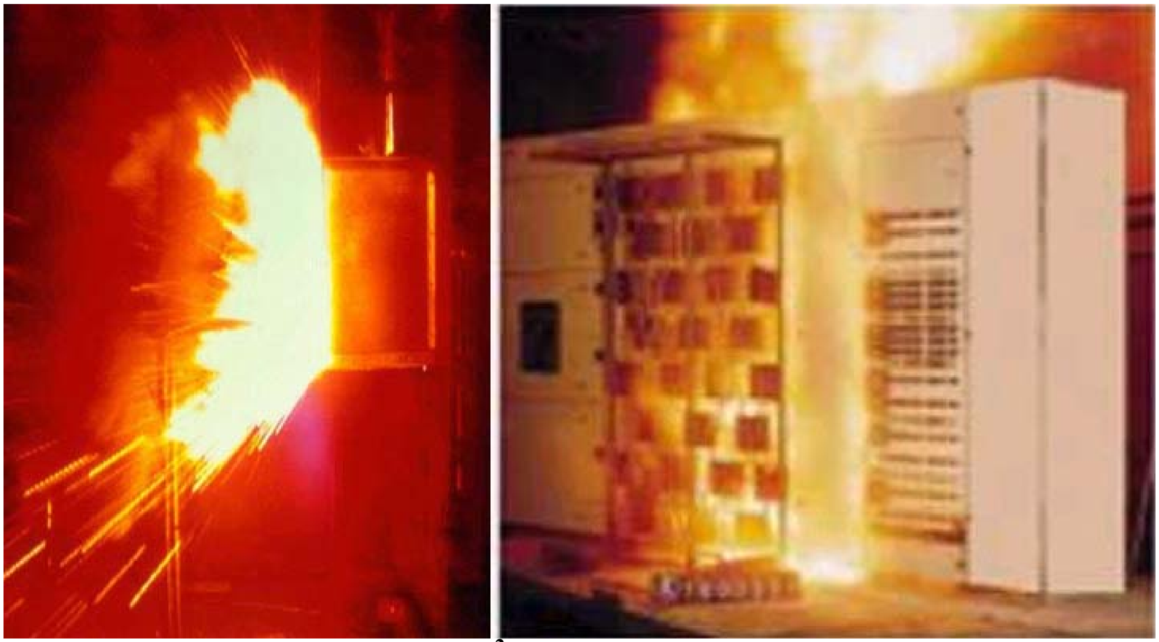


Figure 1.1: (a) Arc blast in box[2] ; (b) Arcing fault in electrical panel board

1.2 The Nature of Electrical Arcs

- Electric arcs produce some of the highest temperatures known to occur on earth – up to 35,000 degrees Fahrenheit[3]. This is four times the surface temperature of the sun.
- The intense heat from arc causes the sudden expansion of air. This results in a blast with very strong air pressure (Lightning is a natural arc).

- All known materials are vaporized at this temperature. When materials vaporize they expand in volume (Copper – 67,000 times, Water–1670 times[4]). The air blast can spread molten metal to great distances with force.

- For a low voltage system (480/277 V), a 3 to 4-inch arc can become "stabilized" and persist for an extended period of time.

- Energy released is a function of system voltage, fault current magnitude and fault duration.

- Arcs in enclosures, such as a Motor Control Center (MCC) or switchgear, magnify blast and energy transmitted as the blast is forced to the open side of the enclosure and toward the worker.

1.3 Hazards of Arcing Faults

Figure 1.2: (a) Hand burned by arc flash[5]; (b) Clothed areas can be burned more severely than exposed skin

Some of the hazards of arcing faults are:

- Heat: *Fatal* burns can occur when the victim is several feet from the arc. Serious burns are common at a distance of 10 feet[6]. Staged tests have shown temperatures greater than 437°F on the neck area and hands for a person standing close to an arc blast[7].

- Objects: Arcs spray droplets of molten metal at high-speed pressure. Blast shrapnel can penetrate the body.

- Pressure: Blast pressure waves have thrown workers across rooms and knocked them off ladders[8]. Pressure on the chest can be higher than 2000 lbs/ sq. ft.

- Clothing can be ignited several feet away. Clothed areas can be burned more severely than exposed skin.

- Hearing loss from sound blast. The sound can have a magnitude as high as 140 dB at a distance of 2 feet from the arc[9].

1.3.1 Probability of Survival

Injuries due to arc flash are known to be very severe. According to statistics from the American Burn Association, the probability of survival decreases with the increasing age of the arc flash burn victim.

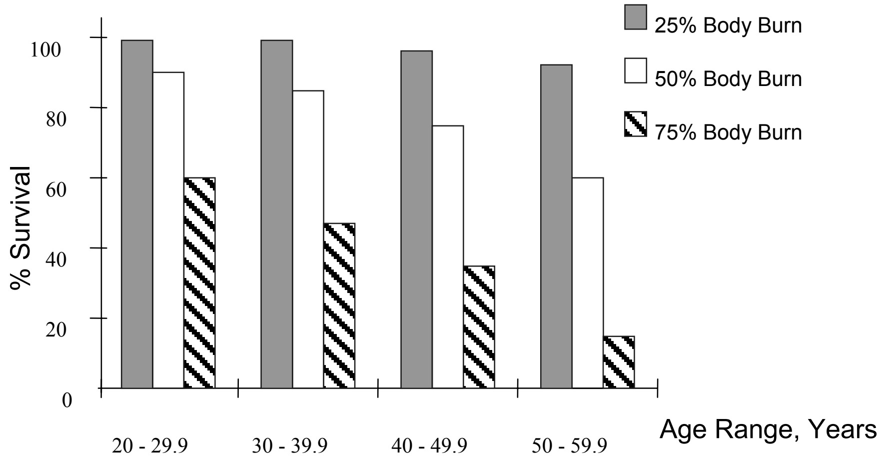


Figure 1.3: Burn Injury Statistics – Probability of Survival (Source: American Burn Association, 1991-1993 Study; Revised March 2002)

1.4 Impacts of Arc Flash

Treatment can require years of skin grafting and rehabilitation. The victim may never return to work or retain the same quality of life. Some of the direct costs are:

- Treatment can exceed $1,000,000/case.

- Litigation fees.

- Production loss.

1.5 Potential Exposure to Arc Flash

Although it may appear that arc flash incidents are uncommon, statistics show that the damage they cause is considerable. Bureau of Labor Statistics data for 1994 show 11,153 cases of reported days away from work due to electrical burns, electrocution/electrical shock injuries, fires and explosions.

The Census of Fatal Injuries noted 548 employees died from the causes of electrical current exposure, fires and explosions of 6,588 work related fatalities nationwide.

In the US Chemical Industry, 56% of the fatalities that occurred over a 5-year period were attributed to burns, fires and explosions, with many of the ignition sources being related to electrical activity.

Capelli-Schellpfeffer, Inc. of Chicago reported that there are 5 to 10 arc flash injuries per day resulting in hospitalization. Many arc flash accidents/injuries occur that do not require a stay or are not properly documented for national tracking purposes. The number of arc flash accidents is greater than many engineers realize since most arc flash accidents do not make the daily news.

IEEE Standard 1584, IEEE Guide for Performing Arc Flash Hazard Calculations, provides 49 arc flash injury case histories in Annex C. A brief description is provided for each case on incident setting, electric system, equipment, activity of worker, event, apparel worn by the worker and the outcome of the incident. Readers are encouraged to read these case histories to gain insights on various conditions leading to such incidents.

The exposure to arc flash depends on the following:

- Number of times the workers work on exposed live equipment.
- Complexity of the task performed, need to use force, available space and safety margins, reach, etc.
- Training, skills, mental and physical agility, coordination with helper.
- Tools used.
- Condition of equipment.

1.6 Recent Developments in Addressing Arc Flash Hazard

Historically, the National Electric Code (NEC) and other safety codes have been primarily concerned with protection from fire, electrocution, and shock hazard – arc flash hazards were not addressed. This is now changing. The 2002 NEC now has requirements for warning labels. The National Fire Protection Association (NFPA®) is responsible for the NEC®. Since the NEC was concerned mainly with electrical design, construction and inspection, it could not be adopted by employers and employees with regard to implementing standards for workplace safety. In order to bridge this gap, a new standard, NFPA 70E, *Standard for Electrical Safety Requirements for Employee Workplaces*[10], was developed. NFPA 70E is intended for use by employers, employees, and the Occupational Safety and Health Administration (OSHA). The publication NFPA 70E (2000) and its proposed revision (May 2003 ROP[11]) include arc flash hazard as a potential danger to workers near and around live exposed electrical parts. NFPA 70E and **IEEE® Std 1584-2002™** provide guidance on implementing appropriate safety procedures and arc flash calculations. For the actual wording, see section 6.1.2.

NEC Article 110.16 requires "field marking" of potential arc flash hazards for panels likely to be serviced or examined in an energized condition. This article also contains a fine print note (FPN) regarding proper signage and an FPN referencing NFPA 70E. These FPNs are not technically part of the NEC, but are recommended practices.

OSHA has *not* specifically addressed arc flash hazards, however, there exists adequate safety requirements for employers to follow to ensure the safety of the worker in the workplace (General Duty clause). Some of these are outlined in Table 6.1 in Chapter 6. The Code of Federal Regulations (Standards – 29 CFR) Part 1910 deals with occupational safety and health standards. Standards on personal protective equipment (PPE) are outlined in subpart 132. In response to an inquiry on OSHA's stand on arc flash hazard, Richard S. Terrili, the Regional Administrator for Occupational Safety and Health, US Department of Labor for the Northwest Region at Seattle, concluded as follows:

> "*Though OSHA does not, per se, enforce the NFPA standard, 2000 Edition, OSHA considers NFPA standard a recognized industry practice. The employer is required to conduct assessment in accordance with CFR 1910.132(d)(1). If an arc flash hazard is present, or likely to be present, then the employer must select and require employees to use the protective apparel. Employers who conduct the hazard/risk assessment, and select and require their employees to use protective clothing and other PPE appropriate for the task, as stated in the NFPA 70E standard, 2000 Edition, are deemed in compliance with the Hazard Assessment and Equipment Selection OSHA standard*."

[12]In 2002, unionized electricians, contractors and federal regulators in Columbus, Ohio, forged an agreement to protect electrical workers on the job by using NFPA-70E. It is claimed that this agreement could serve as a model for the nation and is expected to apply to the 2,500 unionized electrical workers in the Columbus area. The Columbus office of the U.S. Occupational Safety and Health Administration (OSHA), the Central Ohio chapter of the National Electrical Contractors Association (NECA), and Locals 683 and 1105 of the International Brotherhood of Electrical Workers (IBEW) collaborated to develop this pioneering program. The National Joint Apprentice and Training Committee (NJATC), the training arm of IBEW and NECA, provided technical expertise and will be responsible for development and coordination of training for this effort.

1.7 NFPA 70E and Arc Flash Hazard

1.7.1 Protection Boundaries

70E defines a series of **boundaries** relating to electrical safety when working on energized equipment. Only "qualified" people can enter these boundaries and they are required to wear appropriate PPE within these boundaries.

The four protection boundaries are:

1. Flash Protection Boundary
2. Limited Approach Boundary
3. Restricted Approach Boundary
4. Prohibited Approach Boundary

The flash protection boundary is briefly described in this chapter. For further details and description on the other boundaries, see Chapter 4.

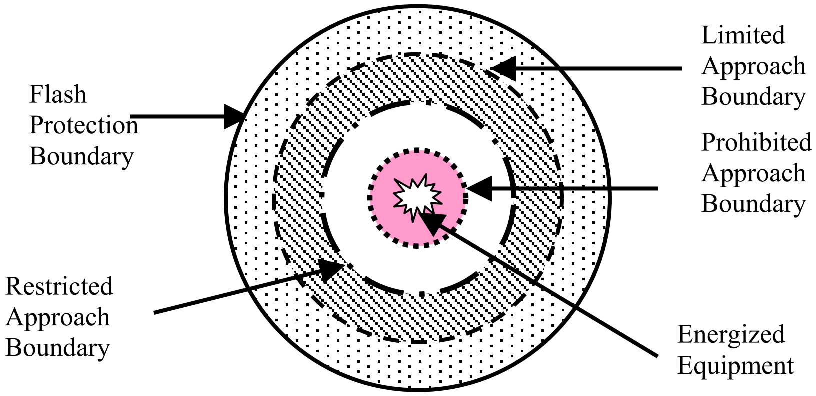


Figure 1.2: Protection boundaries

1.7.2 Flash Protection Boundary

The flash protection boundary is the distance from the arc source (energized exposed equipment) at which the potential incident heat energy from an arcing fault falling on the surface of the skin is 1.2 calories/cm^2. An exposure to 1.2 cal/cm^2 would normally result in a curable second-degree burn. Within this boundary workers are required to wear protective clothing like fire resistant (FR) shirts and pants, and other equipment to cover various parts of the body. This distance may vary from equipment to equipment since it is a function of the available fault current of the system at that point, the voltage and the tripping characteristics of the upstream protective device as well as some other parameters. See Chapter 4 for details.

1.7.3 Personal Protective Equipment

NFPA specifies the requirement of personal protective equipment (PPE) for workers within the flash protection boundary. All parts of the body which may be exposed to the arc flash, need to be covered by the appropriate type and quality of PPE. The entire PPE set may be comprised of FR clothing, helmet or headgear, face shield, safety glasses, gloves, shoes, etc. depending upon the magnitude of the arc energy. The amount of PPE required and its quality needs to be determined on the basis of the calculated incident energy on the worker's body. The calculations need to be performed by a qualified person such as an engineer. The protective clothing should limit the incident energy reaching the chest/face of the worker to less than 1.2 cal/cm^2. FR clothing provides thermal insulation and is also self-extinguishing. Protective clothing is rated in cal/cm^2. For details on PPE, see Chapter 6.

1.7.4 Classification of Hazard/Risk Category

NFPA 70E defines 5 levels of risk category for arc flash hazard based upon the calculated incident energy at the working distance, as shown in Table 1.1. Examples of typical protective clothing that cover the torso are also provided in this table. Other PPE are also required to protect various parts of the body.

Table 1.2: Hazard/risk classification as per NFPA 70E-2000

Category	Energy Level	Typical PPE Examples
0	N/A	Non-melting, flammable materials (e.g. untreated cotton, wool, rayon, etc.)
1	5 cal/cm^2	FR shirt and FR pants
2	8 cal/cm^2	Cotton underwear plus FR shirt & pants
3	25 cal/cm^2	Cotton underwear plus FR shirt & pants plus FR coverall
4	40 cal/cm^2	Cotton underwear plus FR shirt & pants plus double layer switching coat and pants

1.7.5 Determining Flash Protection Boundary and Hazard Category

NFPA 70E-2000 provides two methods of determining flash protection boundary as outlined in Part II section 2-1.3.3.2:

- A fixed distance of 4.0 ft. for a fault with the product of fault current and fault duration less than 5000 ampere seconds.
- Ralph Lees' equation.

In the proposed draft, NFPA 70E-May 2003 ROP, three (3) acceptable methods of determining flash protection boundary and hazard categories are provided. They are listed below. (see Chapter 4 for details):

- Simplified NFPA 70E tables: proposed draft Table 220.2(B)(2)(C) for flash protection boundary and Table 220.6(B)(9)(A) for hazard category.
- Calculations based on NFPA 70E Annex B.
- Calculations based on IEEE Standard 1584.

IEEE Standard 1584 recommends that the person performing arc flash hazard assessment should understand the limitations of the method. Some of the limitations are:

- The equations used in the standards are based on tests performed in a laboratory and the conditions may differ from those in the plant where the application of the standards is sought.
- The equations are based on a range of test values such as available fault current, arc gap, enclosure size, etc. It is necessary to check whether parameters existing for the plant are within the same range.
- The random nature of arcs makes it very difficult to model the arc precisely. The estimate provided by the equation for arc current in the standards is an “average” value.

All of the known standards or methods have some limitation. The tables may be easy to use and require less or no computation. However, these are based on typical equipment and systems and are very approximate. Detailed analysis yields different results than the tables do. Therefore, whatever standard you may choose, it is necessary to understand its limitations. Further detailed analysis can overcome some of these limitations.

1.7.6 Difference between NFPA 70E and IEEE 1584 Calculations

NFPA 70E method estimates incident energy based on a theoretical maximum value of power dissipated by arcing faults, based on Ralph Lee's work. This is believed to be generally conservative. In contrast, IEEE 1584 estimates incident energy with empirical equations developed from statistical analysis of measurements taken from numerous laboratory tests. The IEEE method was intended to be more realistic rather than conservative, and aims to avoid accidents due to limitations provided by over-protection to workers. Over-protection can also lead to the restriction of visibility and movement, discomfort and reduces worker productivity.

1.8 Hazard Assessment Methods

Arc flash hazard calculation can be carried out in several ways. The choice of method may be based on available information, volume of calculation work, necessity for accuracy, availability of resources and quality of arc flash hazard mitigation program. Whatever method is used, the qualified person performing the assessment should be aware of the limitations of the method employed, and should perform further engineering analysis to achieve best results.

1. Table 3-3.9.1 Hazard Risk Category Classifications in NFPA 70E-2000 provides a simple way to determine the hazard category. Simplified tables of proposed NFPA 70E-May 2003 ROP: You can look up Table 220.2(B)(2)(C) and Table 220.6(B)(9)(A) to perform hazard assessment for small radial distribution systems. This method requires the least time and is suitable when limited information is available on the power system. This is the least accurate method because it is very generalized. These tables do not provide you with the exact PPE rating that are required in cal/cm^2.

2. Hand calculations: You can perform hand-calculations using NFPA 70E equations or IEEE 1584 equations for small radial distribution systems. This is very time consuming and is not suitable for large systems. While performing many hand calculations, unnoticed errors may be introduced in the calculations.

3. Spreadsheet calculator: IEEE Standard 1584 comes with a spreadsheet calculator in Excel® that can be used to assess arc flash hazards. Similar spreadsheets can be easily built using NFPA 70E equations. This calculator requires the user to enter available fault current data for each point of assessment. Required data for each point includes short circuit current and protective device trip times for each source. Because of the inability of the spreadsheet calculator to determine the trip time and short circuit currents and because of the time-consuming nature of this process, assumptions and approximations have to be made, which compromise accuracy. This method is limited to radial single source systems and errors increase with the size of the system.

4. Commercial integrated software: This is practical for all systems with multiple power sources and multiple scenarios of interconnections where better accuracy is desired and where the system goes through ongoing changes over time. Once the data is entered into the software, carrying out hazard assessment takes very little time. The results are instantly observed. Graphical integrated power system software like EasyPower® can perform multiple aspects of engineering studies at once. For instance, EasyPower can perform short circuit calculations, protective device

coordination, and arc flash calculations and display results graphically with simple mouse clicks. EasyPower provides an active self-documenting arc flash assessment program to meet the needs of today's changing electrical systems.

The results of the assessment can show up on one-line drawings, detailed arc flash reports and warning labels that can be placed on the hazardous location or equipment. An additional advantage of EasyPower software is the ability to simulate and modify the protective device settings in order to reduce exposure to arc flash hazard. The software can automatically obtain the accurate arcing time from the trip characteristics of the protective devices. All other methods lack this ability and therefore need to rely on some approximate value for arcing time.

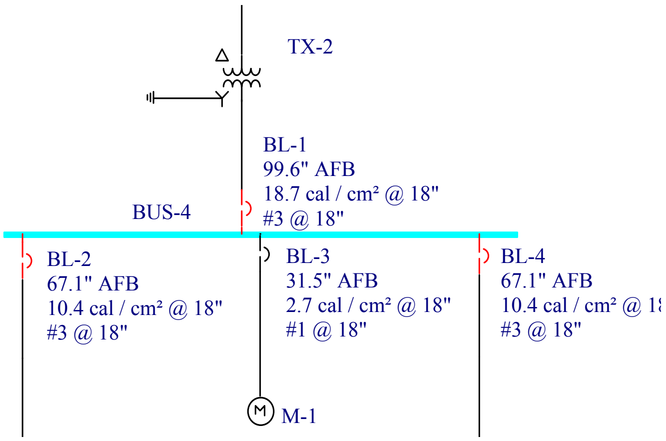
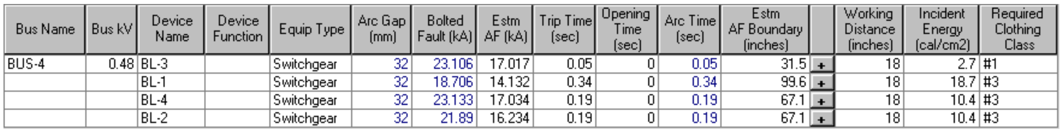


Figure 1.3: Example of arc flash hazard calculation results on one-line diagram in the integrated software EasyPower®.



Bus Name	Bus kV	Device Name	Device Function	Equip Type	Arc Gap (mm)	Bolted Fault (kA)	Estm AF (kA)	Trip Time (sec)	Opening Time (sec)	Arc Time (sec)	Estm AF Boundary (inches)		Working Distance (inches)	Incident Energy (cal/cm2)	Required Clothing Class
BUS-4	0.48	BL-3		Switchgear	32	23.106	17.017	0.05	0	0.05	31.5	+	18	2.7	#1
		BL-1		Switchgear	32	18.706	14.132	0.34	0	0.34	99.6	+	18	18.7	#3
		BL-4		Switchgear	32	23.133	17.034	0.19	0	0.19	67.1	+	18	10.4	#3
		BL-2		Switchgear	32	21.89	16.234	0.19	0	0.19	67.1	+	18	10.4	#3

Figure 1.4: Example of detailed arc flash hazard report for equipment shown in Figure 1.3 produced by the integrated software EasyPower®.

1.9 Reducing Exposure to Arc Flash Hazard

In order to reduce exposure of workers to arc flash hazard, companies and employees can take the following steps:

1. Understand arc flash and its associated hazards and acknowledge the existence of the hazard.

2. Assess the magnitude of the hazard.

3. Develop an arc flash hazard program and integrate it into the safety program.

1.10 Arc Flash Hazard Program

An arc flash hazard program is implemented as part of the electrical safety program, which in turn is part of the overall safety program of the company. The main objective of the program is to prevent or minimize injuries to workers from arc flash. Since arc flash hazard mitigation is a fairly new concept in the industry, it is expected that considerable efforts and allocation of resources will be required to provide an initial thrust to effectively launch the program. The amount of additional resource allocation required for the program and the likely success of the program may depend on what resources are already available in the company and the related existing safety practices. Chapter 2 deals with reviewing existing practices and available resources. This is the first step in carrying out an arc flash hazard program.

The arc flash hazard program consists of the following steps:

1. Hazard assessment: A qualified person performs calculations based on power system parameters to determine the flash protection boundary, the incident energy a worker may be subject to and the hazard/risk category. The basic equations and steps are outlined in Chapters 3. An important task in the assessment is reviewing available technical data and collecting the remaining necessary data. The standards themselves do not provide the various practical issues in carrying out hazard assessment. The practical considerations are outlined in Chapter 4.

2. Documentation: It is necessary to document the results of arc flash hazard assessment in reports and drawings, and also provide signs and labels on equipment and at hazardous areas. Documentation is also a part of the planning process before working on live equipment and after, if work changes are made to the equipment or system. Also required is the documentation of training provided to workers. Chapter 7 provides some insights to documentation. NFPA 70E-2000 requires up-to-date single-line drawings of electrical systems, and the proposed 2004 update provides recommendations for short circuit and protective device study requirements.

3. Personal protective equipment (PPE) plan: Based upon the hazard assessment the appropriate PPE must be selected and provided to the workers. Workers must wear the PPE properly, provide care and maintenance of the PPE, inspect it before every use and dispose of it after its useful life has expired. Chapter 6 describes the various aspects of PPE.

4. Development of procedures to minimize hazard: The potential hazards can be minimized by developing safer working methods, providing protective shields, proper work planning, etc. The exposure to arc flash can also be reduced by improving system designs, using current-limiting devices and solid state relays, and adjusting relay and trip device to safer settings. Chapter 5 outlines some procedures to minimize risk.

5. Training for workers: Workers who are exposed to arc flash hazard should be well trained to understand what the hazard is, how it is initiated, how to read the documents and warning labels, how to properly wear PPE, and how the hazard can be reduced with safer working procedures. Different tasks will require different work practices.

6. Continual improvement: It is expected with more research and development in arc flash hazard, that there will be further additions to what we already know. The arc flash hazard program can be continually improved by including new developments in standards, industry practices and PPE. Since the power system within a company can keep changing with time, it is necessary to update arc flash assessment information on a regular basis. Also, experience can bring in new ideas from workers that can be included in the program. For this reason, it is necessary to keep the program ongoing rather than implement it as a one-time project.

7. Safety audit: Safety audits should be performed regularly to evaluate various aspects of a safety program. The safety audit should include arc flash hazard. If the arc flash hazard program is in its initial stages, then a closer examination is required.

8. Corporate-wide plan: Corporate-wide plan should be implemented to ensure consistency in safety practices. It is not advisable to have each plant or division implement the safety program differently. Communication channels should be established and responsibility should be distributed between various plants or divisions, taking a unified approach.

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[1] Ralph Lee, "Pressures Developed by Arcs", *IEEE Transactions on Industry Applications*, Vol. IA-23, No. 4. July/August 1987, page 760-764.

[2] Source: Thomas E. Neal, Presentation "Insight Into The Arc Hazard", IEEE-PCIC Electrical Safety Workshop, February, 2003; © DuPont Company.

[3] Ralph Lee, "The Other Electrical Hazard: Electrical Arc Blast Burns", *IEEE Transactions on Industry Applications*, Vol. IA-18, No. 3 May/June 1987, page 246-251.

[4] See endnote 1.

[5] Source: Danny P. Ligget, Presentation "Electrical Hazards – Taking Basics to the Future", IEEE-PCIC Electrical Safety Workshop, February, 2003.

[6] See endnote 3.

[7] Ray A. Jones, et al, "Staged Tests Increase Awareness of Arc-Flash Hazards in Electrical Equipment", *IEEE Transactions on Industry Applications*, Vol. 36, No. 2, March/April 2000, page 659-667.

[8] See endnote 1.

[9] See endnote 7.

[10] NFPA 70E, *Standard for Electrical Safety Requirements for Employee Workplaces*[10], 2000 Edition, National Fire Protection Association.

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[11] NFPA 70E – May 2003 ROP is only a proposed version. The 2003 ROP Revision of the standard is scheduled to be published as the 2004 version after multiple changes in January of 2004. Readers should note the differences and follow the published standard after it is released.

[12] NFPA Online, "Landmark agreement to use NFPA 70E protects electricians in Columbus - OSHA, IBEW and NECA contractors forge pact that could lead the nation", September 27, 2002; (http://www.nfpa.org/PressRoom/NewsReleases/ Landmark/ Landmark.asp).

2 Planning for an Arc Flash Hazard Program

2.1 Overview of the Planning Process

The planning process for the arc flash hazard program determines the following:

1. Requirements -What is to be done?
2. Implementation - Who is responsible for what?
3. Scheduling - When and how long?
4. Methodology and procedures – How to go about it?
5. Budget - How much will it cost?
6. End Result - What is to be achieved?

The components of the planning process are:

1. Review of existing practices and resources:
    a. The magnitude of exposure to hazard.
    b. Existing safety program.
    c. Human resources.
    d. Power system size and available technical records.
    e. Financial resources.
2. Formulation of values, goals and objectives for the program.
3. Selection of resource persons.
4. Selection of assessment method.
5. Estimate for human efforts (hours of work).
6. Cost estimate.

The cost of PPE can be determined only after completion of the hazard assessment, however, the tentative initial costs can be estimated for budgeting purposes.

2.2 Review of Existing Practices and Resources

Before commencing an arc flash hazard program, it is necessary to assess the safety practices and exposure to hazards. An arc flash hazard program is generally part of the electrical safety program, which in turn, is part of the overall safety program within the company. The company and its workers must follow other safety practices along with the procedures designed to reduce exposure to arc flash hazard. Arc flash procedures are integral with existing electrical safety procedures such as lockout/tag out.

2.2.1 Benefits of Existing Practices Review

A review of existing situations will provide the following benefits:

1. Provide an idea of what manpower or outsourcing may be required, and how responsibility may be delegated within the existing work groups.

2. Provide an idea of what additional training is required. If the existing training level is inadequate for other safety procedures, arc flash training can be combined with other safety training so that the overall cost, time and efforts are minimized. The training program can also be designed to suit the understanding and experience level of the workers.

3. A snapshot assessment of company safety policies: A companies view on safety matters, and its commitment and priorities are likely to govern the shape of any safety program it is about to implement. The policies would include vision and value statements with regard to safety matters, goals and measurements, corporate safety department/division and delegation of managerial responsibility for safety and budget allocations. This review would provide a platform for changing policies if needed.

4. Provide an idea of how much investment is required. The exact amount of resources required will be clear only after a detailed plan is designed. However, the review is a starting point for carrying out a program. If a company already has a very strong safety program, then including the arc flash hazard program will not take as many resources as it would take in a company where marginal programs, or none at all, have been implemented. The total investment required also depends on the extent of the safety program a company may desire to implement.

2.2.2 Determining Significant Exposure to an Arc Flash Hazard

The establishment of an arc flash hazard mitigation program would depend on the level of risk workers may be exposed to. In order to determine the level of risk, the following considerations should be made:

1. Policies on working on energized equipment: Some companies do not allow electrical workers to work on energized equipment – work is carried out only after de-energizing the equipment. **Working on de-energized equipment should be the goal of every company**. In such cases, there is minimal arc flash hazard. However, it must be remembered that arc flash can occur while switching off a circuit breaker or a switch to de-energize equipment. Arcs can also be initiated by sparks from corroded electrical parts. Workers nearby may be exposed to arc energy even though they may not be working on the equipment.

2. Number of workers working on or near live equipment: The higher the number of workers, the greater the risk. Therefore, the need to have a more elaborate arc flash hazard mitigation program. Consideration must be given to integrate contractors to comply with a program.

3. Number of times workers are exposed to live equipment: When the frequency of exposure to live equipment is small, an elaborate program may not be needed – a few simple procedures may suffice.

4. Voltage level: For low voltage equipment (240V or less) being fed by small transformers (125kVA or less), the potential hazard is small, and therefore does not need to be included in arc flash hazard assessment. The higher the voltage or the size of transformers, the greater the risk.

5. Continuous processes: Continuously operated facilities may require work on energized equipment like MCC's and panels. The exposure to risk is higher for such plants. When possible, schedule work during plant shutdowns.

6. System size: Large systems are likely to have greater arc flash hazard due to the higher fault currents.

7. System condition: Systems that do not receive periodic planned maintenance are likely to have a higher risk of arc flash incidents.

8. Changes in electrical system: Since the level of risk depends on the possible magnitude of arc current, which in turn depends on the interconnections within the power system, a system that changes with time due to the requirements of the company will need review of arc flash hazard when the changes are implemented. Additional effort will need to be incorporated into the safety program to address the changes. A static electrical power system will require the assessment only once and the safety procedures will remain the same unless the fault level of the utility changes or OSHA and NFPA regulations change.

9. Environmental conditions: Are the exposed live parts of electrical equipment subject to corrosive vapors (such as in chemical plants, sea-side, etc.), oxidation, bees, dust, rodents or birds causing electrical disturbances resulting in spark and eventually arc flash? The chance of arc flash exposure is higher in such cases.

2.2.3 Assessing Existing Safety Program

When implementing a new arc flash hazard mitigation program, the additional efforts, manpower, budget and time that is required will depend largely upon what is already in place and what resources are available to the company. As mentioned in the previous sections, the arc flash hazard program is an integral extension of the existing safety program and is not about just sticking labels on equipment and wearing flash suits. The following points should be considered in the preliminary planning stage.

- Existence of an electrical safety program: If no such program exists, the company will need to implement the program from scratch. Companies with rigorous safety programs can easily incorporate the arc flash hazard program since much of the process is similar in principle to the electric shock hazard. The main differences lie in the PPE and the assessment process that requires detailed calculations that should be carried out by an experienced electrical engineer familiar with power systems calculations. Some questions to ask are:

  - Corporate:
    1. Does the company have a safety division or department?
    2. If the company is small, does it have a safety team with a safety coordinator?
  - Are safety meetings conducted periodically and before commencing work?
  - Do workers receive safety training? How often? Is the training documented?
  - Has assessment of electrical hazards been carried out? How often? Are warning labels posted in these areas?
  - Has safety audit been performed? How often?
  - Is PPE provided to workers? Is the PPE adequate? Is PPE properly used and maintained?
  - Does each facility have up-to-date electrical drawings, short circuit, and protective device coordination studies?
  - Is each facility modeled with state of the art graphical power system software to self-document the system and safety assessment in compliance with NFPA-70E?
  - Has the company developed any procedures for safety? Do the workers follow them?
  - Are contractors required to follow the same or similar safety procedures?
  - Is safety training provided to outsourced professionals or contractors?
  - Willingness of workers to comply with changes in safety program: Accepting the arc flash program and wearing arc flash PPE is a significant change to operating habits. Experience shows that workers do not like to comply with additional clothing.

- Existence of arc flash hazard program: If some kind of arc flash hazard program is already in place, then improving the program will not be difficult since the basic concepts will already have been implemented. Any improvement will come in the form of better accuracy in hazard evaluation, better documentation, training and selection of PPE. Since the basic data for calculations will be readily available, the assessment can be conducted relatively quickly.

Which of the following methods does the company use to assess arc flash hazards:

1. Simple NFPA tables?
2. Hand calculations using IEEE 1584 or NFPA 70E equations?
3. Spreadsheet using the above equations?
4. Integrated software?

2.2.4 Assessing Available Human Resources

- Does the company employ safety professionals?
- Does the company employ electrical engineers? How much time can they devote to arc flash hazard program? Can they manage this project? Are they trained or experienced in short circuit studies, protective device coordination and arc flash hazard assessment?
- Does the company employ electrical technicians or use outside technicians for routine maintenance?
- Does the company have safety coordinators for different locations? How much time can they devote to an arc flash hazard program, for both learning and implementing?
- Does the company have personnel for managing the entire arc flash safety program?
- How much time can workers devote to learning about arc flash hazard and its prevention as well as implementation of procedures at work?

2.2.5 Power System Size and Records

- The source of power supply, multiple grid connection, co-generation and multiple generators affect the available fault level, the complexity of the arc flash hazard assessment and the number of scenarios that will be required for analysis. Data is required from the serving utilities.
- Radial distribution versus loops: Radial distribution systems are easier to deal with and hand calculations can be performed for small systems. Looped distribution systems require more rigorous calculations.

- Number of voltage levels: The nature of arcs and therefore the calculation method varies with the voltage level, and so does the risk.

- Number of connection points (buses): Each bus needs to be assessed for arc flash hazard, and therefore contributes to the total project size.

- Number and types of equipment/load: Different data sets are required for different equipment. The calculation details may also change.

- Diversity in settings and characteristics of protective devices (i.e. fuses, relays, circuit breakers). This affects data collection and estimation of arcing time.

- Frequency of changes in the system: If the system is modified frequently, then documentation, assessment and PPE upgrading may be required for each modification. A robust and simpler method of achieving all of the requirements must be selected.

- Does the company have up-to-date drawings and equipment data readily available? Has a short circuit and protective device coordination study been performed recently for the existing system? This determines how much extra work may be needed.

2.2.6 Financial Resources

- What financial resources (budget) is being allocated for safety?

- Is this adequate to meet the safety goals?

- What further allocations can the company make?

- Does the company view this as an expense or investment?

- What are the costs of insurance and worker's compensation?

2.3 Values, Goals and Objectives

Companies usually define their values for human life and safety/well being in their safety policies. These values form the guiding principle for most of their actions. The following reasons for carrying out an arc flash hazard program tie in with company values.

2.3.1 Reasons to Address Arc Flash Hazard

- Protect the workers from potential harm and prevent loss of life.

- Comply with Occupational Safety and Health Administration (OSHA) codes and with National Fire Protection Association (NFPA) standards on employee safety, NFPA-70E.
- Prevent loss to organizations through loss of skilled manpower, litigation fees, higher insurance costs, and loss of morale.
- Increase process uptime by reducing accidents.
- Required by insurance carrier.

2.3.2 Goals of Arc Flash Hazard Program

- Educate all electrical employees on the potential danger.
- Avoid arc flash related accidents.
- Reduce exposure of body parts to arc flash in case of accidents.

2.3.3 Objectives

Objectives are basically an extension of the goals, but are more specific. Typically companies associate measurable statistics with objectives. Some objectives may be associated with the end result, (for instance, zero accidents), whereas some may be objectives of the process involving "what to do" or "how to do".

For example, the process related objectives could be:

- Train 50% of workers with a basic level course and 50% of workers with an advanced level course within 6 months.
- Develop rigorous procedures to avoid accidents within 3 months.
- Accomplish arc flash hazard assessment in 25% of the plant locations within 6 months.
- Select and purchase 50% of the required PPE in three months and complete distribution in six months.
- Provide consistent programs to all plants for OSHA compliance.

Similarly, the result related objectives could be:

- Reduce the lost work day case incident rate (LWDCIR) by 50% within 1 year.
- Reduce OSHA recordable incidents by 30% in the year 2004.

- Reduce the insurance costs by 10% within 2 years.

These are general examples for safety related programs, but specific goals may be set for arc flash hazards.

Some objectives may be set to tie in with the regular safety audits. This is useful for ongoing programs. For example,

- Reduce improper use of PPE to zero.
- Reduce improperly labeled or non-labeled hazardous locations to zero.
- Reduce system change documentation time to one week. In many facilities, documentation is not done after change is implemented in the system. This may lead to accidents. Some companies inspect their facilities to update the drawings every few years. The best practice is to document the changes as soon as they are completed.

The role of defining objectives is critical because program design and resource allocation are based on the objectives.

2.4 Selection of Resource Persons

Arc flash hazard assessment can be very complex. There are a number of factors that are dependent on power system conditions and the random nature of arcs make it necessary to consider multiple scenarios based on statistical data. It is necessary to develop a good understanding of the outcomes of the various methods before selecting the method. Therefore, it is necessary to involve skilled and knowledgeable persons in an arc flash hazard program.

There are 3 ways to select resource persons for the arc flash hazard program:

1. In-house staff: Large companies with high exposure to hazards typically employ qualified and experienced engineers, safety professionals and trainers. These resource people can help launch and implement the program.
2. Consultants: Outsourcing is typical in small and mid-sized companies that do not employ adequate experts. Some large companies do not have the necessary staffing or expertise. Consultants work closely with the company staff providing most, or all, of decision-making roles in the program.
3. Combined implementation: Companies that eventually want their own employees to handle all the work in the future, hire consultants for a designated period. The consultant oversees the process and provides guidance and training. The internal resource persons get trained during the initial phases of the program.

2.5 Selection of Arc Flash Hazard Assessment Method

The four different methods of arc flash hazard assessment were briefly described in Chapter 1. Further details are provided in this section. It is necessary to understand each method before selecting the which method is best for your company.

Table 2.1: Guide for selection of assessment method

Attribute	NFPA Tables	Hand Calculations	Spread-sheet	Integrated software
Number of Buses	< 25	< 25	< 50	50+
Number of Voltage Levels	1-2	1-2	2-3	3+
Radial/Loop Distribution	Radial	Radial	Radial	Either
Power Sources	1	1	1	Multiple
Frequent Changes in System	No	No	No	Yes
Diversity in Protective Devices	Small	Small	Medium	Large
Need for Accuracy	Low	Medium	Medium	High
Separate Short Circuit Studies	Yes	Yes	Yes	No
Separate Coordination Studies	Yes	Yes	Yes	No

Table 2.1 provides a guideline for the selection of assessment method based upon various system attributes. This guide has been prepared taking the following considerations

- Total engineering time for determination of hazard/risk category and boundary.
- Accuracy required.
- Possibility of errors in the various methods.
- Ease of documentation and production of single-line diagrams.
- Overall cost of various methods.

2.5.1 Simplified NFPA 70 Tables

Table 220.2(B)(2)(C) in the proposed NFPA 70E – May 2003 ROP provides the flash protection boundary based on system voltage and enclosure type. This provides very broad ranges and may be too high or too low at times. This table is shown in Chapter 3.

Table 220.6(B)(9)(A) in the proposed NFPA 70E – May 2003 ROP provides the hazard/risk category based on available fault current, voltage, fault clearing time, type of work to be performed and type of equipment. The available fault current is typically not known until someone calculates it from the system data. If the available fault current is not known, then calculations will need to be performed anyway. Once the fault currents are known, then it is fairly easy to look up the tables to find the hazard category. The fault clearing time may not be the same as it is assumed in this method. This could lead to erroneous results and therefore could be risky. The summary of this table for working on live equipment and for testing voltages is provided in Chapter 3.

2.5.2 Hand Calculations

Hand calculations can be performed either using NFPA 70E Annex B or Annex C methods, or using IEEE Standard 1584 equations. Please read the individual standards for details. The summary of the calculation methods for both are provided in Chapter 3.

2.5.3 Spreadsheet Calculator

The IEEE 1584 spreadsheet calculator provides a quick way to obtain arc flash hazard results. However, like both of the previous methods, this requires the input of available fault current and the fault clearing time. For some typical protective devices, the total let through energy can be computed without the need for entering the clearing time. Also if the protective device is a current-limiting device for which characteristics has been determined, the reduced arc current and the associated reduced arc flash energy is calculated. The calculator requires users to enter what percent of arc current is flowing through the protective device. This can only be determined from short circuit studies. Often, loads such as motors, contribute to the arcing fault current. The calculator does not take this into account.

2.5.4 Commercial Integrated Software - EasyPower

EasyPower, power system software provides an extensive array of capabilities to minimize the effort level required to obtain accurate arc flash analysis in compliance with NFPA-70E and IEEE-1584. A brief summary of its integrated features are provided below.

Integrated software may contain several capabilities that reduce the engineering effort to a single arc flash assessment task. Commercial integrated software can have the following features that are necessary for arc flash hazard assessment.

- Short circuit analysis: A single mouse click can calculate the exact short circuit current at every point (bus/equipment), along with the contributing currents from every branch including the branch that contains the upstream protective device. Calculations are provided in accordance with ANSI and IEEE Standards ensuring proper arc current for both total energy and tripping times.

- Protective device coordination analysis: Protective device coordination in EasyPower is as simple as click-and-drag to obtain the proper setting. Automated protection boundaries guide your settings to ensure proper selectivity. Arc flash results are computed and displayed as you set your devices so you can fine tune for both selectivity and arc flash protection.

- Arc flash analysis: EasyPower provides total arc flash integration in both short circuit and protective device coordination modes. Arc flash boundaries, incident energies, PPE requirements and more, are calculated as you change system parameters so you instantly know the effect/danger of any system or parameter change. Assessment reports can be instantly generated and results can also viewed on the one-line diagrams.

- Graphical one-line (single-line) diagrams: EasyPower's graphical one-line diagrams are easy to read and follow. Output of the arc flash assessment results on the one-line diagram are very useful for engineers and electricians before working on the equipment.

- Scenario Manager: EasyPower's Scenario Manager^{TM} provides total scenario control for analyzing arc flash results for any system operating condition including generation changes, shutdown configurations, open and closed tie breakers, and any type of "what-if" analysis. This feature saves hundreds of hours of analysis time and ensures that all modes of operation are accounted for.

- Direct printout of warning signs and labels.

Just like any other method, the basic data is required to operate the software. Once the necessary data has been entered into the software, results can be obtained with a few clicks of the mouse button. EasyPower's fast algorithms, accuracy, ability to perform complex calculations and consider multiple scenarios for various possible connections make it ideal for both large and small systems and those that have frequent additions or changes.

EasyPower's complete integration for all critical aspects of arc flash analysis from data repository, one-line documentation and arc flash results make it the clear choice for a self documenting safety program. A single source program to maintain compliance with the many aspects of NFPA-70E arc flash requirements can greatly simplify a safety program.

2.5.5 Accuracy and Conservatism

Before performing an arc flash hazard assessment, it is necessary to determine how accurate or conservative the assessment needs to be. Arc flash assessment methods rely on theoretical and empirical equations. It has been observed that there is some random behavior of arcing faults that may result in actual occurrences that differ from predicted values. Although the theoretically maximum arcing power has been used by NFPA methods (which is believed to be safer) arcing currents can vary randomly. This affects the fault clearing time, and hence the incident energy to which workers may be exposed.

Therefore, when carrying out the assessment, it is necessary to cover all aspects of variability in order to be truly conservative. This requires us to consider a range of possible values rather than just a single value obtained from short circuit studies. A quick way to consider a whole range is described in Chapter 4. Appendix A provides more details on how to deal with the random behavior of arcing faults.

Additional analysis time is required to consider a range of values instead of a single value. However, this eliminates chances of error and provides greater accuracy.

Recently, it was proposed that over-protection of workers could cause greater chances of accidents as the workers' movement could be limited due to excess PPE[13]. The IEEE Standard 1584 was developed using test results to avoid over-protection from theoretical equations. Although tests performed may have shown that the theoretical maximum arc power was not achieved during the tests, the possibility of its occurrence cannot be ruled out. Therefore, taking theoretical equations to be conservative is valid.

Although not always true, the chart below provides general observations on various calculations methods.

Table 2.2: General observations on various methods

Method	Description
NFPA 70E Annex B	Conservative
IEEE 1584	Statistically Probable
Scenario Analysis	Improved Accuracy

Scenario analysis is a standard feature in EasyPower and provides easy analysis of all system configurations and operating conditions and for bracketing arcing current ranges.

2.5.6 Overprotection

When arc flash hazard assessment is too conservative, the assessed hazard/risk category or the incident energy may require the workers to wear more protective gear than is practically necessary. Extra layers of thick fire resistant clothing, face shields, and thick gloves may render the work rather difficult. This situation has the following disadvantages:

1. The difficulty provided by the PPE may lead to accidents that can be avoided by slightly less but adequate PPE.

2. Longer time is taken by a worker to execute a task when wearing heavier PPE, therefore reducing overall productivity. Safety should not be compromised to increase productivity, however, over-protection cannot achieve greater safety.

3. Workers may be discouraged with the chore of having to wear extra PPE.

2.6 Estimate of Human Efforts

Table 2.3 provides a guide for estimating the hours of work required for various types of work for an expert level. Beginners and trainees should allow for additional 50-100% of time to complete the assessment. Table 2.4 shows an estimate of hours of work required for arc flash hazard assessment for a typical plant. This is only an example and the requirements for human effort may vary with company, complexity of system, and availability of information. In this example, all the analysis is done from scratch, i.e. no short circuit analysis was done previously. Some companies may have up-to-date records of the power system with short circuit and coordination studies already completed. For such companies arc flash hazard assessment is just another step.

The estimates provided include detailed written analysis for each aspect of the study. This type of detailed documentation provides the basis for a complete safety program, and ensures documented reasoning and application should OSHA or your insurer initiate an audit due to an incident.

Table 2.3: A guide for estimating time to complete arc flash hazard assessment.

Task	Category	Hours	Per Equipment
Data Collection		2	Substation
		0.1	Load
Data Entry & Verification	Short Circuit	0.15 – 0.25	Bus
	Protective Device Data	0.1 – 0.25	Device
Short Circuit Study	Analysis	0.1 – 0.25	Bus
	Report	0.1 – 0.25	Bus
Protective Device Coordination	Analysis	0.4	Device
	Report	0.15 – 0.4	Device
Arc flash Hazard	3-Scenario Analysis	0.25	Bus
	1-Scenario Analysis	0.1 – 0.25	Bus
	Report	0.1 – 0.25	Bus
	Warning Labels (by program)	0.05	Equipment

Similarly, estimates can be made for other activities such as worker training, safety audit, documentation (much of the documentation will already have been done during the assessment), procurement and distribution of PPE and development of safety procedures for arc flash hazard.

Table 2.4: Estimate of hours for arc flash hazard assessment for a plant with 350 buses at 4 different voltage levels and 56 substations, using commercial integrated software for computation.

Task	Hours	% of Total
Data Collection	136	18%
Data Entry and Verification	64	9%
Short Circuit Analysis	80	11%
Protective Device Coordination	336	46%
Arc flash Hazard Assessment	120	16%
Total	**736**	

2.7 Cost Estimates

Cost estimates for human efforts can be obtained from the hours of work needed for the arc flash hazard program. The PPE cost can be estimated using the highest likely risk category. This can be roughly determined using the table method for the highest available fault current. Other costs will include consulting fees for safety training and/or management, printing warning labels, etc.

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[13] IEEE-PCIC Electrical Safety Workshop, February 2003, Houston Texas.

3 Arc Flash Calculation Methods

This chapter provides an overview of arc flash hazard calculations recommended by IEEE and NFPA. All equations, data, and calculation methods listed in this chapter are the property of the IEEE and NFPA. You are encouraged to read the standards for details.

3.1 IEEE Std 1584-2002

The following procedures are recommended by IEEE Standard 1584-2002 in the evaluation of arc flash hazard. The empirically derived equations were developed by IEEE working group on arc flash. These equations are based on test results and are applicable for the following conditions.

Table 3.1: Conditions for which the IEEE 1584 equations are applicable

Parameter	Applicable Range
System voltage (kV)	0.208 to 15 kV
Frequencies (Hz)	50 or 60 Hz
Bolted fault current (kA)	0.7 to 106 kA
Gap between electrodes (mm)	13 to 152 mm
Equipment enclosure type	Open air, box, MCC, panel, switchgear, cables
Grounding type	Ungrounded, grounded, high resistance grounded
Phases	3 Phase faults

3.1.1 Step 1: Estimate of Arcing Current

For low voltage systems (<1 kV), the arc current is given by equation (3.1).

$$I_a = 10^{\{K+0.662\log(I_{bf})+0.0966V+0.000526G+0.5588V*\log(I_{bf})-0.00304G*\log(I_{bf})\}} \quad \ldots \quad (3.1)$$

where

log is the $\log_{10}$

I_a = arcing current (kA)

K = –0.153; open configuration

= –0.097; box configuration

I_{bf} = bolted fault current for three-phase faults (symmetrical RMS) (kA)

V = system voltage (kV)

G = gap between conductors, (mm)

For medium voltage systems (>1 kV), the arc current is given by equation (3.2).

$$I_a = 10^{\{0.00402 + 0.983 \log(I_{bf})\}} \tag{3.2}$$

3.1.2 Step 2: Estimate of Normalized Incident Energy

The normalized incident energy, based on 0.2 second arc duration and 610 mm distance from the arc, is given by equation (3.3)

$$E_n = 10^{\{K_1 + K_2 + 1.081 * \log(I_a) + 0.0011G\}} \tag{3.3}$$

where

E_n = incident energy normalized for time and distance (J /cm^2)

K_1 = -0.792; open configuration

= -0.555; box configuration

K_2 = 0; ungrounded and high resistance grounded systems

= -0.113; grounded systems

G = gap between conductors (mm)

3.1.3 Step 3: Estimate of Incident Energy

The normalized incident energy is used to obtain the incident energy at a normal surface at a given distance and arcing time with equation (3.4).

$$E = 4.184\, C_f\, E_n \left(\frac{t}{0.2}\right)\left(\frac{610}{D}\right)^x \tag{3.4}$$

where

E = incident energy (J / cm^2)

C_f = Calculation factor = 1.0; voltage > 1kV

= 1.5; voltage < 1kV

t = arcing time (seconds)

D = working distance from arc (mm)

x = distance exponent as shown in Table 3.2.

Table 3.2: Distance Factor (x) for various voltages and enclosure types

Enclosure Type	0.208 to 1 kV	>1 to 15 kV
Open air	2	2
Switchgear	1.473	0.973
MCC and Panels	1.641	
Cable	2	2

3.1.4 Step 4: Flash Protection Boundary

The flash protection boundary is the distance at which a person without personal protective equipment (PPE) may get a second-degree burn that is curable.

$$D_B = 610 * \left[4.184 C_f E_n \left(\frac{t}{0.2} \right) \left(\frac{1}{E_B} \right) \right]^{\frac{1}{x}} \qquad (3.5)$$

where

D_B = distance of the boundary from the arcing point (mm)

C_f = calculation factor = 1.0; voltage > 1 kV

= 1.5; voltage < 1 kV

E_n = incident energy normalized

E_B = incident energy at the boundary distance (J/cm2); E_B can be set at 5.0 J/cm^2 (1.2 Cal/cm^2) for bare skin.

t = arcing time (seconds)

x = the distance exponent from Table 3.2.

I_{bf} = bolted fault current (kA).

3.2 NFPA 70E Protection Boundaries

3.2.1 Flash Protection Boundary

- Serious injury due to arc flash burns can occur within this area unless appropriate PPE is used.
- Anyone within this area must wear appropriate PPE regardless of what they are doing.
- The distance from the arc source at which the on-set of a second degree burn occurs.

- 1.2 $Cal/cm^2 > 0.1$ sec. is considered a second degree burn threshold.
- Medical treatment may still be required if bare skin is exposed to this level of flash. Full recovery expected.

3.2.2 Limited Approach Boundary

- Defines a boundary around exposed live parts that may not be crossed by "unqualified" persons unless accompanied by "qualified" persons.
- May be closer than flash boundary.
- Defined solely based on the nominal voltage.

3.2.3 Restricted Approach Boundary

- Boundary near exposed live parts that may be crossed only by "qualified" persons using appropriate shock prevention techniques and equipment.
- Concern is a shock hazard.
- Defined solely based on the nominal voltage.

3.2.4 Prohibited Approach Boundary

A shock protection boundary to be crossed by only "qualified" persons using same protection as if direct contact with live part is planned. Defined solely based on the nominal voltage.

3.3 NFPA 70E – May 2003 ROP

The proposed edition of NFPA 70E, Standard for Electrical Safety Requirements for Employee Workplaces, 2004 Edition, has recommended in Annex B and C of the standard, the following methods for evaluating arc flash hazard. The final version has been changed to "Electrical Safety Requirements for Employee Workplaces" and is scheduled to be released in January of 2004. Methods shown here may differ from the final release version. Two different methods are described.

3.3.1 Annex B Method

3.3.1.1 Arc Flash Boundary

The theoretical maximum arc power in MW is half the bolted 3-phase fault MVA[14],[15]. This occurs when the arc current is 70.7% of the bolted fault current. Based on this, the flash protection boundary is calculated as:

$$D_B = \sqrt{2.65 * 1.732 * V * I_{bf} * t} \quad (3.6)$$

where

D_B = distance of the boundary from the arcing point (inches)
V = rated system voltage L-L (kV)
I_{bf} = bolted fault current (kA)
t = arcing time (seconds)

3.3.1.2 Incident Energy

Arc in open air – 0.6 kV or below, 16-50 kA short circuit current

$$E = 5271 D^{-1.9593}\, t\, [0.0016 * I_{bf}^{2} - 0.0076 * I_{bf} + 0.8938] \quad (3.7)$$

Arc in box – 0.6 kV or below, 16-50 kA short circuit current

$$E = 1038.7 D^{-1.4738}\, t\, [0.0093 * I_{bf}^{2} - 0.3453 * I_{bf} + 5.9675] \quad (3.8)$$

Arc in open air – Above 0.6 kV

$$E = 793\, D^{-2}\, V I_{bf}\, t \quad (3.9)$$

where

E = incident energy (cal / cm^2)
I_{bf} = bolted fault current (kA)
t = arcing time (seconds)
D = working distance from arc (inches)

Equations (3.7) and (3.8) are part of the 2000 edition, and equation (3.9) was proposed in the 2003 draft.

3.3.2 Annex C Method (2003)

Table 3.3: Equations for arc in box for calculating arc current, incident energy and flash protection boundary.

	V < 1 kV	1 kV < V < 5 kV	V > 5 kV
I_a =	$0.85 I_{bf} - 0.004 I_{bf}^2$	$0.928 I_{bf}$	I_{bf}
E =	$416 I_a t D^{-1.6}$	$21.8 I_a t D^{-0.77}$	$16.5 I_a t D^{-0.77}$
D_B =	$(416 I_a t / 1.2)^{0.625}$	$(21.8 I_a t / 1.2)^{1.3}$	$(16.5 I_a t / 1.2)^{1.3}$

The equations in Table 3.3 apply only to **arc in box** for short circuit currents between **0.6 kA and 106 kA**.

where

E = incident energy (cal / cm^2)
I_{bf} = bolted fault current (kA)
I_a = arc current (kA)
t = arcing time (seconds)
D = working distance from arc (inches)
D_B = distance of the flash protection boundary from the arcing point (inches)

3.4 NFPA 70E Tables

3.4.1 Flash Protection Boundary

Table 220.2(B)(2)(C) of the proposed NFPA 70E – 2003 ROP provides a simple method of determining flash protection boundary. This is shown in Table 3.5 below. Note that this table is presented here for information purposes only, and ***should not*** be applied unless it is published as part of the standard. This table is extremely approximate – the actual arc flash boundaries may depend upon numerous factors such as available fault level and trip characteristics of the upstream protective device. *Therefore, this table is not recommended for use.*

Table 3.5: Simple method of determining flash protection boundary as per Table 220.2(B)(2)(C) of the proposed NFPA 70E – 2003 ROP.

Arc Location	System Voltage	Flash Protection Boundary (feet)
Arc in Air	200 to 1000 volts	4
Arc in Enclosure	200 to 1000 volts	10
Arc in Enclosure	1000 volts and up	20

3.4.2 Hazard/Risk Category Classifications

The draft of NFPA 70E – 2003 ROP proposes the option of using Table 220.6(B)(9)(A) Hazard Risk Category Classifications[16]. This table does not provide the flash protection boundary, but only prescribes the hazard/risk category number. The table also specifies the requirement of V-rated gloves and V-rated tools. The classification of risk category is based on several factors such as voltage, type of equipment, type of work to be performed, available short circuit current, circuit breaker tripping time or fuse clearing time and the position of the enclosure doors. The various types of work mentioned in the table are; operating circuit breakers or fuses, working on live parts, voltage testing, removing and installing bolted covers, applying safety grounds, working on control circuits, etc.

An example of what 70E (2004) Table 220.6(B)(9)(A) may look like is summarized for two items in Table 3.4: working on live parts and voltage testing. This table is preliminary and is for reference purposes only. Refer to NFPA-70E (2004) for final application guidelines.

The exact short circuit currents for three phase bolted faults can be calculated using commercial software. A simple approximation described in Annex B.2 of proposed NFPA 70E – 2003 ROP draft is using the upstream transformer data in the following equation. The actual short circuit current will be less than this calculated value due to the impedance of the system upstream to transformer.

$$I_{SC} = \left(\frac{\text{MVA Base}}{1.732\ V}\right)\left(\frac{100}{\%Z}\right) \qquad (3.10)$$

where

I_{SC} = 3-phase bolted fault current

MVA Base = rated MVA of the upstream transformer

V = line-to-line voltage at the secondary side of the transformer

%Z = percentage impedance of the transformer.

Table 3.4 (a): Hazard / Risk Category Classification for Working on Live Parts as per Table 220.6(B)(9)(A) of proposed NFPA 70E – 2003 ROP (Note: This table is only a proposed draft and had not been approved or published at the time of writing this book. Please refer to the upcoming edition of NFPA 70E (2004).)

Equipment Type	Equipment Side	Short Circuit Current (kA)	Fault Clearing Time (s)	0.24 kV	0.277 to 0.6 kV	2.3 to 7.2 kV	1 to 38 kV
Panel Board		42	0.03	1			
		< 10	0.03	0	1		
		< 36	0.1		2		
MCC 0.6 kV Class	Load Side of Breaker / fuse	65	0.03		2		
		< 10	0.03		1		
	Bus	42	0.33		4		
	Bus	52	0.2		4		
	Bus	65	0.1		4		
	Bus	62	0.33		5		
	Bus	76	0.2		5		
	Bus	102	0.1		5		
	Bus	< 10	0.1		3		
	Bus	< 10	0.33		4		
Switchgear 0.6 kV Class		35	0.5		4		
		42	0.33		4		
		52	0.2		4		
		65	0.1		4		
		< 25	0.33		3		
		62	0.33		5		
		76	0.2		5		
		102	0.1		5		
Other Equipment 0.6 kV Class		35	0.5		4		
		42	0.33		4		
		52	0.2		4		
		65	0.1		4		
NEMA E2 Motor Starters MV		55	0.35			5	
Metal Clad Switchgear, MV							5
Other Equipment							5

Table 3.4 (b) Hazard / Risk Category Classification for Voltage Testing as per Table 220.6(B)(9)(A) of proposed NFPA 70E – 2003 ROP.

Equipment Type	Equipment Side	Short Circuit Current (kA)	Fault Clearing Time (s)	0.24 kV	0.277 to 0.6 kV	2.3 to 7.2 kV	1 to 38 kV
Panel Board		42	0.03	1			
		< 10	0.03		1		
		< 36	0.1		2		
MCC 0.6 kV Class	Load Side of Breaker / fuse	65	0.03		2		
		< 10	0.03		1		
	Bus	42	0.33		2		
	Bus	52	0.2		2		
	Bus	65	0.1		2		
	Bus	62	0.33		2		
	Bus	76	0.2		2		
	Bus	102	0.1		2		
	Bus	< 10	0.1		1		
	Bus	< 10	0.33		1		
Switchgear 0.6 kV Class		35	0.5		2		
		42	0.33		2		
		52	0.2		2		
		65	0.1		2		
		< 25	0.33		1		
		62	0.33		2		
		76	0.2		2		
		102	0.1		2		
Other Equipment 0.6 kV Class		35	0.5		2		
		42	0.33		2		
		52	0.2		2		
		65	0.1		2		
NEMA E2 Motor Starters MV		55	0.35			2	
Metal Clad Switchgear, MV							5
Other Equipment							5

3.5 Arc Blast Pressure

Another item associated with an electric arc is the blast energy or pressure. This hazard is not presently covered in NFPA 70E or IEEE Standard 1584. This force can be significant and can blow workers away from the arc causing falls and injuries that may be more severe than burns. In Ralph Lee's second IEEE paper[17], *Pressures Developed by*

Arcs in 1987, he cites several case histories. In one case, with approximately 100-kA fault level and arc current of 42 kA, on a 480-V system, an electrician was thrown 25 feet away from the arc. Being forced away from the arc reduces the electricians' exposure to the heat radiation and molten copper, but can subject the worker to falls or impact injuries. The approximate initial impulse force at 24 inches was calculated to be approximately 260 lb/ft^2 as determined from the equation below.

$$\text{Pressure} = \frac{11.58 * I_{arc}}{D^{0.9}} \tag{3.11}$$

where,

Pressure is in pounds per square foot.

D = Distance from arc in feet.

I_{arc} = Arc current in kA.

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[14] Ralph Lee's, "The Other Electrical Hazard: Electrical Arc Blast Burns," *IEEE Transactions on Industry Applications*, Vol. 1A-18, No. 3, Page 246, May/June 1982.

[15] This conclusion is supported by the Maximum Power Transfer Theorem: The power transferred to a load (an arc in our case) is maximum when the impedance of the load is equal to the Thevenin impedance of the source. The theorem was first developed by Moritz Hermann Jacobi.

[16] Proposed NFPA 70E, *Standard for Electrical Safety Requirements for Employee Workplaces*, 2003 ROP Edition, National Fire Protection Association.

[17] Ralph Lee, "Pressures Developed by Arcs", *IEEE Transactions on Industry Applications*, Vol. IA-23, No. 4. July/August 1987, page 760-764.

4 Practical Steps to Arc Flash Calculations

Several methods for arc flash calculations as recognized by proposed NFPA 70E-2004 were described in Chapter 3. Electrical engineers typically perform the calculations, since an understanding of the short circuit behavior of power systems is necessary. If the available short circuit values at various equipment and the associated fault clearing times are known, then a trained person can also perform arc flash hazard assessment (AFH) by using the appropriate NFPA 70E tables. However, this approach has significant drawbacks due to gross oversimplification inherent in this simplified approach. For larger power systems with multiple sources and possible operating conditions, it is preferable to do a detailed engineering analysis that can determine the worst-case arc flash hazard conditions that can occur. As will be seen, this will not necessarily be the conditions with the highest fault current.

The following steps are involved in detailed arc flash study. Prior to beginning the data collection, it should be determined and agreed upon which method of calculation will be used.

1. Identify all locations/equipment for AFH assessment.
2. Data Collection:
    a. Equipment data for short circuit analysis;: voltage, size (MVA/kVA), impedance, X/R ratio, etc.
    b. Equipment data for protective device characteristics; type of device, existing settings for relays, breakers and trip units, rating amps, time-current curves, total clearing time.
    c. Equipment data for arc flash study; type of equipment, type of enclosure (open air, box, etc.), gap between conductors, grounding type, number of phases, and approximate working distance for the equipment.
    d. All power system equipment, their existing connections and possible alternative connections.
3. Prepare a single-line diagram of the system.
4. Short circuit study:
    a. Calculate bolted (available) three-phase fault current for each equipment.
    b. Calculate every contributing branch/load currents.
5. Calculate estimated arc current:
    a. Calculate arc current using empirical formula (NFPA, IEEE, or other standards).

   b. Calculate branch currents contributing to the arc current from every branch.

6. Estimate arcing time from the protective device characteristics and the contributing arc current passing through this device for every branch that significantly contributes to the arc fault.

7. Estimate the incident energy for the equipment at the given working distances.

8. Determine the hazard/risk category (HRC) for the estimated incident energy level.

9. Estimate the flash protection boundary for the equipment.

10. Document the assessment in reports, one-line diagrams and with appropriate labels on the equipment.

4.1 Step 1 – Identification of Locations/Equipment for AFH

Arc flash hazard assessment is needed only for those locations where workers are exposed to the risk. Therefore, it may not be necessary to perform the assessment for each and every piece of equipment in the power system. Panels and switchboards rated 208 volts or less can generally be ignored if the service transformer is less than 125 kVA. The arc will not likely be sustainable at lower voltages and smaller available fault currents. All panels with breakers and fuses should be included in the assessment if there is potential for significant arc flash injury. Incidents may occur when operating the breakers or fused disconnects, even with the door closed. You can consult the existing one-line diagrams for determining the equipment that require assessment. If such a diagram does not exist, it should be constructed as discussed in steps 2 and 3.

4.2 Step 2 – Data Collection

4.2.1 Equipment Data for Short Circuit Analysis

Although some equipment may not require arc flash hazard assessment, data about this equipment may be required in a short circuit analysis. Typical data required for the study is shown in Table 4.1. Short circuit analysis requires data on utility, generators, transformers, cables, transmission lines, motors, etc. The name-plate of the equipment can provide most of the necessary data. In the absence of particular data, it may be possible to obtain the information from the manufacturers or their representatives. Also, typical data can be assumed by referring to books and product literature. Power system software such as EasyPower has an extensive library of manufacturers data covering most electrical equipment in use today. This book is not meant to be a guide for short circuit studies. Refer to standard literature[18, 19, 20] for short circuit studies.

Table 4.1: Typical data needed for equipment for short circuit analysis

Description	Data
Equipment Type	
Voltage	
MVA/KVA	
Impedance	
X/R Ratio	
Phases/connection	

4.2.2 Equipment Data For Protective Device Characteristics

Obtain data on the various protective devices that will determine the arcing time. Table 4.2 shows what kind of information is required. This data may be obtained from existing drawings, relay calibration data, coordination studies and from field inspection. Obtain from the manufacturers the time-current characteristics (TCC) for these devices. **Determine whether the protective device is reliable enough**. This can be done by asking the operators, or by testing if necessary. Some companies have periodic relay testing programs. If the protective device is deteriorating, the data provided by the manufacturer may not be applicable. If the fault interruption does not occur as expected then the arc flash assessment cannot be accurate. It will be necessary to repair or replace such equipment.

Table 4.2: Protective device data to gather

Protective Device	Data to Gather
Relay	Type, CT ratio, pickup (tap) setting, delay type (curve) and setting (time dial).
Fuse	Type, amp rating, voltage, peak let-through current.
Breaker	Type, fault clearing time, pickup setting, delay curve, delay setting.

4.2.3 Equipment Data For Arc Flash Study

Depending on the method of calculation selected, the following equipment data is required for an arc flash hazard study.

Table 4.3: Equipment data for AFH study

Description	Data
Type of enclosure (open air, box, etc.)	
Gap between exposed conductors*	
Grounding type*	
Phases/Connection	
Working Distance	

Data required for IEEE 1584 method has been marked with ' * '. The working distance is an approximate measure that should be based on the type of work being performed and the type of equipment. It may vary based on manufacturer's design and work practices. Working distances should be documented for various work practices and equipment as part of a complete safety program.

4.2.4 Determine All Possible Operating Conditions

Make note of all possible connections (system operating modes) using diagrams and tables. The circuit breaker/switch/fuse status may change during abnormal operations. Parallel feeds can greatly increase the available fault current and resulting arc flash hazard. The contribution of connected motors to the fault will increase the hazard as well. Assessment should include both the normal operating condition as well as the worst possible arc flash scenario. In general, the higher the available fault current, the greater the arc flash energy. However, since arc flash energy is a function of the arc duration as well as the arc current, it cannot be automatically assumed that the highest fault current will always be the worst-case AFH. Figure 4.1 shows the available fault currents for two scenarios of connections: (a) everything connected and (b) generator normally not running and the motor turned off for maintenance. The difference in fault currents can clearly be seen. Table 4.4 is an example worksheet for this case, considering multiple connections.

Table 4.4: Example worksheet for connection scenarios

Equipment Connected	Normal Operation	Co-generation	Maintenance Schedule A	Maintenance Schedule B
Utility	ON	ON	OFF	ON
Generator	OFF	ON	ON	OFF
Motor	ON	ON	ON	OFF
M-2	ON	ON	ON	ON

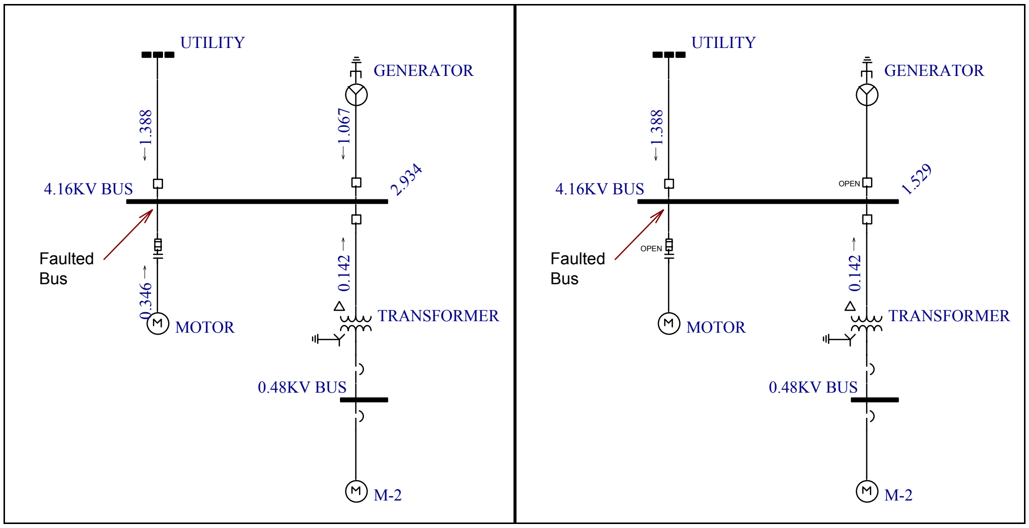


Figure 4.1: EasyPower example of connected equipment for two possible cases

4.3 Step 3 – Prepare single-line diagram of the system

Single-line (one-line) diagrams are powerful tools for documenting and communicating information about power systems. They are easy to read, show the connections and status of equipment and contain data required for analysis. The results of analysis such as short circuit studies and arc flash hazard assessment can easily be placed on the diagrams. Most existing plants should already have one-line diagrams. The accuracy of these should be verified before commencing the assessment. If a new diagram is required, it can be prepared using the data collected.

Assessment using a commercial integrated software like EasyPower requires entry of data to build a power system model. EasyPower provides an advanced graphical drag-and-drop one-line diagram completely integrated with short circuit, protective device coordination, and arc flash analysis. EasyPower provides an easy way to create, update and maintain your power system one-line in compliance with NFPA-70E requirements.

4.4 Step 4 – Short Circuit Study

A complete tutorial on performing short circuit studies is not provided here. But additional considerations related to AFH when performing short circuit studies are described briefly in the sections that follow. Only 3-phase faults are considered when performing AFH. This may seem odd, but it is consistent with the recommendations in IEEE-1584 and NFPA-70E. There are several reasons for this. One is that 3-phase faults generally give the highest possible short circuit energy and represent a worst-case. Another important reason is that experience has shown that arcing faults in equipment or air that begin as line-to-ground faults, can escalate very rapidly into 3-phase faults as the air ionizes across phases. This progression from single-phase to 3-phase happens generally within a few cycles. Because of this, most testing done on arc flash energy has been based on 3-phase faults. For singe-phase systems, IEEE-1584 recommends that calculations be done for an equivalent 3-phase system and states that this will yield conservative results. Based on the data collected for various system operating modes, arc flash calculations should be performed for each possible case. Traditionally, when performing short circuit calculations to determine maximum short circuit current, extremely conservative estimates and assumptions are used. This makes sense if the goal is to determine maximum breaker or equipment duties. However, for AFH, using overly conservative short circuit data can yield non-conservative results since a very high fault current may produce a very short arc duration due to the operation of instantaneous trip elements. The highest fault current does not necessarily imply the highest possible arc flash hazard because the incident energy is a function of arcing time, which may be an inversely proportional function of the arcing current. For AFH determinations, short circuit calculations should be conservative, but not overly conservative.

4.4.1 Calculate Bolted Fault Current

Calculate the **3-phase bolted fault current in symmetrical rms amperes** for all buses or equipment, and for each possible operating mode. Check for the following while considering various interconnections at the concerned bus or equipment:

- Multiple utility sources that may be switched in or out of service.
- Multiple local generator sources that are operated in parallel or isolated depending on the system configuration.
- Emergency operating conditions. This may be with only small backup generators.
- Maintenance conditions where short circuit currents are low but arc duration may be long.
- Parallel feeds to Switchgear or MCC's.
- Tie breakers which can be operated open or closed.
- Large motors or process sections not in operation.

A short circuit/arc flash case should be developed for each operating mode. This can be a daunting task for most software or spreadsheet calculators. EasyPower Scenario Manager provides a simple and easy method to document and analyze each operating mode for quick repeatable analysis.

Hand calculations and spreadsheet calculators may typically neglect the transient short circuit values that last for a few cycles. These are higher than the sustained short circuit values. The generator and motor transients during the fault contribute to the arc fault. To account for these:

- Use sub-transient and transient impedances of the generators to find the bolted fault current if the arcing time is small. For long arcing times, use the sustained short circuit values. This suggests an iterative process, since the arcing time depends upon the fault current passing through the upstream protective device.

- Include contribution of connected motors in the calculations.

4.4.2 Calculate Contributing Branch Currents

Contributing branch currents to faults are calculated to estimate the contributing arc currents by various branches, which again, are used to determine the trip times of the protective devices on the branches. The protective device upstream to the fault sees only the current passing through it. The fault current may be greater than the current passing through the upstream protective device. Therefore, the total fault current cannot be used to find the trip time unless other branch currents are significantly smaller than the upstream current. Similarly, for parallel feeds, the contributing currents from each feed must be calculated to determine the trip time.

Special care is needed when computing branch currents through transformers. This could be one of the common source of errors since the branch current needs to be adjusted by the transformation ratio. When a fault occurs on the low voltage side of a transformer, the protective device on the high voltage side of the transformer sees a smaller current due to the transformer turns ratio.

4.5 Step 5 – Determine Expected Arc Current

4.5.1 Calculate Arc Current

Calculate arc current for every required equipment or bus using one of the empirical formulae recognized by the NFPA-70E (NFPA, IEEE, or other standards). These are described in Chapter 3. The arc current may be a function of the bolted fault current, the open circuit voltage, the type of enclosure and the gap between conductors depending on the calculation method selected.

4.5.2 Consider a range of Arc Current

4.5.2.1 Tolerance due to Random Variation based on IEEE-1584

To cover the variance that can occur in arcs, IEEE procedure suggests the following.

1. Calculate the maximum expected bolted fault condition.
2. Calculate the minimum expected bolted fault condition. The minimum bolted fault current could be a light load condition with many motor loads or generators not running.

3. Calculate the arcing current at 100% of IEEE 1584 estimate for the above two conditions.

4. Calculate the arcing current at 85% of IEEE 1584 estimate for the two above conditions.

5. At these four arcing currents calculate the arc flash incident energy and use the highest of the incident energies to select PPE. The minimum fault current could take longer to clear and could result in a higher arc flash incident energy level than the maximum-fault current condition. The fault current in the main fault current source should be determined since the current in this device may determine the fault clearing time for the major portion of the arc flash incident energy.

Note: Although IEEE recommends considering a range of 85% to 100% of the estimated arc current, IEEE test data shows that the measured values of arc current vary from 67% of the estimate to 157% of the estimate. Further analysis of the IEEE test data was performed by the authors and the results are discussed in detail in Appendix A. Careful application of tolerances is required for the following reasons:

i. The tripping time of inverse-time protective devices is influenced by the arc current.

ii. The incident thermal energy is more sensitive to arcing time than it is to arc current.

iii. A more realistic and reasonably conservative estimate of arcing time can be obtained by proper selection of tolerances of arc current.

The following section provides guidelines based on statistical analysis of test data for various voltage levels and enclosure types.

4.5.2.2 Tolerance due to Random Variation based on Actual Data

Because of the random nature of arc currents, the actual arc current may take any value within a range of possible values. The calculated arc current is only a single estimate within the range possible values. The calculated arc current or the highest possible arc current may not necessarily produce the highest incident energy to which workers may be exposed. The arcing time may depend upon the arc current due to the tripping characteristics of the protective device. Therefore, the incident energy may be greater for smaller arc currents if the contributing branch current of the arc current lies in the inverse-time section of trip characteristics.

Table 4.5: Minimum and maximum tolerances for arc currents obtained from IEEE 1584 test data for confidence level of 95%.

Voltage	Enclosure Type	Minimum Arc Current	Maximum Arc Current
LV	Open	-26.5%	26.0%
LV	Box	-26.9%	33.0%
MV	Open	-6.7%	10.2%
MV	Box	-20.8%	12.3%

When considering the range of the calculated arc current, the simplest way is to take a tolerance. This tolerance is a percentage of the calculated arc current. The tolerance is obtained from statistical analysis of the test data. The tolerances differ for IEEE 1584 method and NFPA 70E methods. For further description see Appendix A. Table 4.5 provides tolerances for IEEE 1584 arc current estimate for a confidence level of 95%. A confidence level of 95% means that there is a probability of 95% that the arc current will be in the tolerance range. To be more conservative, you could also take a confidence level of 99%. This would widen the tolerance range.

<u>Example</u>

For a 0.48 kV equipment in open air, the calculated arc current (I_{arc}) using IEEE 1584 estimate was 40 kA. What is the possible range of the arc current?

From Table 4.5 the minimum and maximum tolerances of arc current are –27.5% and +31.9% respectively.

Minimum arc current = I_{arc} * (100 + Min. Tolerance %)/100

= 40 * (100 – 26.5) / 100 = 29.4 kA.

Maximum arc current = I_{arc} * (100 + Max Tolerance %)/100

= 40 * (100 + 26.0) / 100 = 50.4 kA.

Variation of Arcing Current with Arc Gap

If the exact arc gap (or gap between conductors) was used in obtaining the arc current estimates, then further adjustments need not be applied. However, if the gap is an average value or an assumed value, then the possible range of arc current may need to be adjusted. Appendix A describes in detail the effect of gap on the arc current. The gap is used in calculations in the IEEE 1584 equations. NFPA 70E does not take the gap into account. Table 4.6 provides the sensitivity of arc current to gap. For every mm of difference in gap the arc current value is modified by the sensitivity amount. The voltage across an arc gap is roughly proportional to the length of the gap. Higher voltage means higher arc power for the same arc current. Since the arc resistance is non-linear, the resistance is not directly proportional to the gap length. Therefore statistical approach is preferred in the evaluation of the effect of variation of arc gap length on arc current. The procedure given below should be used only for small differences in arc gap, as with most other sensitivity analyses.

Table 4.6 Sensitivity of arc current to gap for IEEE 1584 method

Voltage	Enclosure	Sensitivity (% / mm)
LV	Box	-1.0%
LV	Open	-0.7%
MV	-	Not Required

Example

The exact gap between conductors for various devices are not known. For low voltage box, it was generally observed that the gap ranged from 25mm to 40mm with an average of 32mm. There are two ways to deal with this. The first method is to obtain two estimates for arc current, one for the least gap and the other for the highest gap. The second method is to adjust the IEEE estimate for the average gap using the sensitivity shown in Table 4.6. Let us say that the arc current for 32mm gap was found to be 40 kA.

Arc current for min. gap = I_{arc} * (1+sensitivity*(Min. gap – Average gap)/100)

= 40 * (1-1.0*(25-32)/100)

= 42.8 kA.

Arc current for max. gap = I_{arc} * (1+sensitivity*(Max. gap – Average gap)/100)

= 40 * (1-1.0*(40-32)/100)

= 36.8 kA.

If the variation in gap is small, then extensive analysis need not be carried out.

4.5.2.3 Limits for Arc Currents

After calculating the range of possible arc current, it is necessary to check whether the calculated values are within the practical range. Check for the following:

- Upper limit: It is not possible for the arc current to be greater than the bolted fault current because of the additional impedance of the arc. Therefore, after applying adjustments for random variations and for gap variations, if the upper limit of the range of arc current is greater than the bolted fault current, then discard that value and take the bolted fault current as the upper limit.

Example

For a bolted fault current of 50 kA at medium voltage equipment in box, the arc current was calculated to be 49 kA using IEEE 1584 equations. To account for random variations tolerance data from Table 4.5 was applied. This takes the upper limit of arc current to 12.3% greater than the estimated value. Therefore, the upper limit of the arc current was calculated to be 49*(100+12.3)/100 = 55 kA. This is higher than the bolted fault current (50 kA), and therefore, is not possible. Take the upper limit of arc current as 50 kA.

- Lower Limit: Arcs do not sustain when the current is very low. For 480-volt systems, the industry accepted minimum level for a sustaining arcing fault current is 38% of the available three-phase fault current[21]. Test data accompanying IEEE Standard 1584 shows arc sustaining for 0.2 seconds at 0.208 kV at a current of 21% of bolted fault current. Table 4.7 shows the minimum arc current as a percentage of bolted fault current obtained during tests. The lower limit of arc current is not yet clear. Until further information is obtained, it may be reasonable to use Table 4.7 as the cut-off minimum arc current as a percentage of the bolted fault current.

Table 4.7: Adjusted minimum arc current as a percentage of bolted fault currents*.

Voltage (kV)	Min Measured I_{arc} % of I_{bf}
0.2/0.25	21%
0.4/0.48	21%
0.6	28%
2.3	51%
4.16	64%
13.8	84%

*The adjustment is based on maximum measured values taken normalized to the bolted fault current.

4.5.3 Calculate Branch Currents Contributing to the Arc Current

This is done using the branch current contributions to the bolted fault current obtained from section 4.4.2. To calculate the contributing currents to the arc fault, use equation (4.1).

$$I_{x,arc} = I_{x,BF} * I_{arc} / I_{BF} \qquad (4.1)$$

Where,

$I_{x,arc}$ = Current through branch x for arc fault

$I_{x,BF}$ = Current through branch x for bolted fault

I_{BF} = Bolted fault current.

Arc currents have been observed to be non-sinusoidal due to the non-linear nature of the arc resistance. The harmonic contribution of different branches may vary, however, the fundamental component can be approximated using the method describe above. It has been observed that although the voltage waveform is highly distorted, the arc current however has low harmonic content. Therefore the linear relation (4.1) is a reasonable approximation.

Section 4.5.2 describes taking upper and lower bounds of the range of arc current. The branch contribution must be calculated for each case. These are later used to determine the trip time of protective devices.

4.6 Step 6 – Determine Arcing Time

Estimate arcing time from the protective device characteristics and the contributing arc current passing through this device for every branch that significantly contributes to the arc fault. Since we are considering a range of arc currents instead of a single value, we need to determine the trip time for each arc current value – the upper bound, the lower bound and the value calculated from NFPA 70E or IEEE 1584 equations.

The trip time of a protective device is obtained from its time-current characteristics (TCC). Information may be obtained from manufacturers in the form of TCC plots or equations. Relays and circuit breaker trip units usually have adjustable time delay for tripping operation. The delay time may depend upon the magnitude of the current sensed by the device. Time delays are provided to coordinate the tripping of the relays so that maximum reliability of supply may be maintained. Refer to literature on protective device coordination for details. Since arc flash hazard can be minimized by reducing the duration of faults, it is beneficial to have a good understanding of protective device coordination. Typically, for lower fault currents, the trip time may be high due to the inverse time-current relationship of the TCC. For higher currents, the arcing-fault current may be greater than the instantaneous pickup of the protective device, and therefore the device may trip at the minimum response time. For fault currents near the transition from the inverse-time curve to the instantaneous trip, a small change in arcing current value can cause a very large difference in calculated arc energy. Refer to Appendix A for details.

Determining the trip time manually requires visual inspection of each time-current curve to determine the operating time for a particular fault current. This also requires adjustment of the fault currents to reflect the transformation ratio of any transformers involved. This must be done before obtaining the trip times of the protective devices across the transformer.

EasyPower's integrated protective device coordination program automatically determines the arcing time for each protective device, operating condition, and arcing current level. Total integration saves you time and resources, and ensures the most accurate solution.

Typically, for any given current, protective devices have a tolerance about the specified trip time. Many low voltage breakers and fuses specify the upper and lower limits of the trip time for different current values. For such cases, the time-current curve looks like a thick band instead of a single line. Relays typically show a single line for the TCC curve, and specify the tolerance as +/-x% (usually 10% to 15%) somewhere in their product literature. Some fuse curves provide only the average melting time or the minimum melting time. Follow the guidelines provided below for determining the trip time.

- TCC with tolerance band: Take the total clearing time (upper bound of the band) corresponding to the branch current seen by the device.

- Relays with single line curve: Find within the TCC data or the product literature, the tolerance for trip time. Add the tolerance to the trip time obtained for the TCC. Breaker opening time must be added to this value.

- Fuse TCC with total clearing time: No adjustment is required since total clearing time is what we need.

- Fuse TCC with average melting time: Obtain the tolerance from the product literature, TCC data or the manufacturer. Add the tolerance to the average melting time obtained for the TCC. If tolerance data is not available, make an assumption using data with similar devices. For most purposes, a tolerance of +/-15% should suffice. IEEE 1584 suggests taking a tolerance of 15% when average trip time is below 0.03 seconds and 10% otherwise. Some commonly used fuse curves have been found to have a tolerance as high as 40%. If the tolerance is known to be small, then additional computation can be ignored.

- Fuse TCC with minimum melting time: Obtain the tolerance from the product literature, TCC data or the manufacturer. Add the tolerance to the minimum melting time obtained for the TCC. If tolerance data is not available, make an assumption using data with similar devices. The tolerance may vary with the slope of the curve. For smaller melting times the total clearing time may be 30% to 100% higher than the minimum melting time.

- Circuit breaker clearing time: The TCC of relay or trip unit accompanying the breaker may or may not include the breaker clearing time. If the breaker clearing time is not included in the TCC data, find the breaker clearing time and add it to the delay of the trip unit. Breakers typically have a maximum clearing time of 3 to 5 cycles after the trip coil is energized.

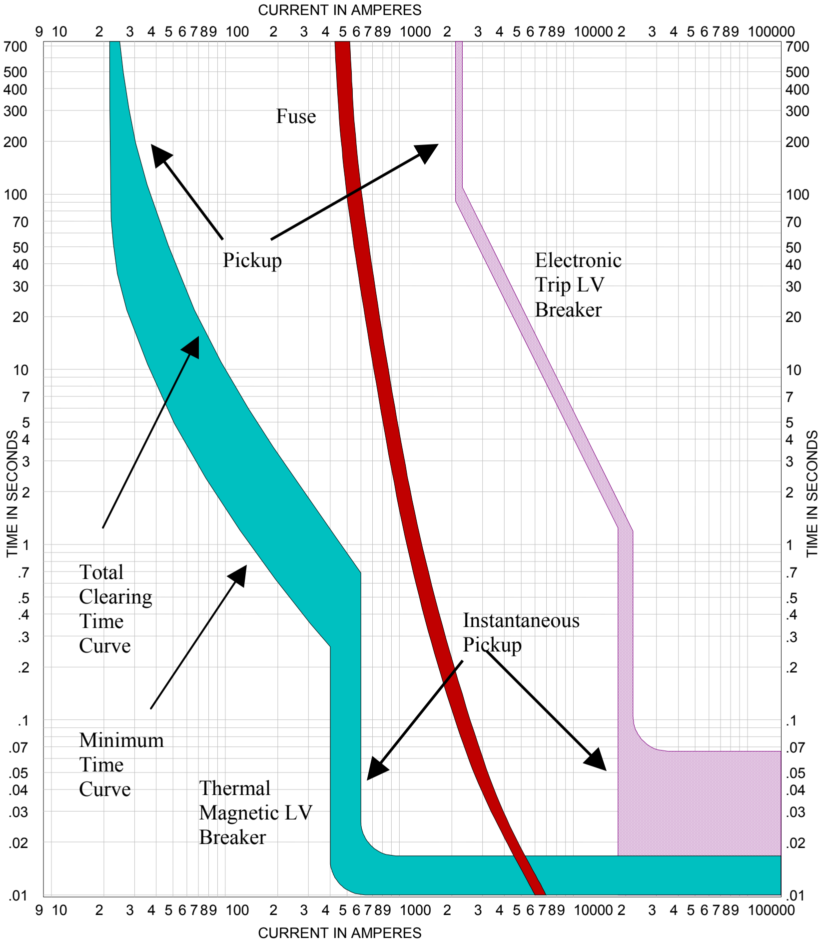


Figure 4.2: Example of TCC plot with tolerance band

4.6.1 Evaluate Protective Device Performance

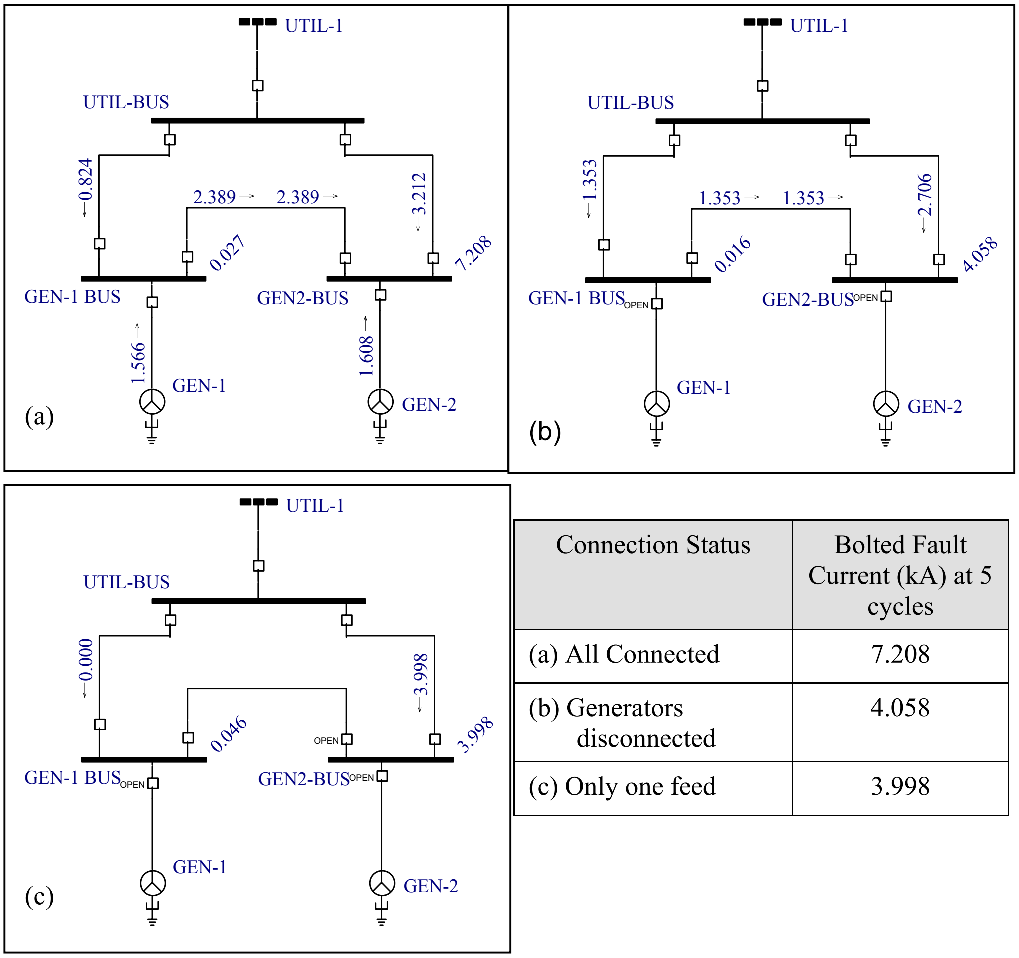
Special attention is required when the calculated branch currents seen by any protective device is close to pickup current of the device. If the branch current is lower than the pickup then the device will not trip. Typically, protective devices are coordinated such that the downstream device trips before upstream device for the same current (or the equivalent current converted to the same voltage base). However in the absence of proper coordination, if the downstream device does not trip at a given fault current, then the upstream device may trip. Therefore, it is necessary to identify which device will interrupt the arc fault. Selective coordination of devices should be maximized by adjustment of trip unit settings, if possible. This will not only improve the continuity of supply but will also provide the opportunity to lower arc flash hazard by reducing the arcing time (although selectivity and arc flash reduction are often conflicting goals).

The arcing fault currents close to pickup current of instantaneous trip function should be examined closely. If the calculated fault current value is within the tolerance band of the pickup, then there is a likelihood of the device not tripping at the expected instantaneous value. In such cases, if the time-overcurrent function exists in the device then the trip time for the time-overcurrent function should be taken for arc flash calculations.

It is also important to realize that any changes to the protective device settings can have a major influence on the arc energy. If device or setting changes are made, the arc flash calculations must be re-checked and appropriate changes made if necessary.

4.6.2 Trip time for multiple feeds

When a bus is fed from multiple sources, as shown in Figure 4.3, a fault at the bus may cause a series of breaker operations. The actual fault current will change as the breakers open, since the sources of power will be sequentially removed from the faulted bus. Since the current seen by the relays will change over time, further calculations are required to determine the actual trip time for each breaker. We cannot simply obtain the trip time corresponding to a single branch current by looking at the TCC data. Protective devices with time-overcurrent functions typically operate like an integrating device. That means, the overcurrent or its function is integrated or "added" over time until the sum reaches a predetermined trip value. This is when the relay trips. For details on how a relay or fuse integrates the function of current, refer to literature on operation of protective devices.



Connection Status	Bolted Fault Current (kA) at 5 cycles
(a) All Connected	7.208
(b) Generators disconnected	4.058
(c) Only one feed	3.998

Figure 4.3: Example showing multiple source fed bus fault and series of operations with fault current changing with breaker operation.

4.7 Step 7 – Determine Incident Energy

Estimate the incident energy for the equipment at the given working distances. The equations for determining the arc flash incident energy are provided in Chapter 3. The incident energy is a function of the arc current, arcing time, the enclosure type and the distance from the arc. IEEE 1584 also includes the gap between electrodes as a parameter. NFPA 70E Annex B method uses the bolted fault current rather than the arc currents.

In steps 5 and 6, various scenarios were considered. Using the selected method, calculate the incident energy for each scenario. Make sure the following cases are evaluated:

1. Arc current based on IEEE-1584 standard and its associated trip time.

2. Lower bound of arc current due to random variations, and its associated trip time.

3. Upper bound of arc current due to random variations and its associated trip time.
4. Multiple feed scenarios:
    a. Evaluate incident energy for each type of possible connections as noted in Step 4.
    b. Evaluate incident energy for arc current changing through series of breaker operations, as described in step 6. An example is presented below.

Example:

In the example shown in Figure 4.3(a), a 3-phase fault at GEN2-BUS results in a 7.2 kA bolted fault current. NFPA 70E-2003 ROP Annex C method is used for this medium voltage arc in box. Working distance of 18 inches is assumed. The contributing branch currents are shown in Table 4.8. The branch currents I_1, I_2 and I_3 respectively are GEN2 current, current from GEN-1 BUS to GEN-2 BUS and current from UTIL-BUS. The generators are disconnected in 0.1 second. This reduces the bolted fault current to 4.05 kA. Next, the GEN-1 BUS is disconnected from GEN-2 BUS at 0.2 seconds. The bolted fault current drops further to 3.99 kA. The last breaker trips at 0.3 seconds. In this example definite time delay functions have been used to obtain the trip time, only for the sake of simplicity. In many cases the delays are of inverse-time function, and the arcing time may be longer as the fault current reduces with sources being removed from the faulted bus.

Table 4.8: Branch currents and trip times used for example shown in Figure 4.3.

Connection Status	Bolted Fault Current (kA) at 5 cycles	Arc Current (kA)	Branch Currents (kA)			Trip Time from Start of Fault (s)		
			I_1	I_2	I_3	T_1	T_2	T_3
All Connected	7.208	7.20	1.60	2.38	3.21	0.2	-	-
Generators disconnected	4.058	4.05	0	1.35	2.70		0.4	-
Only one feed	3.998	3.99	0	0	3.99			0.5

The total incident energy needs to be calculated by adding the incident energies for each sequence of operation as the sources are removed from the fault.

Table 4.9: Total incident energy for example shown in Figure 4.3.

Connection Status	Arc Current (kA)	Duration (s)	Incident Energy (cal/cm^2)
All Connected	7.20	0.2	2.6
Generators disconnected	4.05	0.2	1.4
Only one feed	3.99	0.1	0.7
Total			4.7

Alternatively, we could take a simpler and more conservative approach of using the highest arc current and the total arcing time. If we take the highest arc current, 7.20 kA, and the total fault duration of 0.5 seconds, the calculated incident energy will be 6.4 cal/cm^2. For practical purpose, this small difference will not matter. However, the difference may be significant when the protective devices have inverse-time characteristics.

4.7.1 Tolerance of Calculated Incident Energy

The selected method may have tolerance about the calculated value of incident energy because of the random nature of arcs. Different calculation methods will generally yield different results. For IEEE 1584 equations use Table 4.10 to find a more conservative estimate that accounts for the randomness of arcs. This table is based on further analysis of test data accompanying IEEE Standard 1584, and is described in greater detail in Appendix A. The maximum tolerance should be added to the calculated incident energy. This procedure is suggested to minimize risk to workers since test data has been found to have greater incident energy than that yielded by IEEE 1584 formula.

Table 4.10: Tolerances for IEEE 1584 incident energy estimates.

Voltage/ Type of Enclosure	Maximum Tolerance (% of Calculated Incident Energy)	
	For adjusted arc current [a]	For IEEE 1584 arc current [b]
Low voltage arc in open air	66%	85%
Low voltage arc in box	63%	64%
Medium voltage arc in open air	93%	54%
Medium voltage arc in box	50%	52%

a. This is using the arc current after adjusting for random variations (upper and lower bounds); b. This is using the arc current from IEEE 1584 formula.

Table 4.10 shows incident energy tolerances for two different kinds of arc currents. It can be seen that there is not much difference in incident energy for arc in box whether the exact IEEE 1584 arc current or the arc currents adjusted for random variations is used. The choice of arcing current significantly affects only the arcing time, which in turn affects the incident energy. From the table it can be observed that the calculated incident energy is higher than maximum measured values for low voltage open air. However, for other cases, the estimate may be much lower than the maximum measured values.

Example

The incident energy for low voltage in box was calculated to be 10 cal/cm^2 using the IEEE 1584 equations. The adjusted arc current was used in this estimate. What is the maximum possible incident energy assuming random behavior of arcs?

From Table 4.10, the maximum tolerance is 63% of calculated value.

Maximum possible value of incident energy with +63% tolerance:

$$=10 * (100 + 63)/100 = 16.3 \text{ cal/cm}^2.$$

4.8 Step 8 – Determine Hazard/Risk Category

Hazard/risk category (HRC) is specified as a number representing the level of danger, which depends upon the incident energy. Category 0 represents little or no risk, whereas category 4 is the most dangerous. Table 4.11 provides the classification guide for the risk category number. Refer to NFPA 70E (2004) for classification and updates.

Table 4.11: Hazard/risk classification as per NFPA 70E (2004)

Category	Energy Level
0	< 2 cal/cm^2
1	5 cal/cm^2
2	8 cal/cm^2
3	25 cal/cm^2
4	40 cal/cm^2

Workers should prepare according to the risk category before commencing work or inspection near exposed, live conductors. Documentation and warning labels are also required. Although the incident energy itself may provide a more accurate picture of the risk, the scale of 0 to 4 for the risk category may convey more meaningful information to most workers. Employers are required to perform a complete hazard assessment prior to commencing any work near exposed conductors.

4.9 Step 9 – Determine Flash Protection Boundary

The flash protection boundary is the distance at which persons exposed to arc flash, without appropriate PPE, will obtain second degree burns that are curable. The flash protection boundary is a function of the arc flash incident energy. The higher the arc flash energy, the farther away the boundary will be. Calculate the flash protection boundary using the equation prescribed by the standard being followed. Use the highest incident energy calculated in step 7, after accounting for all the system connections and variations due to randomness of arcs. Use the equation (4.2) to determine the flash protection boundary. This is applicable for both IEEE Std 1584 and proposed NFPA 70E (2004).

$$D_B = D\left(\frac{E}{E_B}\right)^{\frac{1}{x}}$$

where,

D_B = distance of the boundary from the arcing point (see note)

D = working distance (see note)

E = maximum incident energy at working distance in cal/cm^2

E_B = incident energy at boundary, usually 1.2 cal/cm^2 for arcing time > 0.1s.

x = distance exponent factor (see Table 4.12)

Note: Distances D_B and D must both be in the same units. They can be expressed in inches or mm.

Table 4.12: Distance exponent "x"

Enclosure Type	IEEE 1584	NFPA 70E – 2000	NFPA 70E – 2003
Open air (0 – 0.6 kV)	2	1.9593	
Open air (> 0.6 kV)	2	2	2
Switchgear	1.473		
MCC and Panels	1.641		
Cable	2		
Box (0 – 0.6 kV)		1.4738	
Box (< 1 kV)			1.6
Box (> 5 kV)			0.77

Example

The incident energy for a low voltage switchgear at a working distance of 18 inches was found to be 25 cal/cm^2 using the proposed NFPA 70E (2004) method. What is the flash protection boundary for arcing time greater than 0.1s?

Flash protection boundary is:

$D_B = 18 * (25 / 1.2)^{1/1.6} = 120$ inches.

4.10 Step 10 – Document The Arc Flash Hazard Assessment

The arc flash hazard assessment should be documented in detailed reports, one-line diagrams and on the equipment. Provide as much detail as possible. Documentation has the following advantages:

1. Easy for workers to access the necessary details and drawings. This is necessary for safety planning.
2. Compliance with OSHA and NFPA.
3. Easy to implement changes in assessment when power system changes are made or when the standards are revised.
4. In case of arc flash related injuries, investigation is facilitated by documents. Lack of assessment documents may result in penalty to the company.

EasyPower software provides a detailed data repository and self documents the required short circuit, protective device coordination, and arc flash analyses for all system modes of operation. A single source program to maintain compliance with the many aspects of NFPA-70E arc flash requirements can greatly simplify a safety program.

4.10.1 Documentation in Reports

The assessment report should include the following details:

1. Name of person performing the assessment.
2. Date of assessment.
3. All data collected and used in the assessment, including protective device settings.
4. Assumptions used in the absence of data.
5. Method of hazard assessment used – the standard and the revision year.

6. If software was used, the name of the software and the version.
7. The results – incident energy, hazard/risk category and flash protection boundary for every equipment.
8. If various modes of operation are possible, document assessment for each mode.

The assessment report should be available to all concerned persons. Some of these may be:

1. Safety coordinator.
2. Safety division/department.
3. Foremen and electricians.
4. Electrical engineer.
5. Affiliated contractors.

4.10.2 Documentation in One-Line Diagrams

Figure 4.4 shows an example EasyPower one-line diagram. This is the LV part of a substation showing the results of arc flash hazard assessment. The computation and drawing was performed by the commercial integrated software EasyPower®. Four circuit breakers are located in the same switchgear lineup. A person working on the switchgear should inspect the drawing for the arc flash incident energy levels and the hazard category on all the exposed conductor parts. In this example, the line side of the main breaker of the panel would produce the highest incident energy if arc flash were to occur. The arc energy released would depend on the upstream protective devices, relay R-TX-2 and breaker main breaker. Arrows should be placed to indicate the side of breaker (line side versus load side) for which arc flash values are noted in the diagram. This would provide the workers the knowledge of risk at each part of the panel.

The following steps are recommended for a practical documentation of arc flash data on one-line diagrams:

1. Place the arc flash hazard assessment results on every equipment that poses a risk.
2. Specify the flash protection boundary, also known as arc flash boundary (AFB).
3. Specify the incident energy at the estimated working distance in the standard unit, for example in calories per cm^2. Specify the estimated working distance as well. Workers should check whether the working distance will be maintained while working on live equipment. If closer working distances are required, then it may be necessary to revise the assessment to reflect true working condition. The closer the distance the more the incident energy, and higher the risk.

4. Specify the hazard risk category at the estimated working distance.

5. For breakers and fuses, specify the values for both the line side and the load side. Remember that a fault on the load side of the protective device would be interrupted by that device itself. However, should a fault occur at the line side of the protective device, then the fault would be interrupted by the upstream protective device. This would normally have higher incident energy because of longer tripping time. Therefore it is important to evaluate and document arc flash energies for the line side of protective device, and communicate this with workers.

6. Use arrows to provide a clear indication of the load side and line side on the equipment if the arc flash values are different.

7. In any equipment, if different parts have different incident energy values, the worst case should be highlighted or mentioned first in the list.

8. Mention the protective device that limits the incident energy. If that device is at some distance, provide information on its location. It is also suggested that the settings be documented.

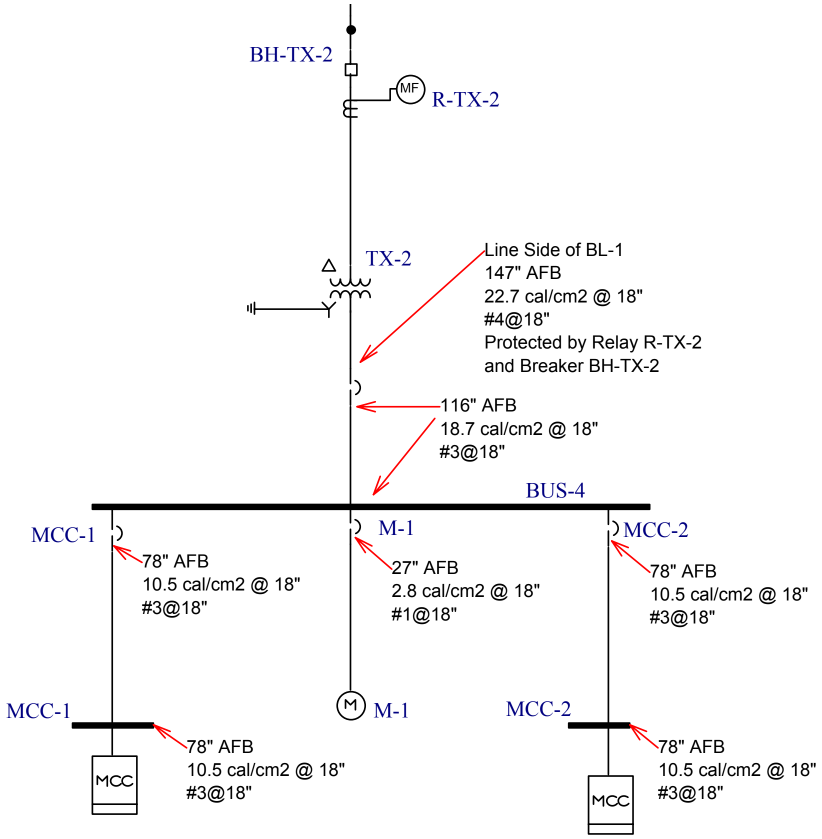


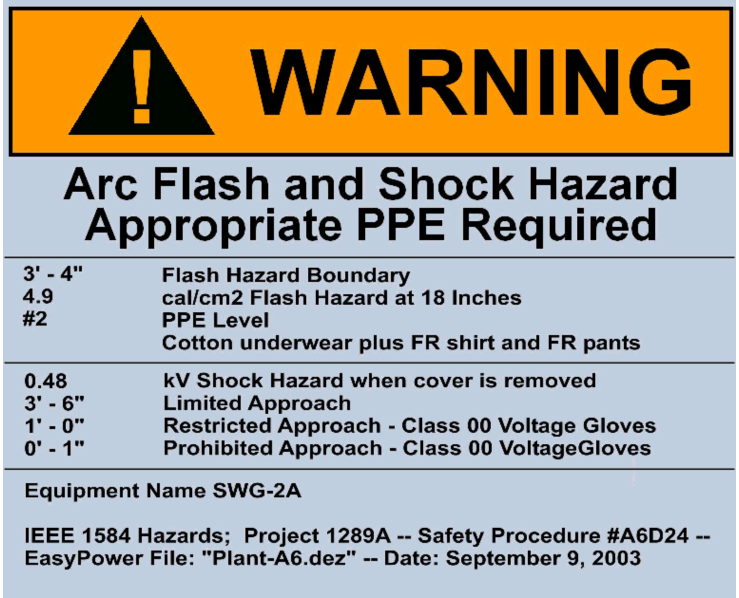
Figure 4.4: Example of arc flash assessment results on EasyPower one-line diagram

9. If there are various possible sources or interconnections, clearly mention in the one-line, which source is connected and/or which breaker is open or closed. Workers should first determine if the assumed condition in the diagram reflects the condition of the power system at the time of work. If the system conditions are different from those for which the assessment was performed, it is necessary to revise the evaluation.

4.10.3 Documentation on Equipment

Three types of documentation are recommended for arc flash hazard assessment results placed on the equipment:

1. Warning labels with arc flash values: Permanent stickers with a warning sign of adequate size. The label should be located in a place that is easily visible and readable from some distance. The flash protection boundary and its units, the incident energy at the estimated working distance and its corresponding risk category number must be clearly printed on the label. Additional information that is useful for future revisions are the date of assessment, the method of calculation, and the software name and version. Warning labels should also be placed just outside the flash protection boundary, so that workers may see it and prepare accordingly before they enter the hazardous area.



WARNING

Arc Flash and Shock Hazard
Appropriate PPE Required

3' - 4"	Flash Hazard Boundary
4.9	cal/cm2 Flash Hazard at 18 Inches
#2	PPE Level Cotton underwear plus FR shirt and FR pants
0.48	kV Shock Hazard when cover is removed
3' - 6"	Limited Approach
1' - 0"	Restricted Approach - Class 00 Voltage Gloves
0' - 1"	Prohibited Approach - Class 00 VoltageGloves

Equipment Name SWG-2A

IEEE 1584 Hazards; Project 1289A -- Safety Procedure #A6D24 --
EasyPower File: "Plant-A6.dez" -- Date: September 9, 2003

Figure 4.5: Example of arc flash warning label printed from EasyPower

2. Arc flash assessment results, in the form of a table and a small one-line diagram as described in the previous section, should be placed on the equipment at a spot which workers can easily access.

3. Large multi-section equipment may be labeled at various sections of the equipment. This facilitates hazard communications. Different sections may have

> different potential arc flash energies. If the same label is to be used on all sections, the highest possible incident energy must be specified. For example, a large transformer can have higher incident energy on the low voltage terminals than on the high voltage terminals. If the incident energy differences are high, different labels can be placed. This avoids workers having to wear extra PPE while working on terminals with less incident energy.

NEC, NFPA and IEEE do not specify the details of the information to be placed on arc flash warning labels. The labels may be more or less detailed than the one shown in Fig. 4.5. The label can be as simple as "Warning – Arc Flash Hazard". It is up to the facilities management to decide on detail desired. Arc flash calculations provide the maximum expected incident energies. There are a number of tasks that can be done around electrical equipment that does not require the maximum PPE to be worn. Referring to NFPA 70E-2000 Table 3.3.9-1 the task of reading meters with the door closed is classified as risk category 0 (zero). While NFPA lists racking in a breaker as risk category 3, if calculations give the maximum PPE as category 4, then risk category 4 should override NFPA risk class 3. Table 4.13 below is a summary of the NFPA task table.

Table 4.13: Summary of NFPA 70E Task and Risk Categories.

"Max. Calculated" is shown for the highest risk values used in the NFPA table. For actual risk category refer to NFPA tables.

Energized Equipment	Task	Risk Category
Panel board, MCC, LV switchgear	Breaker or switch operating with door/covers closed	0
	Breaker or switch operating with door/covers open	1
	Removing bolted covers	Max Calculated
	Racking in/out breakers	Max Calculated
	Reading meters with doors/panels closed	0
	Work on energized parts	Max Calculated
1-15 kV switchgear, motor starters	Breaker or switch operating with doors/covers closed	2
	Breaker or switch operating with door/covers open	Max Calculated
	Removing bolted covers	Max Calculated
	Racking in/out breakers	Max Calculated
	Reading meters with doors/panels closed	0
	Work on energized parts	Max Calculated

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[18] Conrad St. Pierre, *A Practical Guide to Short-Circuit Calculations*, Electrical Power Consultants, LLC, 2001.

[19] "IEEE Red Book" - *IEEE Recommended Practice for Electric Power Distribution for Industrial Plants*, ANSI/IEEE Std 141-1986, IEEE, 1986.

[20] William D. Stevenson, Jr., *Elements of Power System Analysis*, McGraw-Hill.

[21] NFPA 70E — May 2003 ROP, "Standard for Electrical Safety Requirements for Employee Workplaces", 2003 Edition, page 57.

5 Limiting Arc Exposure

Exposure to arc flash can be limited in three ways:

1. Avoiding arc flash accidents.
2. Reducing the level of arc energy released.
3. The proper use of personal protective equipment (PPE).

Arc flash accidents can be reduced by following procedures correctly, use of proper tools, good preventive maintenance, planning and coordination of work, as well as skill development and practical experience. Also important is the mental and physical conditions of the workers such that the dropping of tools, accidental touching, etc., are avoided. Taking care of the causes of arc flash is the principal strategy for avoiding exposure.

Accidents may occur despite precautions taken to avoid them. In such cases, it is always better if the incident energy is low and the worker is prepared for the worst by using appropriate PPE.

This chapter discusses the first two methods. PPE is discussed in chapter 6.

5.1 Avoiding Arc Flash Accidents

Arc flash can be avoided by understanding its causes and taking steps to minimize them. The various causes of arc flash discussed in Chapter 1 are summarized below. The mitigation measures are described in the following sections.

Summary of causes:

- Dust, impurities, and corrosion at contact surfaces producing heat, loosening contact and creating sparks.
- Sparks produced during racking of breakers, replacement of fuses, breakers/fuses closing into faulted lines.
- Failure of insulating materials.
- Snapping of leads at connections due to force – human, rodents or birds.
- Accidental touching and dropping of tools, nuts-bolts, or metal parts.

5.1.1 Preventive Maintenance

Preventive maintenance practices exist in most companies that require high reliability of supply or process continuity. Preventive maintenance also provides for a safer workplace.

Enhance maintenance procedures when carrying out inspections, preventive maintenance, or even breakdown maintenance by including procedures that address arc flash hazards. This reduces the overall cost of implementing an arc flash program. Include the following in maintenance practices.

1. Rodents and birds entering panels and switchgear are not uncommon. These can lead to short-circuits and eventually arc flash[22]. This risk can be prevented by closing all open areas of equipment with wire net or sealant so that rodents and birds cannot enter.

2. Use corrosion resistant terminals. Corrosion can lead to snapping of small wires, which in turn may create sparks and fumes when the tip of the wire hits the metal enclosure or another phase conductor. Check for corroded terminals and parts regularly if the electrical equipment is at a chemical plant or near a marine atmosphere. Electrical contact grease is typically used in joints and terminations. This will reduce corrosion.

3. Check for loose connections and overheated terminals. Impurities at the terminal connectors or dust can create additional contact resistance, heating the terminals. A sign of such case is discoloring of the nearby insulation. Heating of cable insulation can damage the insulation - another cause of flashover. Infra-red thermography can provide valuable data on poor connections and overheated electrical conductors or terminations.

4. Insulate exposed metal parts if possible. If heat dissipation is not really needed from the exposed metal part, and insulating it with some insulating tape, sleeve or cover is not a problem, then it is better to do so, rather than to let them be exposed. Insulation prevents arcing. For example, if a worker drops an uninsulated spanner, which touches bare bus bars of two phases, a short circuit will occur. However, this will not happen if the spanner or the bus bar is insulated.

5. Make sure relays and breakers operate properly. Failure could lead to prolonged exposure to arc flash, which could result in death. Routine inspection and testing of relays are carried out in companies with good maintenance practices. The frequency of relay tests may be a couple of years up to five years, depending upon the manufacturer's suggestions and the policy of the company.

6. Pitting of contacts takes place when fuses are operated. Replace contacts of the fuse holder or the fuse holder itself when excessive pitting is noticed.

7. When a fuse melts, make sure that the fault has cleared before installing a new fuse. Closing on to a fault can produce sparks that could lead to arc flash.

8. Wire harness for control and instrumentation should be kept in proper condition. It is not uncommon for these wires to become bundled and messy over time. Occurrence of arc blasts is possible while opening covers of such switchgear/MCC.

9. Check for excessive moisture or water/ice on insulating surfaces of equipment. This may cause flashover, specially on high voltage equipment.

5.1.2 Working on Live Equipment

1. It is ALWAYS preferable to work on de-energized equipment, regardless of the hazard risk category (HRC). When work on live equipment is unavoidable, then justification and written authorization is required. Incorporate this precautionary measure into the work procedure.

2. Use insulated tools. Dropping of tools can cause momentary faults, sparks and arcs. Insulated tools can help reduce this type of accident.

3. Torque control: When using spanners, wrenches or screwdrivers to fasten or loosen a connection use appropriate torque. When excessive force is required, it is not uncommon to lose control. Slipping of screws or nuts and bolts may cause accidental touching. Corroded or heated fasteners can be difficult to loosen. Work off line if loosening is difficult.

4. Do not use paint, cleaning chemicals, spray, etc., on live exposed metal parts. The fumes or spray may be conductive and it may reduce the insulting property of air and allow an arc to strike through. Spraying directly on live conductor can also provide a conducting path that will result in electric shock.

5.2 Reducing Incident Energy on Worker

The incident energy exposure can be reduced by system design or operating procedures. Given below are several ways to reduce the energy on an existing system.

1. Reduce the fault level
2. Reduce the exposure time
3. Remote operation
4. Remote racking

5.2.1 Reducing the Level of Fault

Fault level can be reduced in the following ways:

1. Change system configurations to reduce available fault current/smaller kVA transformers.
2. Current limiting fuses/breakers.
3. Current limiting reactors.

5.2.1.1 System Configuration

Reducing the fault level depends on the existing system configuration. Double-ended load centers with a normally closed tie (Figure 5.1) is a prime example where the fault level can be reduced by either opening the tie or one incoming breaker. The fault current will be reduced by approximately 50% and the incident fault energy will also be reduced, although not necessarily in the same proportion. If the bus has two sources or a source and a normally closed tie as shown in Figure 5.2, opening one of the sources (or tie) will reduce the fault level while maintenance is done on the equipment. *For both situations, the loading and relay setting should be checked to make sure that the opening of a breaker does not overload the other source.*

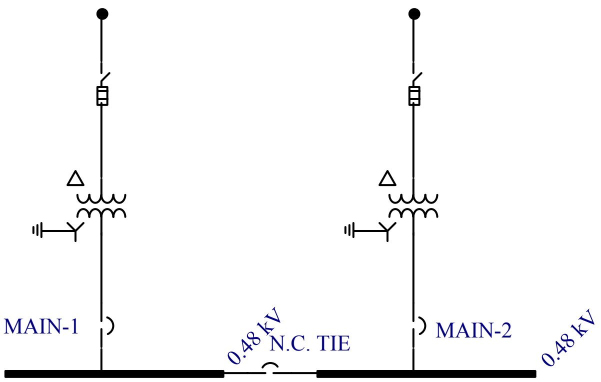

Figure 5.1: Double-End Load Center Configuration

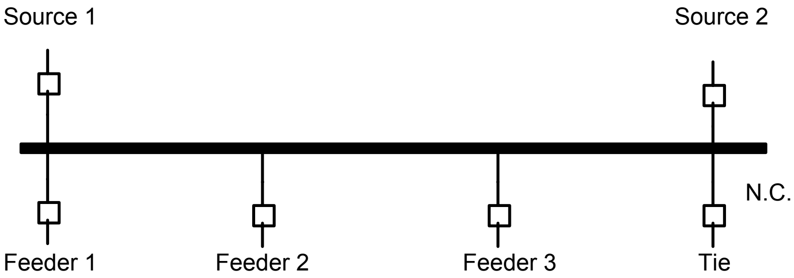

Figure 5.2: Dual Sources

5.2.1.2 Current Limiting Fuses/Breakers

Current limiting fuses/breakers introduce additional resistance within the fuse element while the fuse is melting. This limits the fault current. Fault currents within the current-limiting region of the fuse are cleared quickly, usually within half a cycle. Since the incident arc energy is proportional to arcing time, current limiting fuses/breakers limit the arc energy.

5.2.1.3 Current Limiting Reactors

Current limiting reactors introduce additional impedance in the system and are used to limit the fault current. This not only reduces damages caused by faults but also allows the use of circuit breakers with smaller duty. Limiting the fault current can also increase the fault clearing time if the fault current happens to lie in the inverse time delay characteristics of the protective relays. Therefore, protective device coordination analysis is also required when selecting current limiting reactors.

5.2.2 Reducing Arcing Time

Arcing time can be reduced in several ways. Some changes in the system of settings may be required for this purpose. Some strategies outlined in this section are as follows.

1. Reducing safety margin for relay and breaker operation with improved solid state trip devices.
2. Bus differential protection to combine selectivity with instantaneous operation.
3. Temporary instantaneous trip setting during work.
4. Retrofit time-overcurrent relays with delayed instantaneous trip device if needed.
5. Optical sensor to trip breaker in the event of arc flash.
6. Use smaller fuse size if possible; smaller current limiting fuses may clear faster. Fuses will generally be much faster than breakers at high fault currents – even ignoring current-limiting effect this can greatly reduce arc energy.
7. Protective device coordination study to balance improving reliability with reducing arc flash hazard.

5.2.2.1 Reducing Breaker Response Time Safety Margin

Incident energy increases with time and fault current. Reducing either or both lowers the incident energy due to an arcing fault. Faster acting relays and trip devices can reduce the arcing time to some degree. In this regard, a protective relaying review may be performed in order to see if they can be lowered in time and pick-up. If a protective device study was done a number of years ago when electro-mechanical relays were the norm, 0.4 second margin between relay was common. This allowed for breaker operating time, over-travel, and a time safety margin. Breaker times are now commonly 5 cycles rather than the 8 cycles of older breakers. Microprocessor relays are now being used, for which the over travel has essentially been eliminated. The repeatability of the microprocessor relay is better than that of the electro-mechanical relay. Therefore, the safety margin can be reduced. The end result is that the relay coordination margins can be 0.2 to 0.25 seconds instead of 0.4 seconds. This is a 25%-35% reduction in arc energy exposure.

5.2.2.2 Bus Differential Protection

A major improvement in clearing time would result if an instantaneous relay could be used instead of time-delay relays. Feeders on both low and high voltage systems are likely to have instantaneous settings and therefore, would limit the arc exposure time. However, a fault on the main bus is often cleared by time-delay relays for selectivity reasons. In high voltage systems, using bus-differential relaying reduces the arc exposure time to a minimum. The arc energy exposure can easily be 5 to 30 times less than that of the delayed clearing time.

5.2.2.3 Temporary Instantaneous Setting

Replacement low-voltage trip devices from Satin, Joslyn, Carriere and possibly others, have an instantaneous unit that that can be turned on or off. This has a high advantage on the incoming main breakers. In many cases, for coordination purposes, the instantaneous is not set and fault clearing times are delayed for selectivity. A main breaker clearing time with a load center tie and feeder breakers could easily have a short time setting of 0.4 seconds. If the instantaneous trip could easily be enabled while work is being preformed lower fault currents could be tripped and cleared in less than 0.04 seconds. The incident energy exposure is reduced to 10% of its previous value. During maintenance, full selectivity of devices may be lost, but the reduction in arc flash exposure makes it worthwhile. The temporary instantaneous setting should be disabled and the original protective setting should be restored for normal operations after the work is completed. Separate instantaneous trip devices with increased protection can also be added to shunt trip or transfer trip for added protection during work procedures.

5.2.2.4 Retrofit Instantaneous Trip Device

If bus-differential relaying is not possible then the main relay can be retrofitted with an instantaneous protective device and a safety control switch. As shown in Figure 5.3, a selector switch can be used to place the instantaneous in service when maintenance is being done. Normally the instantaneous protection would not be functional due to the open contact of the selector switch. However, when work is being done on the energized equipment, the safety switch would be turned ‘ON’ and thereby limiting the arc exposure time to the worker should an arcing fault accident occur. The delayed fault clearing time could be in the range of 0.4 to 2.0 seconds on the main breaker instead of 0.1 second. The delayed trip time greatly increases the arc exposure time and amount of radiation a worker would receive if the arc blast pressure were not enough to propel the worker away from the fault. The time-selective protection system would be eliminated for duration of the work in the interest of safety. The selector switch should be lockable in the maintenance position. Ideally, positive feedback from the trip unit would be used for an indicating light associated with the switch to confirm the setting change was in effect.

Many medium voltage multifunction relays have provisions for different protective settings for various operating modes. For example, one group of setting is used for normal operation; a second group of settings is used for emergency mode. Another group setting could be for maintenance where the tripping and current pick-up settings are reduced and set as instantaneous. Again, these temporary settings could result in the loss of selectivity with a gain in human protection.

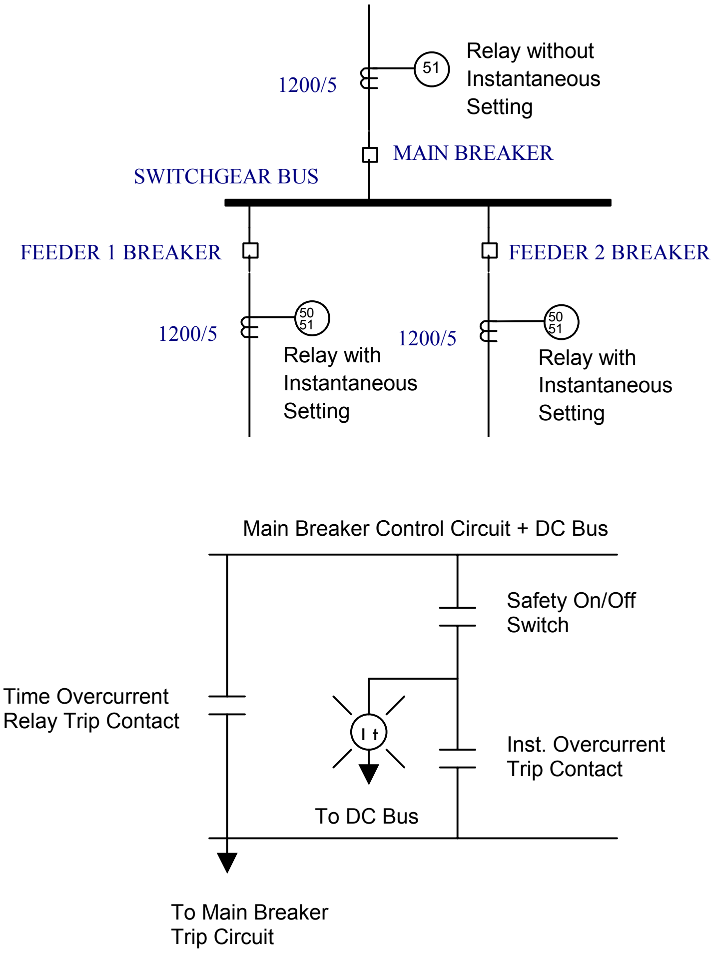

Figure 5.3: Schematic to Control Arc Exposure on Relayed Breakers

Figure 5.4 shows the possible time current curves of a load center. The relay operating times for both the 100% and 85% fault currents are shown in Table 5.1. If an instantaneous trip were set on the main breaker at 3 times the long time pick-up, a fault on the bus would be cleared in approximately 0.05 seconds with the incident energy being approximately 1.0 cal/cm^2 instead of the 4.4 and 5.3 cal/cm^2 as shown in Table 1.

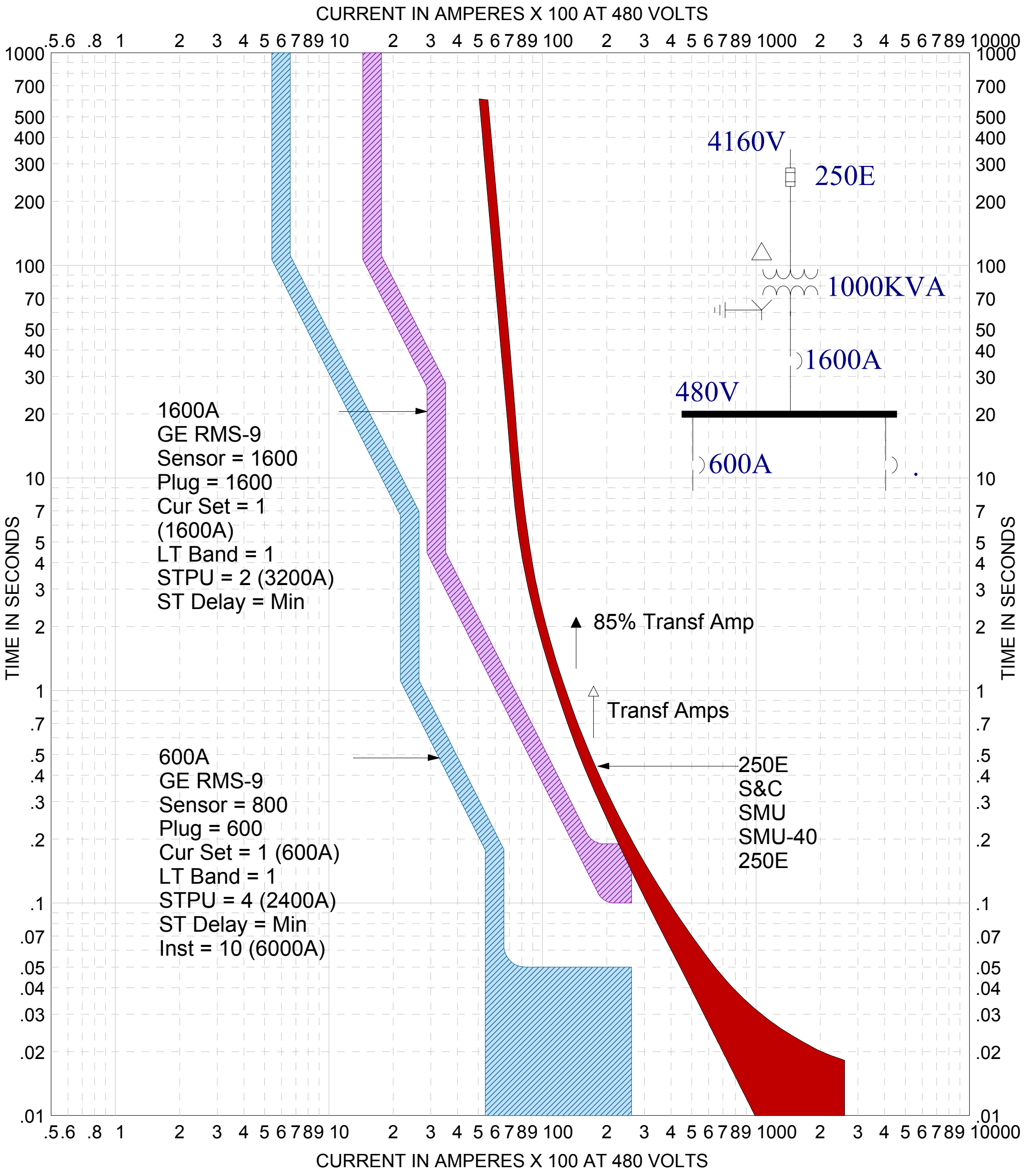

Figure 5.4: Load center time current curves

Table 5.1: Clearing times and Incident Energy for a 1000-kVA load Center

100% Calculated Fault Current			
Clearing Device	kA at 480V	Operating Time	Cal/cm^2
Main	17.3	0.21	4.4
Feeder	23.2	0.05	1.4
Fuse	17.3	0.42	8.8
85% Calculated Fault Current			
Clearing Device	kA at 480V	Operating Time	Cal/cm^2
Main	14.3	0.30	5.3
Feeder	19.7	0.05	1.2
Fuse	14.3	1.0	17.6

5.2.2.5 Optical Sensor Trip

ABB has an “Arc Guard System TVOC” which has a light sensor to detect an electrical arc flash. It can be activated by light only or light input supervised with an overcurrent detector. Its output is used to trip a breaker and has an operating time of 10 milliseconds. If auxiliary tripping relays are needed to trip several breakers at once, then the auxiliary relay time needs to be factored in to the total clearing time. Placement of the detector and its control wiring could be critical. These should be placed close enough to detect an arc but not be damaged by the initial arc rendering the protection useless.

5.2.2.6 Fuse Size and Speed

Fuse sizes could be reviewed to determine if smaller fuses can be used. Smaller fuses reduce the exposure time. This can be significant when the arcing current or 85% of arcing current is not in the current limiting range of the fuse. Referring to Fig. 4, while the 250E fuse satisfies the NEC, a smaller 175E fuse would also satisfy the NEC. The smaller fuse would operate quicker and reduce the arc energy exposure, should the main breaker fail or should a fault occur between the transformer and main breaker. Speed of fuses are selected to coordinate with other protective devices and the over-current capacity of equipment being protected. A disadvantage of lowering the fuse size is the possibility of fuses not being able to discern a temporary fault from a persistent fault. A temporary fault, such as those found in overhead distribution lines, exist for a few cycles. Some fuses are selected such that they allow temporary faults but interrupt persistent faults. If the fuse size is lowered with the intent of reducing arc flash hazard, then the fuse may melt upon temporary faults, thus reducing the reliability of supply.

Operating fuses can create sparks and may lead to arc flash accidents. Fuses should not be temporarily lowered just for the purpose of working on live line.

5.2.2.7 Temporary Relay Settings

It has to be recognized that the act of changing protective settings on electrical equipment could place the workman in jeopardy. While the protective devices are at low voltage a spontaneous fault could occur in the switchgear at this time. Most relay resetting are done with a keypad and not with screwdrivers, the chance of a fault at this time is extremely low.

Review protective devices to see if they can be lowered in time and pick-up. Due to reliability reasons using temporary settings is usually not a preferred practice. Tampering with settings of protective devices is prohibited. However, if a qualified person, for instance the engineer, can temporarily provide the alternate settings during the work period, then the incident energy can be reduced by lowering the trip time.

5.2.2.8 Protective Device Coordination Study

A protective device coordination study is carried out to improve system reliability. This study can be done on a regular basis, perhaps every few years or whenever there are changes in the system. Such studies could also include as one of its goals, the reduction of incident energy from arc flash. The engineer performing the study should simultaneously evaluate the arc flash hazard, and seek to minimize the hazard by keeping the arcing time as low as possible.

5.2.3 Remote Operation and Racking

Placing distance between electrical conductors and the worker greatly reduces the arc incident energy and the arc blast force. The reduction is not linear. For example, a worker twice as far as another worker from the arc will receive 25 to 50% less energy than the closer worker. New high voltage equipment can be ordered with the breaker “Open” and “Close” switches remote from the breaker unit. These could be placed on a non-breaker unit, in a separate control panel, or in a remote room. Older switchgears can be retrofitted with remote control switches.

New microprocessor-relays can be programmed to supervise manually the closing of a breaker using a “punch and run” time, that allows the operator 3 to 10 seconds after initiating a “close” to evacuate the vicinity before the breaker is actually closed.

While fully electrically operated low voltage breakers are available they are not the norm. Low voltage breakers that are fully electrically operated would be useful for remotely located control switches. As the insurance companies and OSHA begin to demand better arc flash safety measures, fully operated electrically low voltage breakers may become more common.

Placing a breaker in or out of a switchgear cubicle exposes the worker to a possible arc flash hazard. While the breaker’s mechanical indicator may note that the breaker is fully open, there have been cases where it was not open due to contact or indicator failure. Placing a breaker in a cubicle when it is not in the fully open condition can result in an arc. While the distance from live conductors to the worker can be over an arm's length away, the arc gases can flow around the breaker and result in burns. For breakers that are being withdrawn from a cubicle, check the following three items before withdrawal – the mechanical indicator shows the breaker open, the breaker indicating lights show the breaker open, and the ammeter shows all three phases with zero current.

Using a longer operating arm to rack in the breaker can provide the needed distance. Remotely controlled breaker racking mechanisms are available for some breakers as part of the new equipment or as retrofits.

Placing a barrier such as a closed door or a portable shield as shown in Figure 5.7 would limit the arc flash exposure. While the shield as shown would help remove direct arc burns, radiant energy burns are still possible and PPE is still needed. With a shield the surface area is increased, therefore making the force exerted by the arc blast more of a concern.

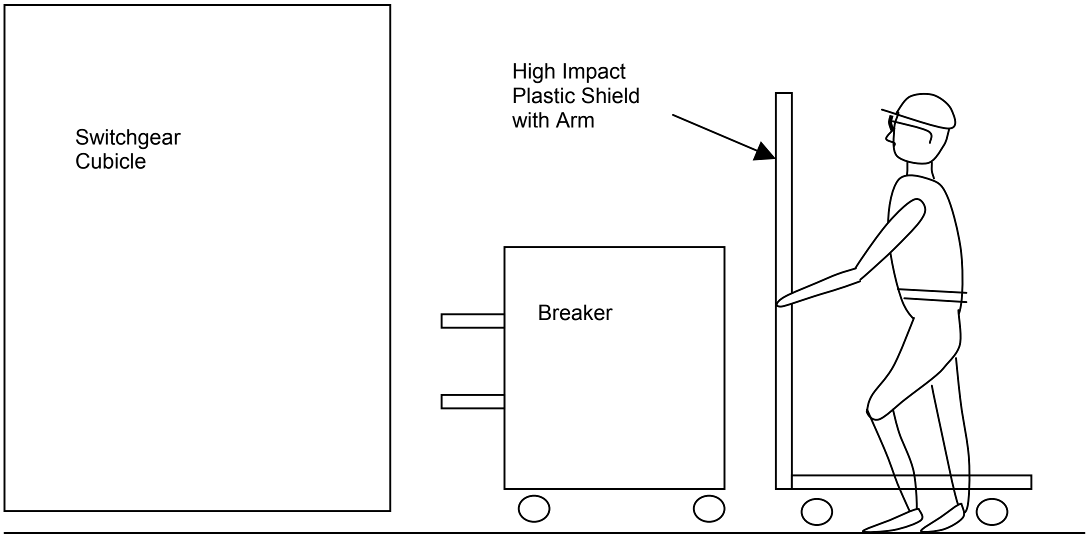

Figure 5.7: Using a shield when racking in a circuit breaker

Although not a way to reduce arc incident energy, it is good practice to use the buddy system. In the event an incident should happen, help can be summoned quickly if a second person is around.

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[22] Some of the authors inspected a substation of an irrigation pump in Eastern Oregon in January, 2003. The switchgear had been damaged by arc-flash. It was observed that both rodents and birds had inhabited the MCC/panel. The leads to the primary side of the potential transformer had snapped and touched the metal enclosure creating sparks. The arc traveled from the mains side of the 4.16 kV copper bus bar towards the remote end and melted the bus bar butts and the steel sheet cover. The recloser at the utility substation tripped several times.

6 Personal Protective Equipment

Personal protective equipment (PPE) is required by various standards such as NFPA and OSHA to protect workers from hazards in the workplace. The type of PPE required depends upon the hazard that has been assessed and documented. In the case of arc flash hazard, the main purpose of PPE is to reduce burn injury to worker to a level of curable burn.

Personal protective equipment may, or may not, provide adequate protection in the case of arc flash exposure. It is important that workers understand the use, care and limitations. Employers should ensure that the workers have adequate understanding and training on the use of PPE. Workers must not treat PPE as a substitute for common sense and safe work practices.

The most common and industry accepted PPE that protects the body is flame resistant (FR) clothing. Flame resistance is the characteristic of a cloth that causes it not to burn in air. This is achieved by treating the cloth fiber such as cotton with flame retardant chemicals. Synthetic FR clothing is also widely used.

Purpose of flame resistant fabric:

1. Resistance to flame and self-extinguishing.

2. Provides thermal insulation to the body from heat radiation.

6.1 Standards on Personal Protective Equipment

Some of the standards on personal protective equipment are briefly outlined in the following sections. Note that these are only some of the main standards and not all of them. It is important that PPE selection and training be carried out in the guidance of an experienced safety professional that is aware of all the applicable standards.

6.1.1 OSHA

Table 6.1: Various OSHA standards on personal protective equipment

1910.132(a), 1926.95(a)	Application What?: Protection shall be provided for eyes, face, head and extremities. When?: Whenever it is necessary by reason of hazards of processes or environment, chemical hazards, radiological hazards, or mechanical irritants in a manner capable of causing injury or impairment in the function of any part of the body through absorption, inhalation or physical contact. How?: Protective clothing, respiratory devices, protective shields and barriers.
1910.132(b), 1926.95(b)	Employee-owned equipment: The owner shall be responsible to assure its adequacy, including proper maintenance and sanitation.
1910.132(c), 1926.95(c)	Design: PPE shall be of safe design and construction.
1910.132(d)	Hazard assessment and equipment selection: (1) Employer shall assess the workplace to determine if hazards are present or likely to be present, which necessitate the use of PPE. If hazard exists or may arise, the employer shall: • Select, and have each affected employee use the appropriate PPE as per the hazard assessment. • Communicate selection decisions to each affected employee. • Select PPE that properly fits each affected employee. (2) Documentation of hazard assessment: • written certification, • identification of workplace evaluated, • person certifying the evaluation, • date(s) of hazard assessment.
1910.132(e)	Defective and damaged equipment shall not be used.
1910.132(f)	Training: When PPE is necessary, what PPE is necessary, how to properly use the PPE, and how to care, maintain and dispose the PPE. Each affected employee shall demonstrate an understanding of the training. Retraining may be required depending upon changes in workplace or PPE. The required training shall be certified and documented.
1926.100(a)	Employees working in areas where there is a possible danger of head injury from impact, or from falling or flying objects, or from electrical shock and burns, shall be protected by protective helmets.
1926.100(b)	Helmets for the protection of employees against impact and penetration of falling and flying objects shall meet the specifications contained in American National Standards Institute, Z89.1-1969, Safety Requirements for Industrial Head Protection.
1926.100(c)	Helmets for the head protection of employees exposed to high voltage electrical shock and burns shall meet the specifications contained in American National Standards Institute, Z89.2-1971.

6.1.2 NFPA 70E

Proposed NFPA 70E (2003 ROP) Article 220.2(B)(3): *Protective Clothing and Personal Protective Equipment for Application with a Flash Hazard Analysis*. The employer is required to carry out an evaluation of arc flash hazard, and document the incident energy, in calories per square centimeter, that a worker may be exposed to arc heat on the face and chest. The worker is required to wear FR clothing and PPE adequate to protect the body from injury from the calculated exposure to heat from arc.

Proposed NFPA 70E (2003 ROP) Article 220.6: Workers must use adequate PPE on various parts of the body suitable for the work to be performed. Various standard pertaining to care, testing and use of PPE are outlined in this section. Please refer to the standards for details. Some of the main requirements are as follows:

- All employees within the flash protection boundary are required to wear PPE.
- PPE should cover all other clothing that can be ignited.
- PPE should not restrict visibility and movement.
- Non-conductive protective headwear is required when in contact with live parts or when there is a possibility of electrical explosion. The face, neck and chin must be protected.
- Eye protection is required.
- FR clothing should be worn when the estimated incident energy at the body may cause a second degree (curable) burn (1.2 cal/cm^2 for arc time greater than 0.1 second or 1.5 cal/cm^2 for arc time 0.1 seconds or less).
- Leather or FR gloves are required to protect the hand.
- If incident energy exceeds 4 cal/cm^2, heavy duty boots are required to protect the feet.

6.1.3 ASTM

American Society for Testing and Materials (ASTM) develops standards that specify the quality of various materials including safety materials such as PPE. The following standards are applicable to arc flash hazard protection equipment.

ASTM F1506: *Standard Performance Specification for Textile Materials for Wearing Apparel for Use by Electrical Workers Exposed to Momentary Arc and Related Thermal Hazards*, 2002. This standard specifies the requirements for flame resistant clothing. There are three basic requirements in this standard:

a) The fabric under test must self-extinguish in less than 2 seconds after the ignition source has been removed.

b) Char length for ASTM Test Method D6413 must be less than 6 inches. A fabric specimen of 12 inch length is hung vertically in an enclosed space and the bottom is exposed to a methane flame for 12 seconds. The length of the fabric destroyed by flame is the char length. This test is also known as the standard vertical flame test.

c) Apart from meeting these pass/fail tests, the fabric is also tested for the Arc Thermal Performance Value (ATPV) as per ASTMF1959. Manufacturers are required to report the test results to the end users of the material as an Arc rating on a garment label.

Any fabric that meets the ASTM F1506 complies with OSHA 1910.269. This performance specification does not cover coated fabrics commonly used in rainwear.

ASTM F1959: *Standard Test Method for Determining Arc Thermal Performance (Value) of Textile Materials for Clothing by Electric Arc and Related Thermal Hazards*. This test determines how much incident energy is blocked by the fabric before the wearer of the protective clothing may get a second degree burn. The amount of energy blocked is reported as Arc Thermal Heat Performance Value (ATPV). If the fabric breaks open the value is also called the Breakopen Energy Threshold.

ASTM F1891: *Standard Specification for Arc and Flame Resistant Rainwear*. See ASTM F1506 for the three basic requirements.

Any fabric that meets the ASTM F1506 complies with OSHA 1910.269.

ASTM F1449: *Standard Guide for Care and Maintenance of Flame, Thermally and Arc Resistant Clothing*. This guide provides recommendations for the care and maintenance of clothing that is flame, thermal and arc resistant. The standard focuses on the industrial laundering process and also identifies inspection criteria that are significant to the performance of clothing.

6.2 Fire Resistant Clothing

6.2.1 Factors Affecting Protection Level From Arc

Material: *Untreated natural fabrics* may continue to burn until the fabric is totally consumed. *Synthetic fabrics that are not flame resistant* will burn with melting and dripping and may cause severe burns to the skin. *Flame resistant fabric* will be charred by arc flash heat, but will not continue to burn after the arcing ceases. The burning of garments may cause greater injury to the skin than direct exposure to the heat from the arc.

Weight: The weight of FR fabric is specified in weight per unit area (ounces/square yard or g/m^2). Higher weights provide more thermal insulation.

Layers: Multiple layers of clothing retain air space between the layers, thus providing greater thermal insulation than a single layer. Single, thick clothing provide less physical comfort, whereas multiple layers allow flexibility. Comfort and flexibility are important in avoiding accidents while working on live equipment.

6.2.2 Care of FR Clothing

Laundering: Obtain complete instructions on care of FR clothing from the manufacturer. Some cleaning chemicals such as chlorine bleach may affect the finish, reduce the fabric strength and remove the color of the cloth. Some manufacturers claim that the flame resistance property is not affected by the bleach[23]. Follow laundering instructions provided by the manufacturer.

Contamination: Grease, oil, or other flammable materials catch fire easily and will continue to burn even after the arc ceases. Therefore FR clothing contaminated with these substances should not be used. Care should be taken at work to avoid contaminating FR clothing from such materials.

Storage: The clothing should be stored in a safe condition so that it is reliable.

6.2.3 Useful Life of PPE

The useful life of a PPE may depend on various factors such as the material with which it is made, the severity of work activity and the abrasion resistance characteristics of the PPE. Obtain information from the manufacturer to determine the useful life.

The useful life of a PPE is normally stated following some assumptions. It must be remembered that if the actual conditions are different from these assumptions, then the stated expected life may not be applicable. It is best if the PPE user obtains from the manufacturer, the useful life of the PPE for the intended use.

Table 6.2: Examples of expected useful life of FR Clothing

Fabric	Industrial Launderings	Expected Service Life (months)
INDURA 100% Cotton[24]	36-50*	18-24#
INDURA Ultra Soft 88% Cotton 12% High Tenacity Nylon	60-80*	28-38#

*The manufacturer clearly states that the launderings cited in the table are based on market experience for these types of fabrics and relate to average expected wear life. These estimates do not take into account work activities leading to extreme wear and exposure to thermal sources of high heat and long duration.

#The expected service life is estimated with the assumption that clothing is industrially laundered every other week.

The useful life for any PPE suggested by a manufacturer may be applicable for normal wear and tear. OSHA requires the worker to carry out a visual inspection of the PPE prior to its use. The PPE should not be used if it appears to have deteriorated, even though the PPE may not have reached its expected useful life.

6.2.4 Selection of PPE

PPE should be selected according to the needs of the worker and the nature of work performed. Some of the factors are discussed below.

Comfort: It is vital that the worker is not uncomfortable. Otherwise there could be a risk of accidents occurring. Comfort is important both physically and mentally. PPE for high incident energy (hazard/risk category #4 or greater) may have thick and heavy clothing, headgear and gloves. The comfort level may differ from one individual to another. It is necessary to ensure that each worker feels as comfortable as possible, wearing the PPE. Different workers may find different materials more comfortable than others. It may be beneficial to let the workers try out the PPE to make sure that it is satisfactory in terms of comfort. It may take some time before a worker adjusts to new PPE. Therefore, it is recommended that the worker practice wearing the PPE before working on live exposed equipment. This also ensures that the PPE does not interfere with the task.

Fit: A loose fitting PPE provides more thermal insulation through the air trapped inside. However, it should not be too tight or too loose so as to interfere with the task.

Layers: As mentioned in the previous section, multiple layers provide additional air insulation and greater degree of protection. Multi-layer FR clothing is also more comfortable than a single layer of thick and heavy clothing.

Materials: Choice of fabric material can affect both comfort and weight. There are different types of treated cotton and synthetic fabric available from various manufacturers. For multi-layer clothing, the workers may choose to have untreated flammable fabric such as cotton or wool for inner garments at lower incident energies.

Abrasion Resistance: Some FR clothing is available with high abrasion resistance quality. Employees who do heavy duty work should use this kind of PPE. Clothing without such quality can be easily damaged, and may fail to adequately protect the worker from an arc flash.

6.2.5 Types of FR Clothing

(a) (b) (c)

Figure 6.1: FR clothing (a) jacket; (b) bib overall; (c) complete flash suit (courtesy W.H. Salisbury & Co.)

Vest/Undergarment: These can be worn underneath shirts, jackets or pants. They provide an extra layer of protection. Multi-layered clothing is more flexible, easy to work with and has trapped air to provide additional thermal insulation. Combination of vest/undergarment with a shirt increases the total arc rating.

Shirt/Pant: FR shirts and pants can be used for incident energy of 4.0 cal/cm^2 or below. These can be multi-layered for higher arc rating.

Bib Overall: Bib overalls worn with a shirt provides higher protection to the chest area than a shirt worn with a pant. See Figure 6.1 (b).

Coverall: Coveralls are equivalent to shirt and pant.

Jacket: These are usually multi-layered and are like multi-layered shirts. See Figure 6.1 (a).

Hood: The hood is part of the headgear, has face protection and has FR fabric covering the head, ears, neck and shoulders.

6.3 Other PPE

Figure 6.2: Headgears (courtesy W.H. Salisbury & Co.)

Headgear: The headgear consists of a non-conductive helmet and hood that covers the head, ears, neck and shoulders. It also has a face shield and chin cover. See Figure 6.2. The face shield absorbs some of the incident energy. However, it should not impair visibility. Safety glasses should be worn underneath the headgear.

Gloves: Gloves provide insulation from both electricity and heat. A combination of rubber (worn inside) and leather (worn outside) materials is typically used. The gloves should be long enough to cover the sleeves.

Table 8.1 - Voltage Classification of Gloves

Glove Voltage Classification	Maximum Working Voltage	Proof Test kV
Class 00	500	2.5
Class 0	1,000	5.0
Class 1	7,500	10
Class 2	17,000	20
Class 3	26,500	30
Class 4	36,000	40

Figure 6.3: Gloves (rubber and leather) and boots (courtesy W.H. Salisbury & Co.)

Boots: Heavy duty shoes[25] or boots should be worn where incident energies are higher than 4 cal/cm^2.

Hot Stick: Hot sticks are use to operate fuses and switches. These provide insulation from the high voltage parts. They also allow the worker to maintain increased working distance, so that the incident energy is less.

Arc Suppression Blanket: This provides a barrier from arc flash.

Ear Muffs: Arc blast can cause severe ear injuries. Ear muffs should be worn to provide sound insulation and reduce the impact.

Mechanical Barriers: As mentioned in the previous chapter, mechanical barriers can provide protection from thermal radiation as well as from blast pressure. They can be used for racking breakers, but are not suitable for most other work.

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[23] Indura, Nomex.

[24] Westex Inc., Product Literature: *INDURA Ultra-Soft Flame Resistance Fabrics*, September 2002.

[25] Proposed NFPA 70E- May 2003 ROP, page 45.

7 Arc Flash Hazard Program

7.1 Electrical Safety Program

Ray Jones[26], *et al*, describe in their book, *Electrical Safety in the Workplace*: “A safety program is an organized effort to reduce injuries. Any electrical safety program should be a subset of an overall site safety program.” For these programs to be effective, it is necessary for safety professionals and technical professionals to collaborate. Much of this chapter follows their book. Additional discussions are provided so that arc flash hazard related topics will be addressed in greater detail.

7.2 Training

Training must provide people the knowledge and understanding of the existence, nature, causes and methods to prevent electrical hazards. The training should also include the selection and use of appropriate PPE.

As part of regular electrical safety training it would be beneficial to include the following arc flash related topics. Special arc flash hazard sessions are recommended for introductory training exercises.

7.2.1 Awareness

b. Existence of the arc flash hazard: Arc flash accidents are not as common as electrical shock. Therefore, many are not aware of the hazard. Trainers and managers need to place adequate effort in trying to convince the workers that arc flash hazard is indeed something to take seriously.

c. Causes: Knowing the causes helps immensely in avoiding the hazard.

d. Nature of arcs: This can relate to the degree of potential damage and possible ways to reduce hazard.

e. Possible injuries/damage: Findings and statistics from various studies and reported incidents reveal the gravity of the hazard.

f. Historical cases: Literature on arc flash incidents can be found in many documents. Review of these cases is illuminating and convincing and is likely to influence workers to consider taking measures to avoid arc flash injuries.

Chapter 1 provides a brief introduction on the first four topics. IEEE Standard 1584 and numerous papers on electrical safety provide examples of historical cases. The awareness training should not be limited to electrical worker only. Since it is the responsibility of the employer to provide training, PPE and other means of minimizing the hazard for the electrical worker, managers or the responsible persons should be included in the training.

7.2.2 Standards and Codes

Standards and codes not only provide information on what employers and workers are required to do, but also suggest solutions/methodology. In following the standards and codes, "compliance" should not be the only motive. The following provide the standards and codes. Some of the related topics are summarized in Chapters 3 and 6.

a. NFPA 70E
b. OSHA

7.2.3 Understanding of Arc Flash Quantities

Workers are expected to read signs/labels, drawings and tables to understand the degree of hazard a worker may be exposed to. Some of these pertain to the rating of the required PPE or protection boundaries. It is important that workers understand the following quantities and their units. An understanding of the physical significance of these quantities is helpful.

a. Flash protection boundary
b. Working distance
c. Incident energy
d. Hazard/risk category
e. ATPV of PPE.

7.2.4 PPE

Chapter 6 provides some information on PPE. More detailed information can be obtained from PPE vendors. Use of PPE can restrict visibility and movement, cause discomfort, and slow down the work. Practice is recommended with PPE before working on energized equipment. The following topics should be included in training on PPE.

a. Selection of PPE
b. Information/Labels on PPE
c. Training with new PPE
d. Inspection, care & maintenance
e. Useful life & disposal
f. Documentation of use and maintenance of PPE
g. Limitations and potential risks using PPE
h. Limitation of PPE & degree of protection provided

7.2.5 Reading and Following Warning Signs and Labels

Warning signs and labels are part of any safety program. When new labels or signs are placed, workers need to be able to understand the meaning, and follow instructions precisely.

7.2.6 Methods to Reduce Risk While Working on Live Exposed Parts

Chapter 5 provides some methods of reducing risk. Many procedures can be developed in-house to suit the system and type of work the workers may need to perform. Practice on de-energized systems will greatly augment the knowledge, and make the work safer. New procedures are introduced during the initial stages of the arc flash program with the help of experienced workers and safety professionals. Formulation of new procedures as an ongoing process is expected. Clear communication between different workers who are part of procedure formulation expedites resolving safety issues.

7.2.7 Arc Flash Hazard Assessment

Arc flash hazard assessment should be carried out by skilled and experienced professionals. In-house engineers can be provided with the necessary training. Chapter 4 provides practical steps to performing an assessment. It is necessary for the engineer to apply short circuit analysis and protective device coordination, along with arc flash energy calculations. Engineers should be aware of the limitations of the standards or methods they employ and also have a good understanding of how these limitations can be overcome. It should be noted that only some of the practical issues are discussed in this book because of time limitations. AFH programs, calculations, and procedures are new to the industry and changing at a rapid pace. Participation in seminars and forums, reading of publications, and peer discussions are recommended.

7.2.8 Documentation

Documentation is described in greater detail later in this chapter. Workers should be able to document any changes performed in the power system, update the single-line diagrams, and also make note of any discrepancy between the actual equipment/system interconnection and the single-line diagrams. Workers should also understand the consequences of the drawings not truly reflecting the actual system condition. Illustrations can be provided as to how such circumstances may lead to selection of wrong PPE or wrong procedures.

7.3 Safety Audit

Safety audits are performed on a regular basis to evaluate various aspects of a safety program. Audit intervals should not exceed one year[27]. The audit should be performed by experienced safety professionals.

7.3.1 Purpose of Safety Audit

- Evaluate the effectiveness of safety program.
- Evaluate the performance of workers with regard to safety procedures.
- Evaluate the status of safety related activities such as documentation, training, communications, etc.
- Recommend actions for improvement.

7.3.2 Arc Flash Hazard and Safety Audit

As part of the regular safety audit, the following arc flash hazard related points should be examined.

1. System changes: Since the last audit, were there any changes in the power system? If "yes":
   a. Was the change properly documented? Were drawings updated?
   b. Were any new arc flash calculations performed?
   c. Were new warning labels installed at the affected locations?
2. PPE: Do the employees have the PPE needed for the highest level of arc flash exposure in the facility? What is the condition of PPE?
3. Do workers follow arc flash hazard warning labels, signs and instructions regarding flash protection boundary and appropriate PPE?
4. Are arc flash hazard procedures followed correctly as they are documented?
5. Do the existing procedures provide protection adequately?
6. Do workers have adequate knowledge and training in arc flash hazard?
7. Have protective device settings been tampered with or modified from the intended settings? Are the fuse sizes the same as those specified by the engineer?
8. If any equipment requires special operation/maintenance procedures for safety reasons, is the information readily available to workers? What is their understanding of the special procedures?
9. Do workers have the tools and equipment for working safely? (Insulated tools, shields, hot sticks, etc.)
10. Review of accidents and near misses.

7.3.3 Methods of Obtaining Information for Audit

1. Interview with safety coordinators, responsible persons, trainers.
2. Inspection of records, documents, labels, signs, drawings pertaining to arc flash hazard.
3. Interview with electrical workers.
4. Observation of work procedures.
5. Inspection of PPE, safety tools and equipment.

7.4 Safety Meetings

Safety meetings (or job briefings) are usually carried out before working on energized equipment. This provides a review of the following:

- Work to be performed.
- Potential hazards.
- Individual responsibilities.
- Specific procedures that require attention.

Regular safety meetings are also conducted in companies in which workers are continually exposed to hazards. Monday morning meetings are held briefly to talk about safety. Accidents and near misses are discussed. Safety meetings are instrumental in disseminating information, bringing new issues to attention, and discussing possible solutions. The Monday morning meetings also provide the workers an opportunity to focus on safety matters after returning to work from their weekend. Workers should be encouraged to discuss openly and share their ideas. For example, if a worker drops a tool on exposed live equipment, it should be discussed, since this event could have led to arc flash. This discussion could lead to reasoning why the tool was dropped, and whether a better method or tool would have avoided the incident. From these insights, the procedures for arc flash hazards can be enhanced.

7.5 Documentation

1. Document all data that was used for the arc flash hazard assessment. This is useful for implementing changes and future assessment.
2. Prepare a report of the assessment identifying the type, name/ID, incident energy at working distances, flash protection boundary, hazard/risk category, and other

pertinent information such as voltage, available fault current, protective device description and its trip time, arc gap and arc current.

3. Prepare electrical drawings that contain the results of the arc flash analysis. Electrical drawings a usually referred to for planning out maintenance jobs.

4. Circulate documents to all concerned people.

5. Install easily visible warning signs at the door, fence, etc. of the location where the hazard exists, with information on the hazard, the arc flash boundary and the requirement of PPE within the area.

6. Install warning labels on the equipment at some easily visible location near the exposed live part with information on hazard/risk category, estimated incident energy at working distances, requirement of PPE, and the flash protection boundary.

7. If the equipment has a cover that needs to be removed before working on exposed live conductors, install similar warning labels inside so that the worker may see it after removing the cover.

8. Document and report the installation of all warning signs and labels.

9. Document the safety audit and use it for continual improvement.

10. Document arc flash related accidents and near misses. OSHA requires documentation and reporting of all injuries that result in loss of workday. Documentation is suggested for near misses as well, with the hope that prevention can be achieved more effectively.

7.6 Personal Protective Equipment

The following steps need to be taken regarding PPE. See Chapter 6 for details.

1. Select PPE based on arc flash hazard assessment.

2. Provide information/labels on PPE on thermal rating.

3. Train with new PPE.

4. Provide regular inspection, care and maintenance of PPE.

5. Document use and maintenance of PPE.

6. Dispose PPE after useful life has exceeded.

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[26] Ray Jones & Jane Jones, "Electrical Safety in the Workplace", page 147, National Fire Protection Association, 2000.

[27] See endnote 26.

Appendices

A. Uncertainties in Arc Flash Hazard Analysis and Methods to Deal with Them

The random nature of arcs has made it impossible to predict exactly the arc currents and its associated incident energies. This section considers some statistical methods of evaluating the randomness based on measured data. Other areas of uncertainties are also explored and some simple methods to deal with these uncertainties have been proposed. The calculation methods proposed in various standards provide specific values of arcing current, incident energy and flash protection boundary. The statistical methods suggested in this section consider a range of values about the calculated value given the uncertainty in the behavior of arcing faults.

Various standards and studies have indicated that there are numerous factors such as ambient temperature, humidity, pressure, surroundings, etc. that may affect actual arc fault characteristics other than those factors included in the equations provided in the standards. Approximations and assumptions in the data collection process prior to computation may also result in variation of actual arc characteristics from the expected.

Although it is possible to adopt highly conservative calculation methods, caution has been placed with workers wearing excess personal protective equipment (PPE). It is believed that heavy and thick PPE could lead to difficulty in work, and therefore would increase the chances of accidents and the possibility of arc flash hazards. In order to provide "adequate" protection to the workers without being too conservative, it is necessary for the engineer carrying out the arc flash hazard assessment to understand the risks due to uncertainty and to be able to use statistical probability based on measured data.

Variation of Arc Current from Estimate

Random Variations

Table A.1 shows the variation of measured arc current from the IEEE 1584 estimate of arc current for low voltages. For the test data conditions, the arc current was calculated using the proposed formula. These values were compared against the actual measured arc current. The measured values of arc current were found to range between -37.5% and 57.2% of the estimated values. Bare in mind that the equations presented in IEEE 1584 for estimating arcing current are empirical equations based on regression analysis. This equation is a best-fit curve with an R-square of 98.3%. R-square is a measure of the equation fit to the data; 100% is perfect[28]. Therefore, after calculating the arc current from the equation it is necessary to consider the upper and lower limits of the arc current due to the random nature of arcs. The upper and lower limits would render the arc current as a possible range rather than a definite calculated value. Applying the variation limits presented in Table A.1 may not be the practical approach. It is customary in engineering practices to define probable ranges based on statistical analysis.

Table A.1: Variation of measured data about arc current estimated with IEEE 1584 equation for low voltage (includes both open and box)

Voltage (kV)	Percent Variation from Estimate (%)	
	Minimum	Maximum
0.2 / 0.24	-10 %	+57.2 %
0.4 / 0.48	-37.5 %	+23.4 %
0.6	-27.6 %	+27.4%

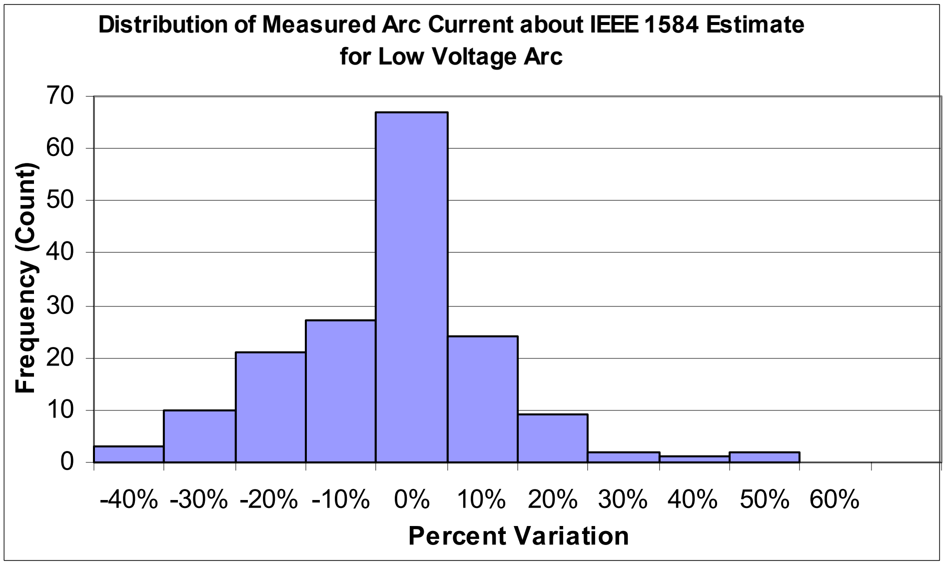

Figure A.1: Distribution of measured arc currents about IEEE 1584 equations for low voltage arc currents from bolted fault currents.

Figure A.1 shows the distribution of measured arc currents as deviation from the IEEE 1584 estimate for low voltage, in percentages of estimated arc current. This histogram is the result of further analysis of the data published and used by IEEE for the equations in 1584. For 166 arc tests, the mean deviation from estimated arc current was 2% and the standard deviation of the variation from estimated arc current was found to be 15.2% of estimated arc current. The distribution has a skewness of 0.236 and a kurtosis of 1.553. Although the skewness and kurtosis suggest that the data is slightly off normal distribution, it may be assumed that with more data samples, the random nature of arc will follow normal distribution. Therefore, further statistical analysis will follow the assumption of normal distribution.

Table A.2 presents limits for low-voltage arcing current for various confidence levels. For a confidence level of 95%, the arc current can have any value between -23.0% and +27.1% of calculated arc current. The confidence level is a measure of probability or likelihood. A 95% confidence level implies that out of 100 random samples, 95 samples of observations will be in the specified range, and 5 samples will be above or below the specified range. Therefore, there is 95% probability that a measured arc current at low voltage may have a value between –23.0% to +27.1% of the estimated arc current. The higher the confidence level, the greater the range. It is up to the engineer to select the confidence level based on how conservative the arc flash evaluation needs to be. A confidence level of 99% may appear to be too conservative for practical purpose. It is suggested that 95% be used. As a rule of thumb, the arc current can be considered to be within the range of +/-25% of the calculated value from IEEE 1584 equations for systems with voltages less than a 1000V.

Table A.2: Minimum and maximum likely deviations in low-voltage arc currents from the calculated arc current for various confidence levels.

Mean Variation	Standard Deviation	Confidence Level	Minimum Arc Current	Maximum Arc Current
2.0%	15.2%	95%	-23.0%	27.1%
		99%	-33.4%	37.4%
		90%	-17.5%	21.5%
		68%	-5.1%	9.1%

Table A.3: Variation of arc currents from estimate for various confidence levels for 2.4 to 15 kV

Arc in	Percent Variation from Estimate (%)		Mean Variation	Standard Deviation	Confidence Level	Probable Arc Current Range	
	Min	Max				Max	Max
Box	-38.9%	21.1%	-2.2%	8.9%	95.0%	-16.8%	12.4%
					99%	-22.8%	18.4%
					90%	-13.6%	9.1%
Open	-4.2%	7.6%	0.1%	2.5%	95%	-4.0%	4.2%
					99%	-5.7%	5.9%
					90%	-3.1%	3.3%

For medium voltages, the variation of arc current from the calculated value may be less than for low voltages, as shown in Table A.3. Arc in open air appears to be more predictable than arc in box. For a 95% confidence level take a tolerance of approximately +/-14% from the calculated arc current in box. For arc in open air on medium voltages, the variation of +/-4% is small enough to be ignored.

There are two reasons for considering the deviation in arc current from the estimate:

a) The incident energy is calculated from the arc current.

b) The arc current affects the clearing time of a protective device. As described in the previous chapter, the incident energy is proportional to the arc time.

Gap Between Electrodes

For low voltages, the gap between electrodes affects magnitude of the arc current. The gap (G) is part of the IEEE 1584 equation (1, 30, 31) for estimating the arc current. Using this equation, the graph shown in Figure A.2 was plotted for arcing current as a function of electrode gaps for various voltage levels, bolted fault current and enclosure type. For all conditions, the arcing current reduces with increased gap. For medium voltage systems the gap distance is not an issue for typical switchgear and cable spacing.

The arc voltage is roughly proportional to the arc gap length[29]. Although the arc resistance is expected to increase with gap length, it is not a linear relationship. The arc current decreases with arc resistance. However, since resistance is highly non-linear, it is preferable to use the empirically derived method of evaluating the effect of gap on arc current.

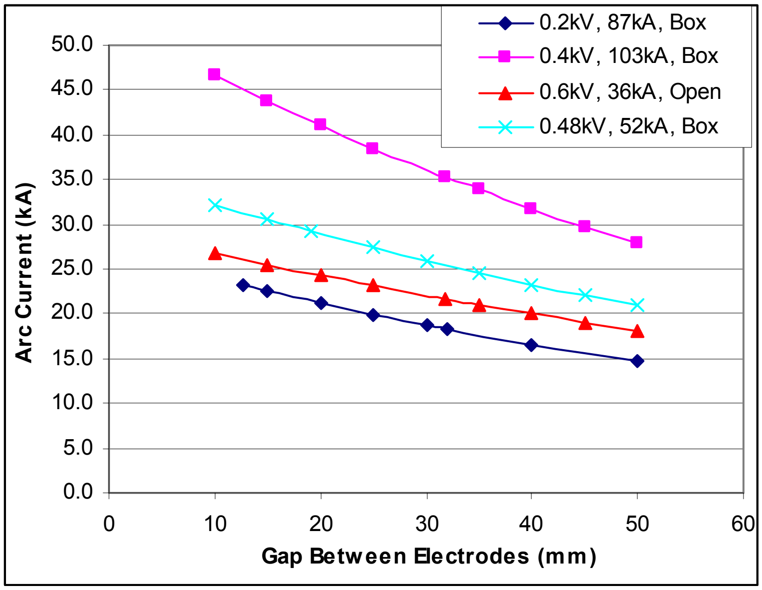

Figure A.2: Effect of gap between electrodes on calculated arc current for low voltages (<1000V) using IEEE 1584 equation.

The phase conductor spacing required by NEMA for various voltages is presented in Table A.4. Similarly, IEEE 1584 guide mentions typical gaps. When we assume a certain arc gap distance for low voltages, either based on NEMA or some typical value, we must be aware of the fact that any variation in the actual electrode gap could lead to variation in actual arc current. Therefore, the incident energy to which a worker may be exposed may vary. The gap between exposed conductors may vary from equipment to equipment. Also, at the terminal of a given equipment, the gap between conductors may vary depending upon the shape and layout. For conductors that are not exactly parallel (spatially), the minimum and maximum gap may be of interest. Arcs travel away from the power source[30]. Therefore, it may be sufficient to record the gap between the tip of the exposed conductor away from the source. For these reasons, it may be very difficult for the engineer to determine the exact electrode gap for every equipment, especially if the equipment is live. Although it can be safely assumed that the NEMA gap will be maintained for all manufactured equipment, the same cannot be guaranteed about the field installations of conductors, tap-offs and terminations, or repair jobs. If the exact gaps are known, it is always better to use the data. In case the gaps tend to vary with equipment, and the engineer may have an idea of the approximate variation from typical values, then analysis can be carried out for various scenarios such as typical, minimum, and maximum gaps.

Table A.4: NEMA gap between conductors for various voltage levels

System kV, L-L	Equipment Type	NEMA Gap between conductors	Gap Unit
0.1 - 1.0	Switchgear	32	mm
	MCC/Panel	25	mm
	Open Air	32	mm
	Conductor	13	mm
1.0 - 5.0	Switchgear	102	mm
	MCC/Panel	102	mm
	Open Air	102	mm
	Conductor	13	mm
5.0 - 15	Switchgear	153	mm
	MCC/Panel	153	mm
	Open Air	153	mm
	Conductor	13	mm

Considering multiple scenarios for electrode gaps may be somewhat time consuming, although more reliable. A quick method of examining the effect of variation in electrode gap is the sensitivity analysis. Figure A.2 shows the relation between electrode gap and arc current to be almost linear. Table A.5 shows the sensitivity of arc current to electrode gap for various voltages, bolted fault currents and enclosure type. The sensitivity is the percent variation in arc current for 1 mm variation in electrode gap.

The sensitivity varies with the system voltage and the available fault current. However, for practical purpose the average sensitivity of –1% can be used. The following example illustrates how sensitivity analysis can be used to quickly determine the possible range of arc current due to variation in arc gap.

Table A.5: Sensitivity of arc current to electrode gap for various conditions

Enclosure	Voltage L-L (kV)	Bolted Fault Current (kA)	Sensitivity (% / mm)
Box	0.208	36	-1.0%
Box	0.400	53	-1.3%
Open	0.610	88	-0.7%
Box	0.485	103	-1.0%
		Average	-1.0%

Example:

For a system with line-line voltage of 0.6 kV, assumed electrode gap of 32 mm, and bolted fault current of 22.6 kA, the arc current in box was estimated to be 15.7 kA using IEEE 1584 equation. It was also observed that the electrode gaps varied approximately from 25mm to 40mm at different terminals and connections. What is the likely arcing current?

Case 1: Gap, G = 25mm.

Variation in gap, g = 25 – 32 = - 7mm.

Assume sensitivity of -1%/mm.

Variation in arc current = - 7 * (-1%) = 7%

Maximum arc current = 15.7 * (1 + 0.07) = 16.8 kA.

Case 2: Gap, G = 40mm.

Variation in gap, g = 40 – 32 = 8mm.

Assume sensitivity of -1%/mm.

Variation in arc current = 8 * (-1%) = -8%

Minimum arc current = 15.7 * (1 - 0.08) = 14.5 kA.

The calculated arc current can have values anywhere between 16.8 kA and 14.5 kA. Further variations can be considered due to randomness of arcs. For a confidence level of 95% the arc current can be within the limit of +/- 25% of the estimated value.

Lower limit of arc current = 14.5 * (1 – 0.25) = 10.8 kA.

Upper limit of arc current = 16.8 * (1 + 0.25) = 21.0 kA.

NOTE: It is **not** possible for the arc current to be higher than the bolted fault current. This condition is not violated for an upper limit in arc current of 21 kA. In cases where the estimated arc current exceeds the bolted fault current, take the arc current as equal to the bolted fault current. For very low arcing currents, it is beneficial to check whether the arc current is likely to be self-sustaining under the given system parameters. For 480 volt systems, the industry accepted minimum level for a sustaining arcing fault current is 38% of the available three phase fault current[31].

Variation of Incident Energy from Estimate

Random Variations

The measured incident energy may deviate more widely than the arc current from their respective calculated values. Figure A.3 shows the deviation of measured incident energy about the calculated incident energy using the IEEE 1584 equations for low voltages. First, the incident energy was calculated for various test conditions. Then it was compared with the measured values. The deviation here is the difference in percent of calculated values. For low voltage arcs in open air, the measured incident energies during various tests were found to be lower than the calculated incident energy. The smallest negative deviation is -25%. It can be concluded that highest possible incident energy is about 75% of the calculated incident energy when using the IEEE 1584 equations for low voltage arcs in open air. For LV arc in box, it can be seen from Figure A.3 that the maximum deviation is very high. The maximum deviation was found to be about 62%. Therefore, if the calculated incident energy for a case is 10 cal/cm^2, there is a possibility that the actual incident energy may be as high as 10*1.62 or 16.2 cal/cm^2.

Although the nature of arcs is highly unpredictable, it is observed that arcs in open air, for both low voltage and medium voltage, are more predictable than those in box. This can be concluded from the shape of the histogram (or frequency distribution). The plots for arcs in air have higher peaks and narrower bases (bottoms) than do the curves for arcs in box.

The deviation of measured incident energy for medium voltages is shown in Figure A.4. The maximum deviations are 46% for open air and 49% for box. Therefore if the incident energy for a case of medium voltage in open air is calculated to be 10 cal/cm^2 the actual energy may be as high as 10*1.46 or 14.6 cal/cm^2.

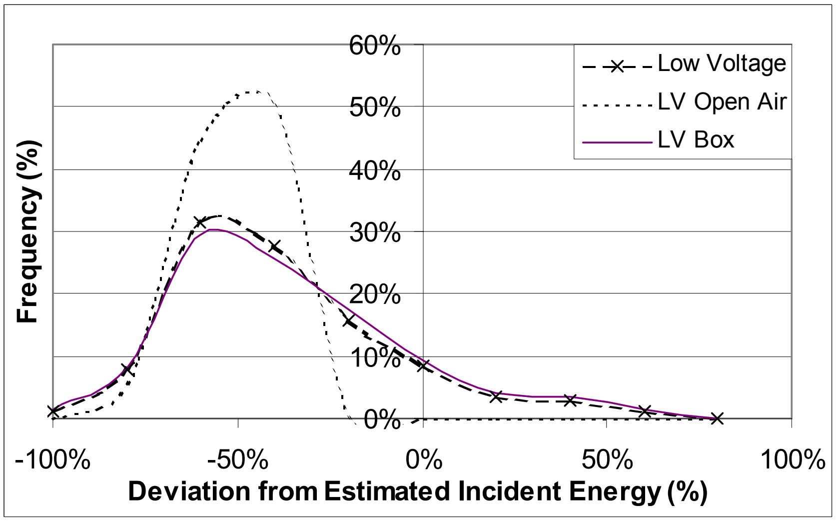

Figure A.3: Frequency distribution of deviation of measured incident energy from calculated value for <1.0-kV using IEEE 1584 equations.

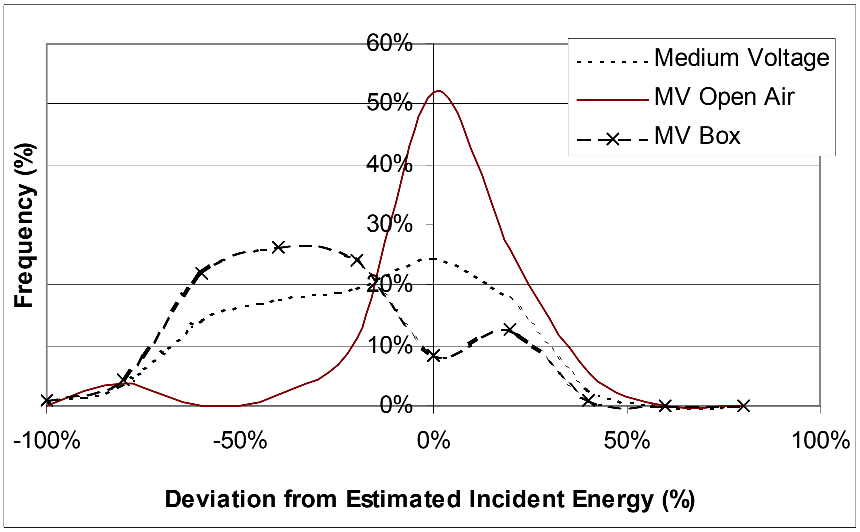

Figure A.4: Frequency distribution of deviation of measured incident energy from calculated value for 1.0 to 15-kV using IEEE 1584 equations.

For the sake of simplicity, the discussions in this section have been based upon univariate analysis. In reality, the variations can be dependent upon multiple factors. To see the effect of bolted fault current on the deviation let us look at Figure A.5. It can be observed from this plot that the deviations tend to decrease with increasing bolted fault current. In Figure A.5, trend lines are drawn for the maximum incident energies. For higher bolted fault currents, the number of observations are small, and therefore it is not possible to guarantee that the actual incident energy will not be higher than the predicted value after accounting for deviations. It is learned at the time of writing of this article that further tests on arc flash are being planned. It is hoped that more conclusive information will be available in the future. In the mean time, with the available data, the following procedures can be adopted as a rule of thumb.

The medium voltage trend line in Figure A.5 shows almost constant deviation with respect to bolted fault current. Therefore, we can assume that the maximum possible incident energy is 49% higher than the estimate provided by the IEEE 1584 equations. For low voltage, the maximum possible deviations of incident energy from the calculated values are about 60% at 10 kA IBF, 40% at 40 kA, and 25% at 60 kA, 10% at 80 kA and 0% at 100 kA. Further breakdown is possible with various enclosure types – in air or in box, but is not discussed in this text. Readers are encouraged to obtain the test data from IEEE and compare the results. This chapter deals with applying the statistical adjustments on calculated results without changing the calculation methods proposed in the standards. Another approach with similar results is to vary the calculation factors (C_f) in the IEEE 1584 equations to obtain more reasonable results directly.

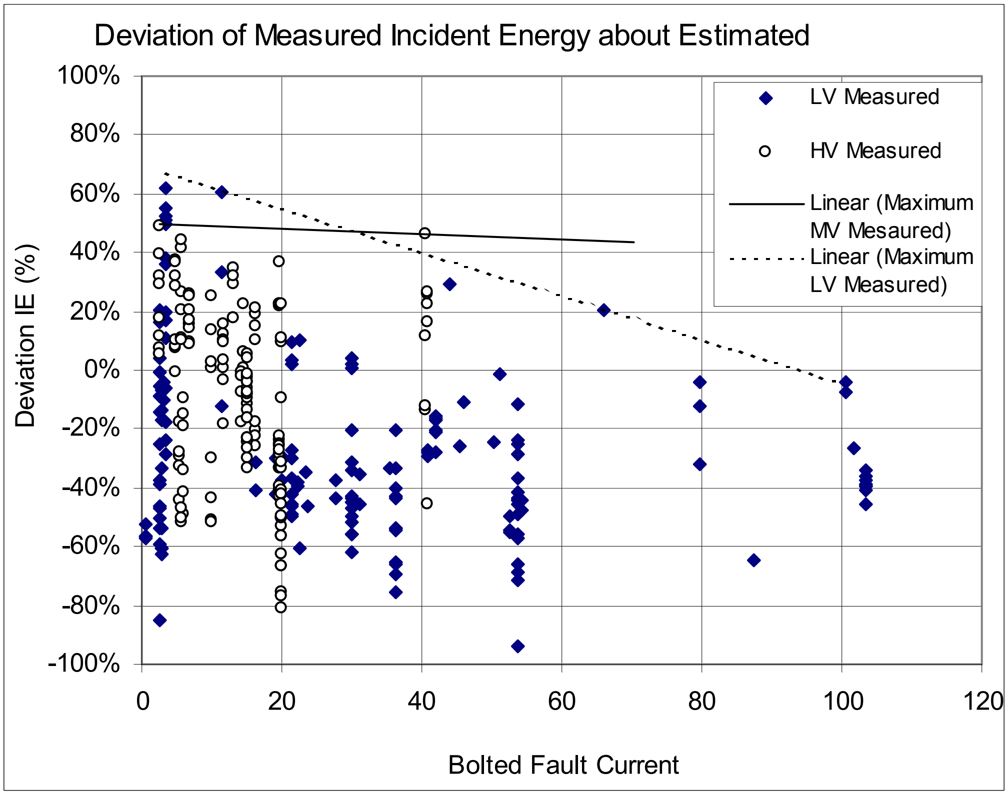

Figure A.5: Deviation of measured incident energy from calculated value for various bolted fault currents using IEEE 1584 equations.

Arc Gap

The arc voltage varies with the arc gap length. A higher arc voltage means a higher arc power for the same arc current. Therefore the incident energy can be expected to increase with arc gap length, as long as the arc current is not sharply reduced.

In the IEEE 1584 equations, the incident energy is also a function of the gap between electrodes. As mentioned in the previous section on arc current, the actual gap may vary from the NEMA gaps or assumed gaps due to various reasons. Further adjustments can be made to account for the variation in incident energy as a result of variation in gap between electrodes. Figure A.6 shows the effect of arc gap on the IEEE estimate for incident energy.

For low voltage, the sensitivity of calculated incident energy is about 0.3% per mm deviation in arc gap. For a 10mm deviation in gap, the incident energy can be expected to be 3% higher, which is a rather small increment and can be neglected. In most cases the variation in gap is not likely to be substantial, and therefore the effect of variation in gap on the incident energy can be ignored.

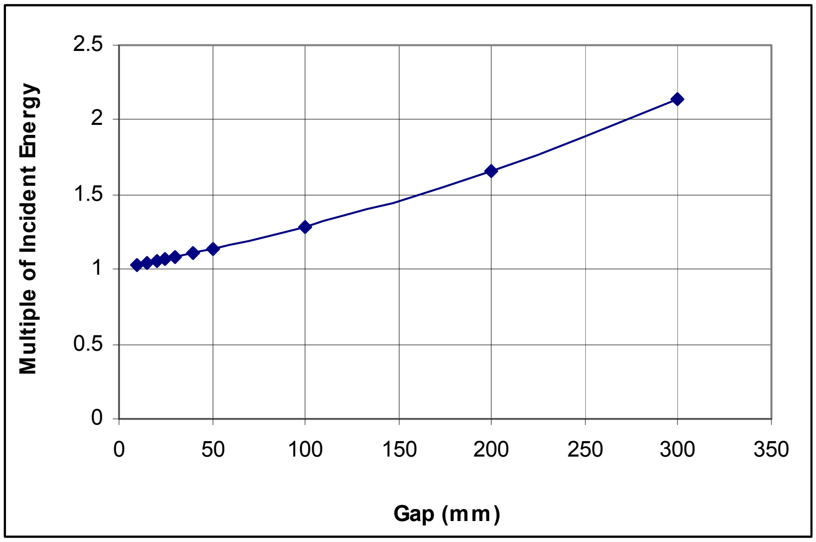

Figure A.6: Effect arc gap on incident energy using IEEE 1584 equations.

In obtaining the incident energy based on IEEE equations for the test data, the measured values of the arc current were used instead of the calculated arc currents. This was done because we will be using the various adjusted values of arc current rather than just the calculated arc current. This will cover the entire possible range of arc currents and also provide more conservative and reliable results in the evaluation of incident energy.

Variations in Arcing Time

Arcing time depends upon the trip characteristics of the upstream protective device. The trip characteristics themselves can have a some degree of randomness about the specified trip time value. For instance, a relay may have tolerance of –15% to +15% about the curve provided in the time-current characteristics (TCC). Tolerances are measured by the manufacturer and the information is usually provided with the device data documents. The incident energy is directly proportional to the arcing time. For the purpose of safety it is better to use the maximum trip time, since the workers need to be prepared for the worst possible condition. Persons carrying out the arc flash hazard assessment should read the protective device data documents carefully to ensure that the maximum trip time has been taken for the calculations and not the average, median or minimum trip times. Some manufacturers publish fuse TCC for just the minimum melting time of the fuse. In such cases, it is necessary to contact the manufacturer and obtain the total clearing time curve or apply a tolerance to estimate the total clearing time. The tolerance may be provided in the fuse data document or it can be assumed to be similar to the tolerance of other similar fuses.

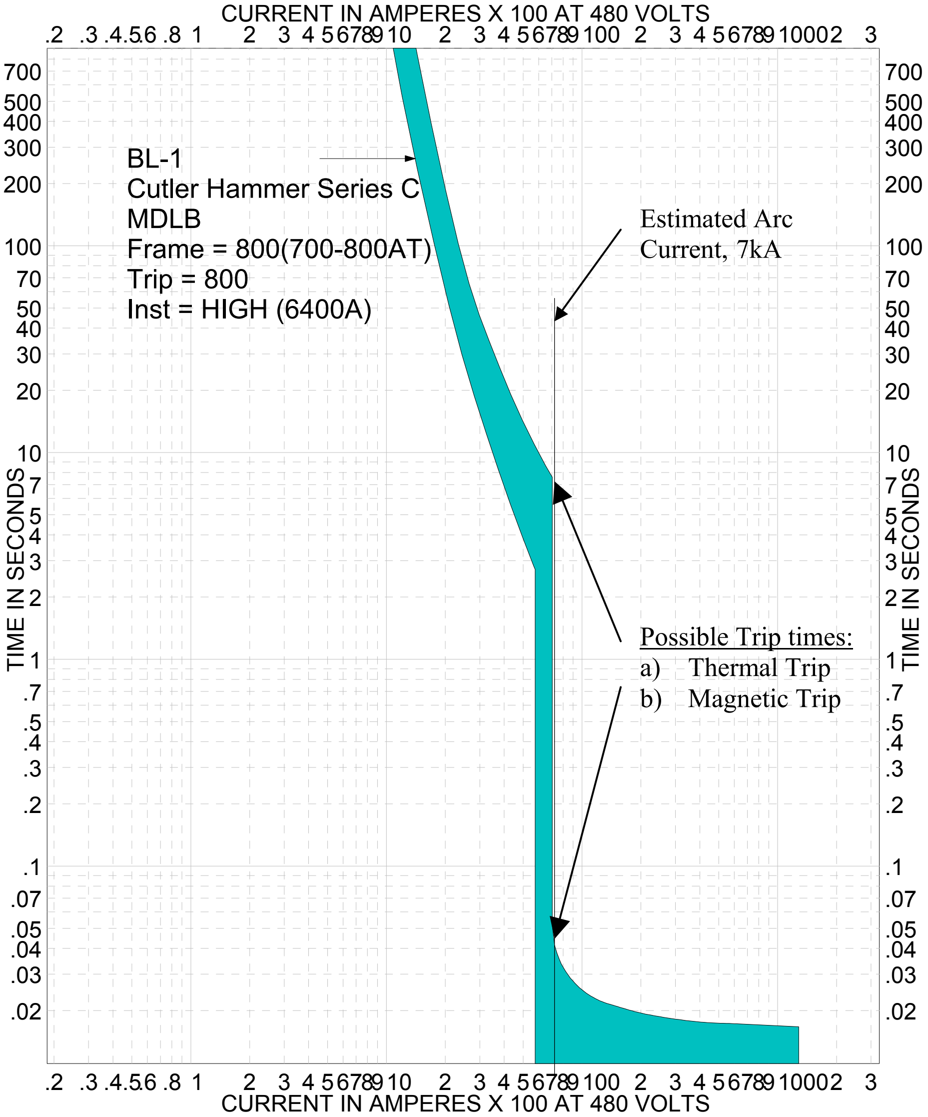

Figure A.7: Trip time at instantaneous pickup current for thermo magnetic breaker.

Figure A.7 shows the TCC of a thermal magnetic molded case circuit breaker (MCCB). The estimated arc current of 7 kA shown here as an example, is equal to the pickup of the magnetic trip. It is likely that the magnetic trip will activate and stop the arcing current at or below 0.04 seconds. However, there is also a possibility that the MCCB may not trip at that value pickup value. In such a case the thermal unit will trip the breaker at a much higher time, at 6 seconds. This is a great difference in trip time and hence will result in great difference in estimated incident energy. Close attention is required in obtaining the trip times at arc current values close to pickup values.

Figure A.8 shows the incident energies for various values of arc current for a typical solid state trip device using the IEEE equations. At the IEEE estimate of arc current, the calculated incident energy is 2.5 cal/cm^2. It was mentioned in the previous section that the actual arc current could be as low as 75% of the IEEE estimate. At 75% of the IEEE estimate, the trip is much higher and therefore the high incident energy of 9 cal/cm^2. The sharp change in the incident energy at about 82% of the IEEE estimate of arc current is due to the pickup of short time delay unit of the device, similar to the observation made for the MCCB in Figure A.7.

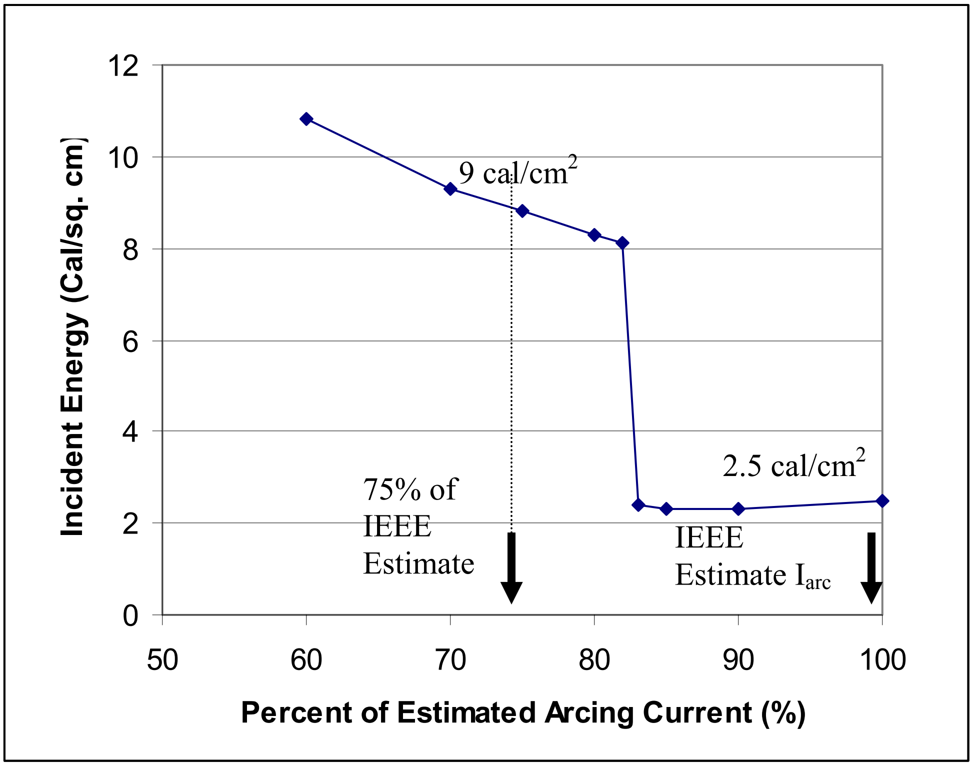

Figure A.8: Incident energies for various arc current values for typical solid state trip device.

Arc Protection Boundary

The arc protection boundary can be worked backwards using the adjusted maximum possible incident energy. This would mean adjusting the normalized incident energy (E_n). The uncertainties mentioned previously in this chapter affects the boundary in a similar way.

Theoretical Formulas

Ralph Lee[32] proposed the arc flash boundary in terms of the bolted fault MVA. This assumes the maximum possible arc power, which is half the total available fault MVA or bolted fault MVA. Calculation of the incident energy is based upon this formula.

$$D_B = \sqrt{2.65 * 1.732 * V * I_{bf} * t} \qquad (A.1)$$

where

D_B = distance of the boundary from the arcing point (feet)

V = system voltage L-L (kV)

I_{bf} = bolted fault current (kA).

t = arcing time (seconds)

This formula is applicable when definite time trip function is used to interrupt the fault. A definite time trip function is a fixed time delay, and is independent of the fault current passing through the protective device. Instantaneous trips are also approximately fixed time in most devices. If the trip time is independent of the fault current, then making the assumption that the arc current may have a value that will yield the maximum arc power is justified. However, this formula needs to be modified if the trip time is a function of the fault current. Inverse type relays, fuses, thermal trip units and solid state trip units with I^2T time delays have current dependent trip time. Assessment for inverse time functions can be approached using the same circuit assumptions with which the above equation (A.1) was derived.

Equivalent Circuit Model

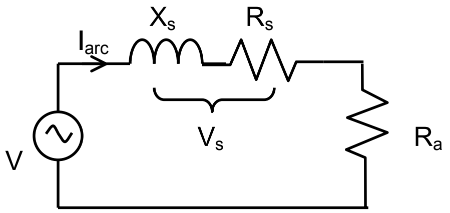

Figure A.9: Equivalent circuit diagram with Thevenin source and impedance, and arc resistance.

The Thevenin equivalent circuit for the arc fault is shown in Figure A.9. Here, V is the system voltage at the point of fault, R_a is the equivalent arc resistance, X_s and R_s are components of the Thevenin impedance Z_s, and I_{arc} is the arc current. When the arc resistance is zero (a hypothetical case), the arc current is equal to the bolted fault current. No power is dissipated through the arc. As the arc resistance increases, the arc current decreases. The arc power reaches a maximum when the arc current is approximately 0.7

per unit of the bolted fault current. This holds true only if the X/R ratio of the system is very high (R_s is negligible). If the X/R ratio is low, then the maximum power transfer occurs when arc current ratio (I_{arc}/I_{BF}) is less than 0.7, and the maximum arc power is less than 0.5 times the bolted fault MVA. A plot of arc power as a function of arc current is shown in Figure A.10. The arc power and arc current have been normalized in this plot.

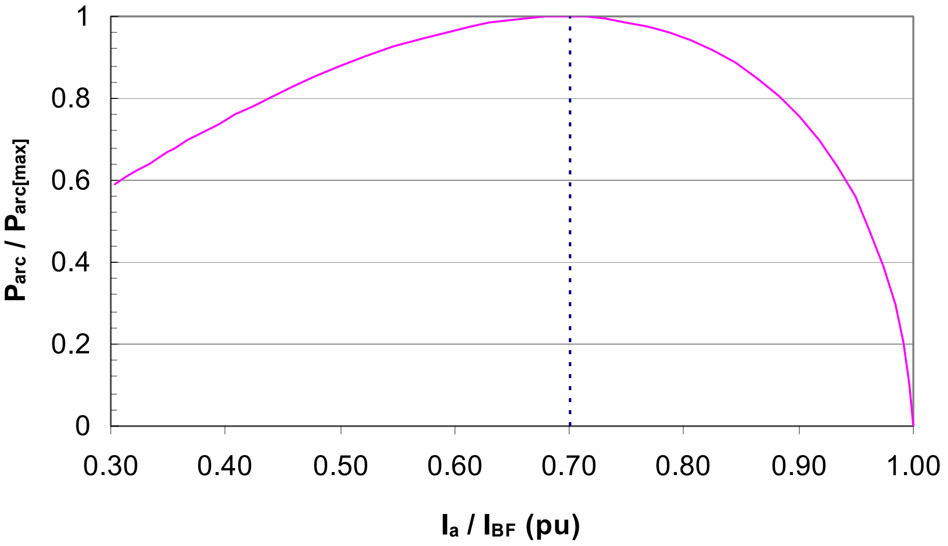

Figure A.10: Plot of arc power as function of arc current. (Arc current is expressed in per unit of the bolted fault current and the arc power is expressed in per unit of the maximum arc power.)

We can substitute the bolted fault MVA term (1.732 * V * I_{BF}) in equation (A.1) by 2*P_{arc}, since the maximum arc power is released when P_{arc} = 0.5 * MVA_{BF}. The equation now becomes:

$$D_B = \sqrt{2.65 * 2 * P_{arc} * t} \qquad (A.2)$$

For inverse type trip functions, both the arc power and the arcing time are dependent on the arc current. Since the total energy released by the arc, E_{arc}, is equal to P_{arc}* t, this too is a function of the arc current. We are now interested in finding the maximum arc energy released as allowed by the protective device.

For an inverse square time-current function, the trip curve may be expressed as:

$$t = K / I^2 \qquad (A.3)$$

From Figure A.9, the arc power may be derived as:

$$P_{arc} = I_{arc}^{\ 2} * \left[\sqrt{\left(\frac{V}{I_{arc}}\right)^2 - X_s^{\ 2}} - R_s \right] \qquad (A.4)$$

Assuming the current seen by the trip device is equal to the arc current, we can express the total arc energy as allowed to be released by the inverse-square time-current trip device:

$$E_{arc} = P_{arc} * t = K * \left[\sqrt{\left(\frac{V}{I_{arc}}\right)^2 - X_s^{\ 2}} - R_s \right] \tag{A.5}$$

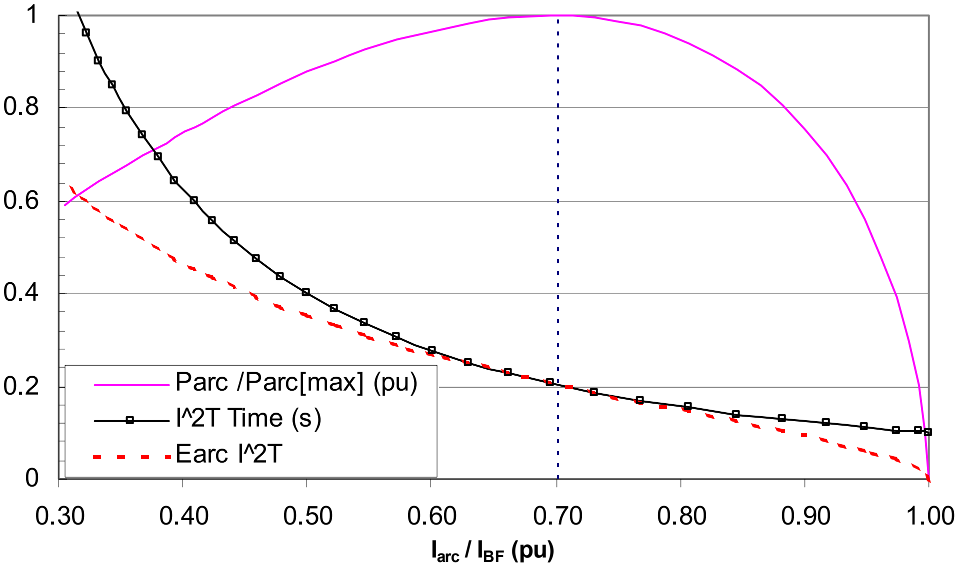

Figure A.11: Plot of arc power, trip time and arc energy released as function of arc current. All values in the plot are normalized: P_{arc} is in per unit of maximum arc energy (0.5*MVA$_{BF}$); trip time for inverse square curve (I^2T) is 0.1 seconds for Iarc = I_{BF}; E_{arc} is normalized P_{arc} times arcing time.

The plot of trip time and arc energy released as a function of arc current is shown in Figure A.11. This shows that the arc current at which the arc power is maximum (70% of bolted fault current in this case) does not yield the maximum arc energy. Because of the inverse-square time-current trip device, the highest energy released is for the lowest arc current. For the example shown in Figure A.11, the arc energy released when the arc current is 30% of bolted fault current is about five times greater than that when the arc current is 70% of bolted fault current.

From (A.2) and (A.5), we get the arc flash boundary as a function of the arc current when inverse-square trip function is used.

$$D_B = \sqrt{2.65 * 2 * K * \left[\sqrt{\left(\frac{V}{I_{arc}}\right)^2 - X_s^{\ 2}} - R_s \right]} \tag{A.6}$$

Summary

- Engineers carrying out arc flash hazard assessment need to be aware of the various uncertainties in the nature of arcs and other factors affecting the evaluation process.

- The test result upon which IEEE equations are based is available through IEEE. Statistical analysis based on this data can provide insight into the deviation of possible outcomes from the estimated values.

- Probability based deviations can provide likely ranges of arc current or incident energy for a given confidence level. Using these deviations, adjustment can be made for the IEEE estimates to obtain more reasonable estimates.

- Uncertainties in arc gaps and trip time can cause the actual outcome to differ from the estimate. The highest calculated cal/cm² should be considered to provide the worker maximum safety.

- For equations based on theoretical formulas such equation A.1, modification is required if the trip time varies inversely with the arc current. If the arc current is not close to 70% of the bolted fault current, then the condition of maximum power transfer will not hold true.

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[28] IEEE Standards 1584-2002, *IEEE Guide for Performing Arc-Flash Hazard Calculations*, IEEE Industry Applications Society, September 23, 2002. (SH95023)

[29] A. P. Strom, “Long 60-Cycle Arcs in Air”, *AIEE Transactions*, Vol. 65, pages 113-117, March 1946.

[30] Lawrence E. Fisher, "Resistance of Low-Voltage AC Arcs", *IEEE Transactions on Industry and General Applications*, Vol. IGA-6, No. 6, November/December 1970.

[31] NFPA 70E — May 2003 ROP, "Standard for Electrical Safety Requirements for Employee Workplaces", 2003 Edition, page 57.

[32] Ralph Lee, “The other Electrical Hazard: Electric Arc Blast Burns”, IEEE Transactions on Industry Applications, Vol. IA-18, No. 3, May/June 1982.

B. Implementing The New Arc Flash Standards

The nature of explosive equipment failures and the rate of serious burn injuries in the electrical industry have been studied for many years. Detailed investigation into the arc flash phenomena by many researchers has led the NFPA to adopt arc flash guidelines in NFPA-70E (2000) for work on or near energized electrical equipment. The 2002 National Electric Code also adopted Arc flash Hazard labeling requirements. In September 2002, the IEEE-1584 “IEEE Guide For Performing Arc Flash Hazard Calculations” was released, providing the detailed equations for determining arc flash energies. Proposed NFPA-70E (2004) scheduled for release in January of 2004 enhances the original 70E guidelines and adopts IEEE-1584 as one of the methods for determining arc flash energies.

Arc flash hazard studies require knowledge of both the electrical power system in a facility and the systems electrical protection. Arc flash studies can be considered a continuation of the short circuit and coordination aspects of a power system since the results for each are required to assess flash hazards. The effort required to perform an arc hazard assessment is greatly reduced with close integration between the short circuit, protective device coordination, and the arc flash software.

This paper provides a guideline for performing an arc hazard assessment using power system analysis software. All references and examples in this paper refer to EasyPower® software. In order to minimize space requirements, it will assume the user has the power system modeled in EasyPower, and has performed a short circuit and protective device coordination study.

Step 1. Data Collection And System Modeling

The greatest single effort in performing an arc flash study is data collection. For a system with up-to-date one-line diagrams, data collection can take from 25-40 percent of the study effort. The main difference between an arc hazard assessment and other studies is that you may need to model the system in more detail, increasing the data collection time and study effort. The results given from the software printout requires engineering judgment based on physical equipment design. If the equipment has the potential to be worked on while energized, it should be assessed. This includes branch circuits in data centers, panels and switchboards being served by smaller (<500 kVA) transformers at 480 volts. Panels and switchboards rated below 240 volts can be ignored if the service transformer is less than 125 kVA. See Figure B.1.

In years past, it was common practice for some engineers to exclude cable impedances and sometimes equipment resistance in the system model to ensure the highest possible short circuit values when calculating withstand duties for equipment. This is not recommended for several reasons. First, EasyPower® can accurately model all equipment types in detail, so there are no reasons for minimized models or built in safety factors. Secondly, conductor impedances and X/R ratios should be modeled for all equipment in order to obtain realistic short circuit values. When assessing arc flash hazards, higher short circuit currents may actually be non-conservative as far as PPE level is concerned due to fast clearing times. Higher PPE can result at lower fault levels because of the inverse characteristics of many protective devices. Depending on the maximum fault level to provide the maximum PPE may result in decreased worker safety.

It should be noted that the study results will only be as good as the system model. Every effort should be made to model the actual equipment as found in the field.

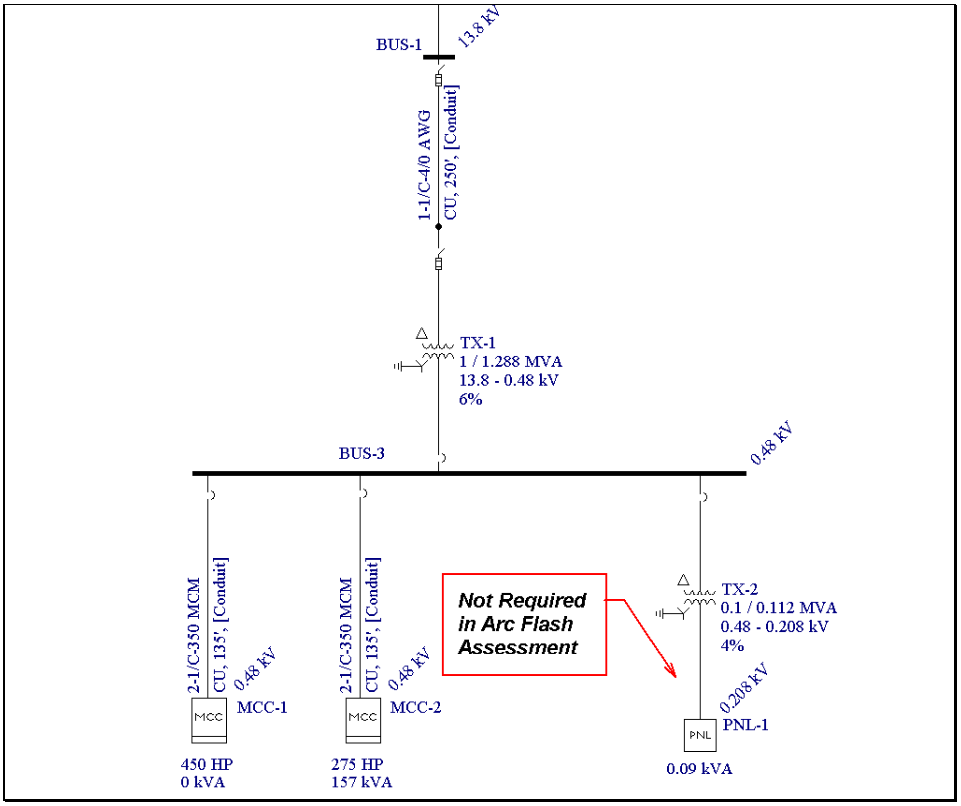


Figure B.1: Example showing bus excluded from arc flash assessment

Step 2. System Operating Modes

For plants with simple radial service from the utility, only one mode of operation typically exists – normal. However, for larger plants, there may be multiple modes of operation. These may include:

- Multiple utility sources that are switched in or out.

- Multiple generator sources that are operated in parallel or isolated depending on the system configuration.
- Emergency operating conditions. This may be with only small backup generators.
- Maintenance conditions where short circuit currents are low and trip time high.
- Parallel feeds to Switchgear or MCC's.
- Tie breakers which can be operated open or closed.
- Large motors or process sections not in operation.

What is important is that each one of these conditions may change the level of short circuit current, which in turn changes the clearing time of the protective devices. These changes can have a significant impact on the arc flash hazard and the PPE requirements for each piece of equipment.

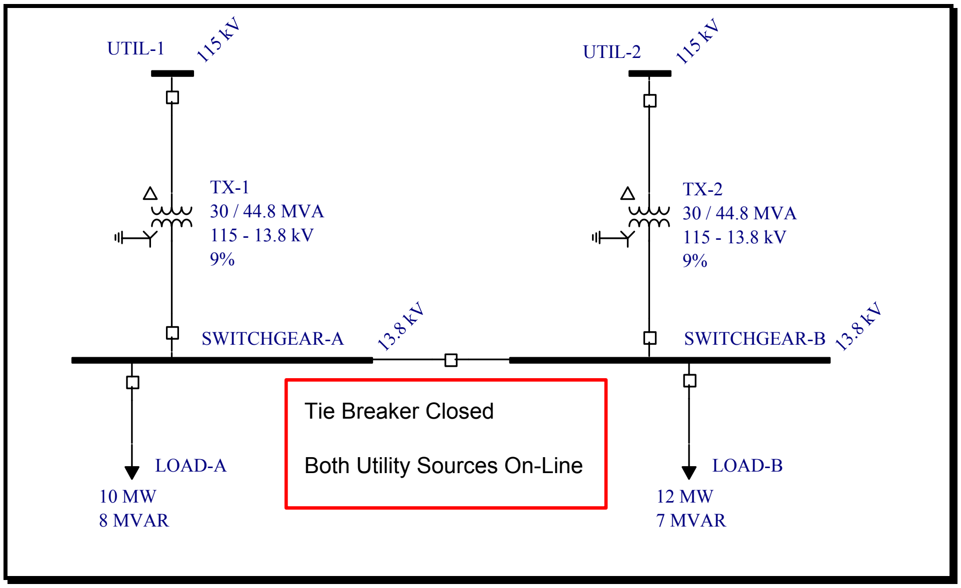


Figure B.2: Closed tie breaker increases available short circuit current.

In Figure B.2, an example system with maximum available short circuit current is shown. Both utility sources are online and the switchgear tiebreaker is closed.

In Figure B.3, an example system with minimum short circuit current is shown. Both utility sources are online and the switchgear tiebreaker is open, reducing the available short circuit current on each bus. The examples above consider a double-ended utility tie system, but the application applies to either low voltage systems with tie breakers or to emergency generation providing stand alone power or working in parallel with the normal system.

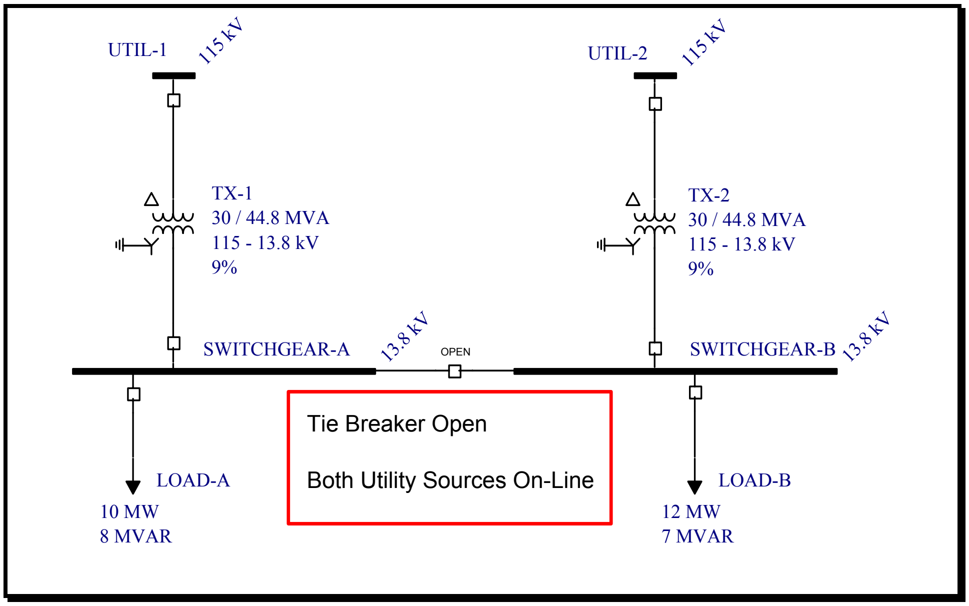


Figure B.3: Open tie breaker reduces available fault current.

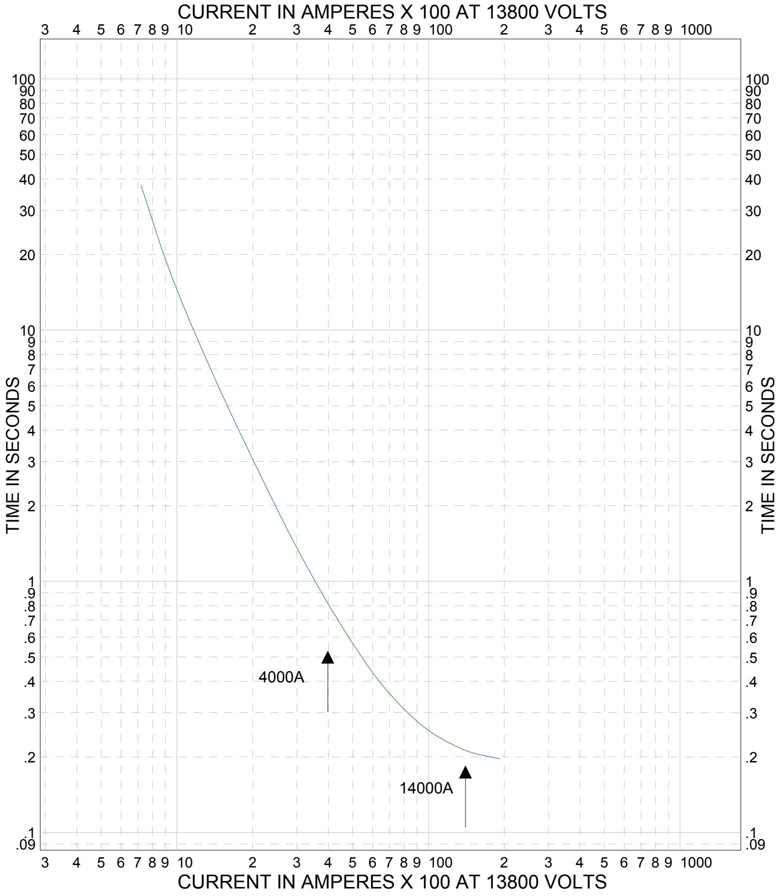


Figure B.4 Extremely inverse relay TCC.

The time current curve (TCC) of Figure B.4 shows an extremely inverse relay characteristic with the trip time increasing as the current decreases. Decreased short circuit current (opening a tie breaker, removing generation, etc.) can cause longer trip times and may increase incident energies and the resulting arc flash hazard.

In summary, arc flash assessment should include each operating mode for the power system to insure correct incident energies are calculated for all system conditions.

Step 3. Working Distance and Threshold Boundaries

Before running the actual analysis portion of the study, the user should determine the parameters on which the study will be based. These include; working distances, units of measurement, threshold boundaries, and the calculation standard or the "equations" for the analysis.

Working Distance

The arc flash incident energy and associated protection requirements are based on potential burns to the person's chest or face, not the hands or arms. The degree of injury depends on the percentage of the person's skin that is burned and the critical nature of the burn. Obviously, the head and chest areas are more critical to survival than fingers or arms.

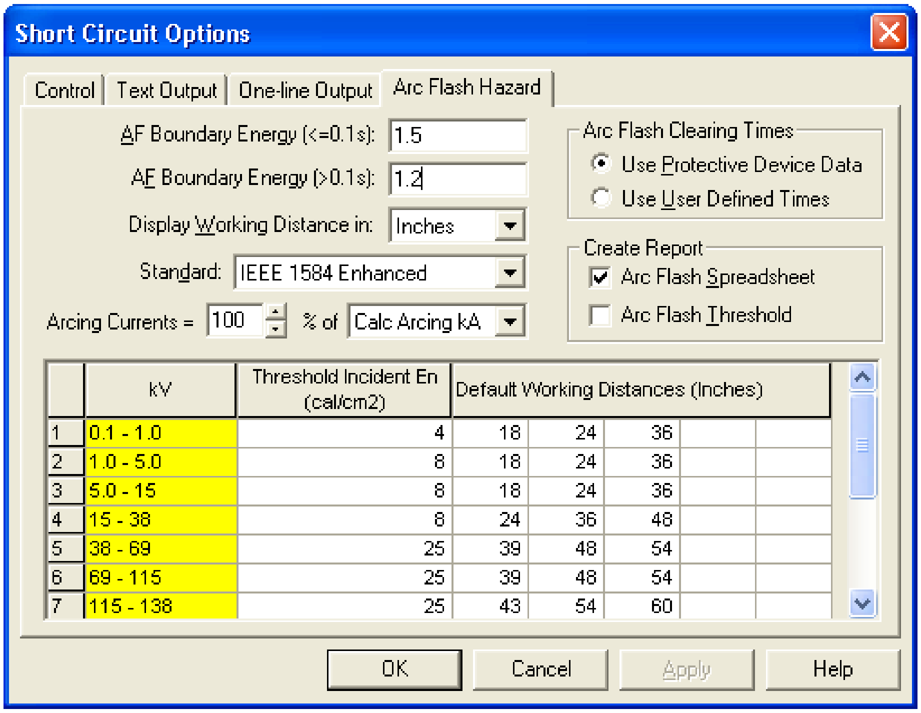
Appropriate working distances for most operations can be estimated by placing your elbow at your side and extending your hand to the equipment. A typical average for this distance is 18 inches. By extending the arm to the full out position, this can be increased to 24-28 inches for most people, but out-stretched arms are not a typical working distance. See Figure B.5.

Figure B.5: Working distance

EasyPower® provides up to five (5) commonly used working distances for each voltage level. This allows the user to develop a safety program where distances can be modified for a specific operation or maintenance function, allowing easy standardization of clothing levels and safety benefits. For certain types of work practices like hot stick operation, or when the energized bus is set back from the worker, greater distances may be used to correctly model the reduction in incident energy potential.

Unit of Measure

Working distances and arc flash boundaries are calculated and displayed in various units of measure including; inches, feet, mm, or meters. Select the appropriate unit that will be easily recognized and adhered to by workers. Critical safety programs such as arc flash hazards should not confuse workers with units of measure. Example: For US markets most workers are more familiar with inches and feet than mm and meters. The opposite would be true for facilities in Europe.



AF Boundary Energy (<=0.1s): 1.5

AF Boundary Energy (>0.1s): 1.2

Display Working Distance in: Inches

Standard: IEEE 1584 Enhanced

Arcing Currents = 100 % of Calc Arcing kA

Arc Flash Clearing Times
● Use Protective Device Data
○ Use User Defined Times

Create Report
☑ Arc Flash Spreadsheet
☐ Arc Flash Threshold

	kV	Threshold Incident En (cal/cm2)	Default Working Distances (Inches)				
1	0.1 - 1.0	4	18	24	36		
2	1.0 - 5.0	8	18	24	36		
3	5.0 - 15	8	18	24	36		
4	15 - 38	8	24	36	48		
5	38 - 69	25	39	48	54		
6	69 - 115	25	39	48	54		
7	115 - 138	25	43	54	60		

Figure B.6: Selecting various arc flash assessment options in EasyPower.

Arc Flash Boundary

The arc flash boundary is defined as the distance from the arc source where the onset of second degree burns can occur. This is typically defined by medical researchers as 1.2 cal/cm^2 or 5.0 Joules/cm^2. Some research indicates that up to 1.5 cal/cm^2 can be used for exposure less than 6 cycles (0.1 seconds).

EasyPower® provides the user with options based on clearing times less than 0.1 seconds and clearing times greater than 0.1 seconds. EasyPower® automatically determines the operating time from the system protection characteristics, or from user defined times.

The arc-flash boundary incident energy must be set at the minimum energy level in which a second-degree burn could occur. Do not increase the level from those shown in the dialog box. Reduced values may be used based on your safety or insurance requirements.

Calculation Standard

EasyPower® provides four calculation standards, NFPA-70 (2000), proposed NFPA-70E (2004), IEEE-1584 and ESA's enhanced version of IEEE-1584. ESA's extensive research has corrected some of the potential inconsistencies in the 1584 standard which may lead to non-conservative results. The enhanced version uses the tolerance bands described in Appendix A rather than the single 85% of bolted fault current in IEEE-1584. We recommend that the enhanced version of 1584 be used or NFPA-70E (2004) to ensure more realistic results.

Threshold Incident Energy

Incident energy is defined as the amount of energy impressed on a surface area at a specific distance away from the source during an electrical arc event. It is sometimes called surface energy density and is directly related to the distance from the arc. Incident energy is measured in joules per centimeter squared (J/cm^2) or in calories per centimeter squared (cal/cm^2).

EasyPower® provides a threshold incident energy level for different voltage ranges. If the incident energy level of a particular device is above the threshold, the device will be highlighted on the one-line as an immediate danger. (Detailed user reports are also provided.) See Figure B.7.

Electrical workers and safety managers can use this threshold to immediately identify areas where current personal protective equipment (PPE) standards will not provide the required safety margins.

For this 480 volt system, the incident energy threshold was set at 4.0-cal/cm^2 or a PPE of 1 as defined in NFPA-70E (2004). All protective devices with let through energies above this value are highlighted red indicating danger. Notice that for work on this switchgear, a minimum PPE of 3 is required for all work except on the load side of breaker BL-3. Table B.1 from the proposed NFPA-70E (2004) lists PPE requirements in relation to incident energy.

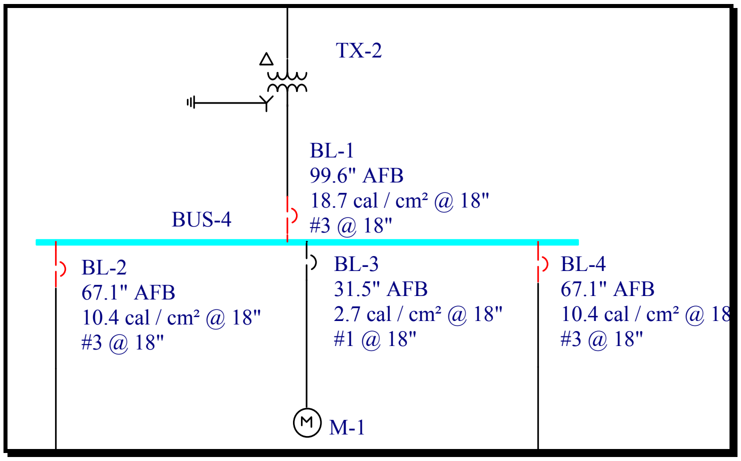


Figure B.7: Red breakers indicating incident energy exceeds user specified threshold value.

Table B.1: Proposed NFPA-70E 2004 PPE Requirements

Risk Category	Min. Arc Rating of PPE	PPE Requirements
Class #0	0-2 cal/cm^2	Untreated cotton
Class #1	2-4 cal/cm^2	Flame Resistant (FR) shirt and FR pants
Class #2	4-8 cal/cm^2	Cotton underwear plus FR shirt and FR pants
Class #3	8-25 cal/cm^2	Cotton underwear plus FR shirt and FR pants plus FR Coverall
Class #4	25-40 cal/cm^2	Cotton underwear plus FR shirt and FR pants plus multi-layer flash suit

Step 4. Protective Device Coordination Study

After the system model is built and the operating modes are determined, the following procedures are used to determine arcing fault incident energies.

Determine bolted fault (short circuit) currents at each bus in the system.

a) Use calculated currents to perform a protective device coordination study and develop system relay and direct acting trip (DAT) settings. Settings are typically determined by plotting protective devices on time current curves (TCC's).

b) Determine arcing fault currents at each bus in the system using IEEE-1584 or NFPA-70E equations. Note that different equations or multipliers are used for voltages <1.0kV, 1.0kV<kV<15.0kV, open air, inside box, and various system parameters.

c) Apply arcing currents and breaker/relay trip times to each device to determine arc hazard incident energies, arc flash boundaries, working distances, and PPE requirements.

The steps shown are required for performing the calculations with power analysis software as well as by hand. Depending on the system size (number of buses) performing this procedure can be extremely time consuming or nearly impossible without software tools. Only software based tools that provide true, seamless integration of short circuit, protective device coordination and arc flash hazard analysis can provide accurate information for better worker protection and reduced productivity losses due to over specification of gear. EasyPower®'s inherent one-line/analysis integration eliminates the separate steps required by other programs and integrates the short circuit, protective device, and arc hazard functions, thereby greatly reducing the time and effort to perform the analysis.

Protective Device Coordination Using EasyPower®

Using EasyPower®, the process will be broken down into two steps for clarification purposes.

a) System wide protective device coordination.

b) Arc flash calculations.

While this guide does not provide the details for performing a protective device coordination study, it should be stressed that this study is the cornerstone to providing accurate arc flash calculations. Accurate protective device clearing times are essential for providing correct incident energy calculations and the resulting AF boundaries.

Accurate protective device clearing times are essential for providing correct incident energy calculations and the resulting AF boundaries.

While arc flash calculations can be performed using standard operating times/characteristics of breakers and relays, this method does not ensure conservative results and may compromise safety. Several examples showing this reasoning are provided below.

In Figure B.8, the substation secondary main breaker provides selective coordination using either setting. However, the arc flash incident energy is increased from 11 cal/cm to 29 cal/cm for the higher short time delay setting. This increases the PPE requirement from 3 to 4 significantly increasing costs and the probability workers may try to bypass the higher PPE clothing requirements. This scenario is common to plants where an accurate protective device coordination study has never been performed, or when workers unfamiliar with protection system requirements make changes to protective device settings.

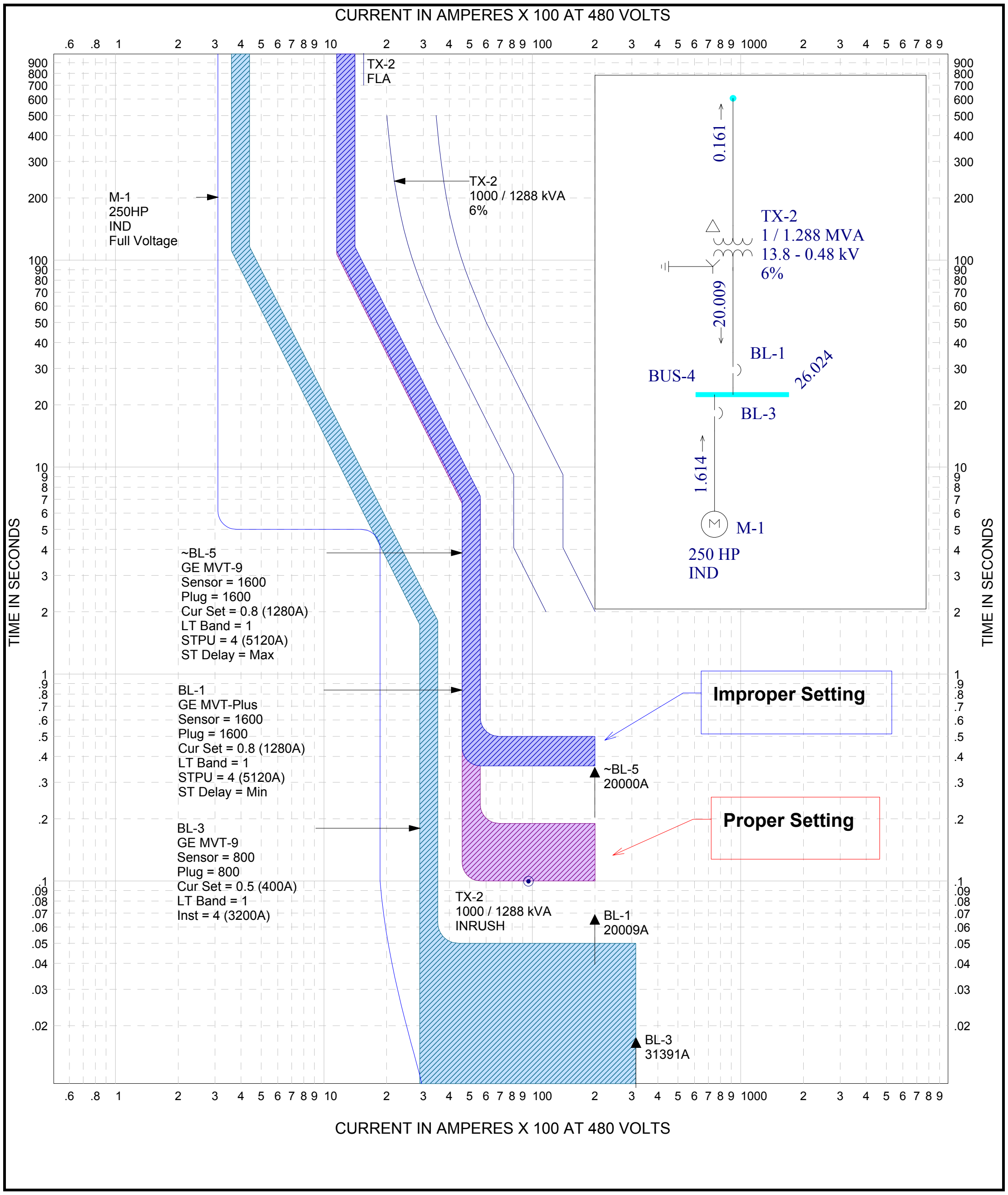


Figure B.8: Typical example of improper trip delay setting.

In this next example, Figure B.9, the secondary main breaker is properly set except the I^2t function is left in. This raises the arc flash incident energy from 11.0 cal/cm^2 to 16 cal/cm^2. If increased arcing impedance is modeled, reducing the arcing current to 80%, the incident energy is raised to over 20 cal/cm^2. This increase in energy can result in an increased cost of personal protective equipment and ongoing worker productivity losses associated with the increased PPE requirements.

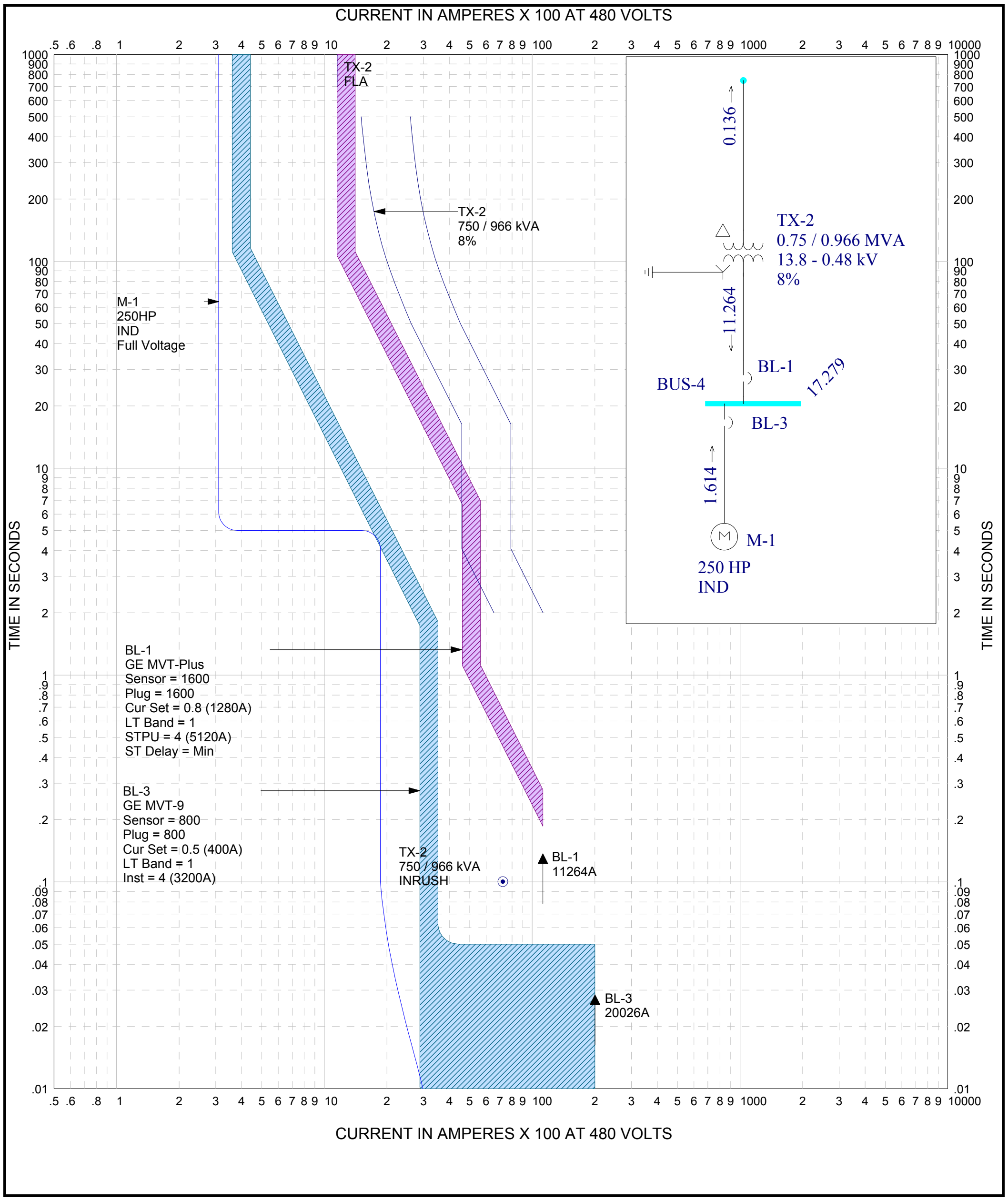


Figure B.9: Typical example of short time I^2T trip curve used in place of definite time delay (flat)

In medium and high voltage systems, it is quite common to find relay settings that are set far above proper protective boundaries. This is especially true when new systems have been added to older systems, or when system studies have not been updated on a regular basis.

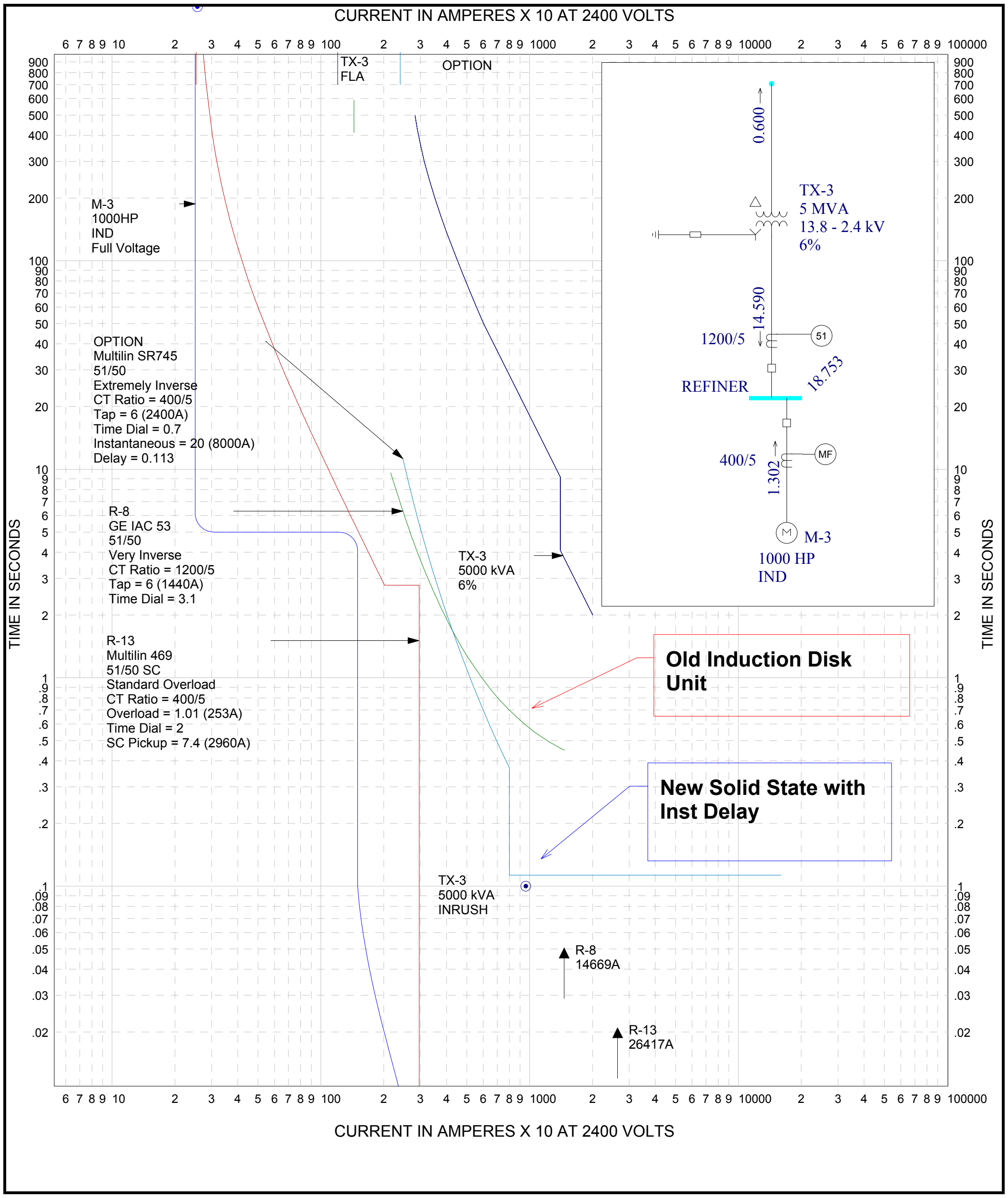


Figure B.10: Relay trip time compared with solid state device.

Figure B.10 shows an older style induction disk relay providing protection to a 2400 volt MCC line-up. This unit must be set above the motor protective relays for selective coordination but low enough to provide proper protection. A standard instantaneous unit cannot be used without tripping the entire lineup for a motor fault. The tap and time dial setting shown is a good compromise and typical of many systems. The unit will clear a bus fault in approximately 0.5 seconds (30 cycles). The arc flash incident energy is over 30 cal/cm^2 and requires a PPE of 4. Using a new solid-state relay with delayed instantaneous setting for selective coordination, the incident energy is lowered to 10 cal/cm^2, greatly enhancing worker safety.

As can be seen, proper protective device settings can greatly enhance worker safety and system reliability. Performing an arc flash assessment without first providing proper protection settings can significantly impact the assessment.

Arc Flash Calculations Using EasyPower®

In the previous sections, we have provided the basis for setting up the system model for proper arc flash calculations. In this section we will provide the details for actually performing the arc flash study and understanding the results, as well as, some tricks of the trade.

Arc flash calculations are performed in EasyPower®'s ShortCircuit focus. EasyPower®'s SmartClick interface allows the users to simply double click any bus for instantaneous results, to fault selective buses, or to "Fault All" buses.

In the example below (Figure B.11) select the ArcFlash button on the EasyPower® toolbar. Double click on Bus-4. The results appear on the one-line.

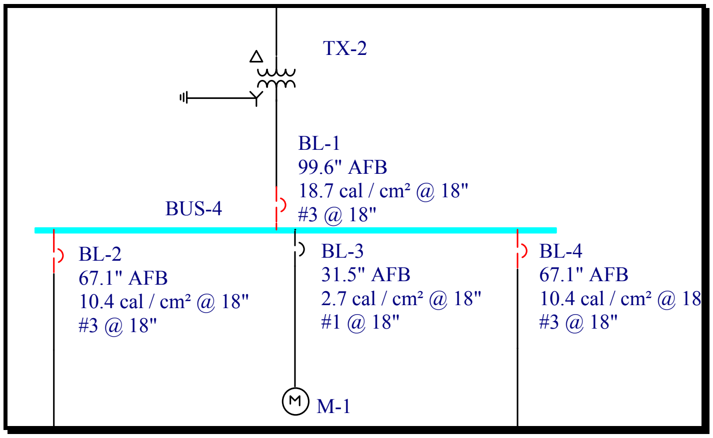


Figure B.11: Observing arc flash results by double clicking on a bus.

Each protective device displays the required arc flash boundary, let through energy in cal/cm^2, and PPE requirement at a user specified working distance.

The values displayed on the one-line are based on the let through energy of the protective device, i.e. the energy on the load side of the device, not the line side.

Note: The values displayed are based on the let through energy of the protective device, i.e. the energy on the load side of the device, not the line side. This important safety aspect must be understood when applying arc flash results. When working on the line side of a protective device, i.e. the incoming terminals, breaker stabs, or incoming bus work the incident energy on the line side must be found from the let through energy of the upstream device, not the device you are working on. For example, when working on the primary stabs of breaker BL-2, the incident energy available to the worker is found from the first upstream device protecting BL-2. This is the let through energy of the secondary main device BL-1, which is 18.7 cal/cm^2. If the worker is working on the load side stabs of BL-2, the let through energy is controlled by BL-2. In EasyPower® these results are associated with that breaker, in this case, 10.4 cal/cm^2.

Figure B.12 below shows the same system, but with a primary fuse protecting the buswork from the TX-2 secondary terminal through the primary or line side bus stabs of breaker BL-1. Work in this area will require a PPE level 4 requirement and be subject to a let through energy of 30.8 cal/cm^2.

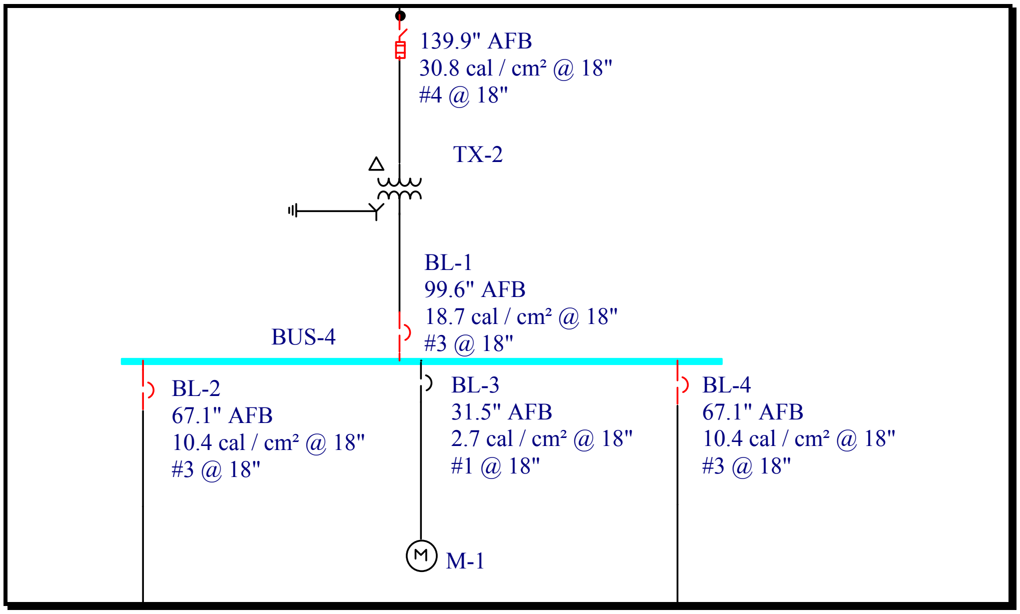


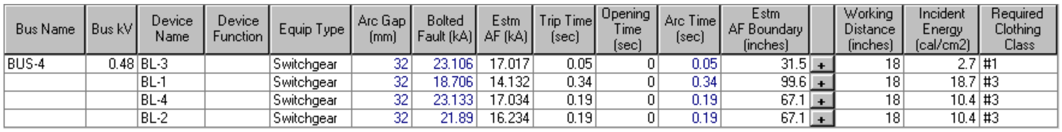
Figure B.12: Primary side fuse protects line side of breaker BL-1 on BUS-4 but has higher incident energy.

When laying out your safety plan, keep in mind that you will always be working on either the line side (upstream) or load side (downstream) of a protective device.

When displaying the results graphically, EasyPower® provides the user with a clear picture of line side and load side let through energies, as well as, a visual indication of problem areas and correct clothing compliance. This information can be posted in the electrical room providing workers with a clear picture of the system and the hazards that may not be as easily apparent with just stick on labels. With the click of a mouse you can change system parameters and compare different operating scenarios. This provides valuable training information that helps engineers and electricians understand how system changes impact arc flash hazard ratings.

For most large studies, however, it is typically more efficient to display results in spreadsheet form and print the “Arc flash” hazard warning labels for each device. To perform this operation, simply go to **Tools→ ShortCircuit Options → ArcFlash Tab**, and check ☑ ArcFlash Spreadsheet in the “**Create Report**” section of the tab in the EasyPower® menu. See Figure B.6.

Now instead of double clicking on the bus to initiate the fault, select **Fault All** from the toolbar, and then from the menu choose **Window → ArcFlash Hazard Report**. A spreadsheet similar to Figure B.13 below will tile in the foreground of the window.



Bus Name	Bus kV	Device Name	Device Function	Equip Type	Arc Gap (mm)	Bolted Fault (kA)	Estm AF (kA)	Trip Time (sec)	Opening Time (sec)	Arc Time (sec)	Estm AF Boundary (inches)		Working Distance (inches)	Incident Energy (cal/cm2)	Required Clothing Class
BUS-4	0.48	BL-3		Switchgear	32	23.106	17.017	0.05	0	0.05	31.5	+	18	2.7	#1
		BL-1		Switchgear	32	18.706	14.132	0.34	0	0.34	99.6	+	18	18.7	#3
		BL-4		Switchgear	32	23.133	17.034	0.19	0	0.19	67.1	+	18	10.4	#3
		BL-2		Switchgear	32	21.89	16.234	0.19	0	0.19	67.1	+	18	10.4	#3

Figure B.13: Arc flash results reported in spreadsheet

The EasyPower® ArcFlash spreadsheet provides all the data used in the calculations to determine AF Boundary, Incident energy, and PPE requirements for each protective device in the system. This data can be applied directly to comply with NEC 2002 and NFPA-70E by simply clicking on **File→ Print Labels** in the menu.

Before you print labels it is recommended that you refer to STEP-2, and review your modes of operation. It is highly recommended that you save your different operating modes in EasyPower®’s Scenario Manager. This will allow you to refer to each case without affecting the base case system as you make changes and fine-tune your arc flash assessment.

Summary

1) Run base case arc flash calculations.

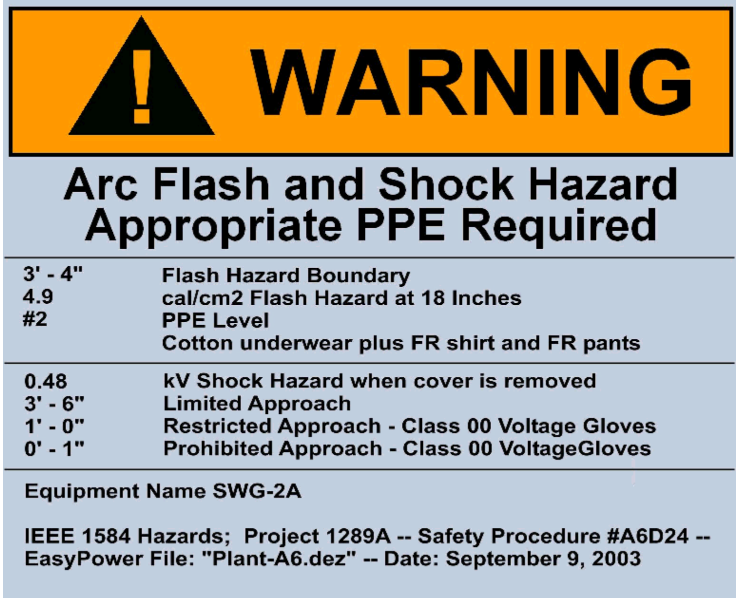
2) Switch to different operating modes as defined in Scenario Manager.

3) Run arc flash calculations for each operating mode to determine highest arc hazard.

4) Compare the highest incident energies from the base case and scenarios. Take the case with the highest values (there may be multiple cases for different parts of the system) and modify the arcing current to reflect a high impedance arcing current. This will lower the arcing current, which may cause longer trip times and result in higher incident energies. See STEP-2, and Figure B.6. Note: A good starting place is 80% of the calculated arcing current. Going much lower than this may result in current values that cannot be realistically maintained.

5) Compare the incident energies of the case selected in task 4 above with the high impedance values of the same case. Print labels.

The following labels can be printed on plastic stock through most laser printers, or via commercially available label printers. EasyPower® provides direct output to selected label printers so you will avoid hours of data conversion routines.



WARNING

Arc Flash and Shock Hazard
Appropriate PPE Required

3' - 4"	Flash Hazard Boundary
4.9	cal/cm2 Flash Hazard at 18 Inches
#2	PPE Level
	Cotton underwear plus FR shirt and FR pants
0.48	kV Shock Hazard when cover is removed
3' - 6"	Limited Approach
1' - 0"	Restricted Approach - Class 00 Voltage Gloves
0' - 1"	Prohibited Approach - Class 00 VoltageGloves

Equipment Name SWG-2A

IEEE 1584 Hazards; Project 1289A -- Safety Procedure #A6D24 --
EasyPower File: "Plant-A6.dez" -- Date: September 9, 2003

Figure B.14: Warning label that can be printed directly from EasyPower ArcFlash program.

Economic Benefits

The economic benefits of performing arc flash assessments using dedicated power system analysis software becomes readily apparent when the alternative is to use a spreadsheet calculator like those provided in IEEE-1584. Arc hazard assessments using a spreadsheet calculator requires the following tasks:

1) Transfer data from the short circuit program to the spreadsheet calculator. This includes short circuit calculations, bus names, and bus voltages.

2) Determine the arc gap for each calculation or equipment in the spreadsheet.

3) Determine the trip time for each device or bus in the spreadsheet. There are usually multiple trip times required for each bus.

4) Run the calculation.

5) Apply NFPA-70 PPE requirements to each calculation.

6) Spreadsheet calculations DO NOT provide for a device-by-device analysis, unless the users accounts for each device in the system.

7) Perform the calculation for a change in tie breaker status or generation (mode of operation).

8) Take the highest results (case) and re-run using a higher impedance arcing fault to insure accurate results.

As can be seen, the man hours required to perform an arc flash assessment can be cost prohibitive using a spreadsheet calculator. When applied to large systems, such as those in the petrochemical or the pulp and paper industries, it becomes almost impossible. Another consideration is the potential for errors when applying the hand calculations, trip time look-ups, and spreadsheet work.

EasyPower®'s complete integration of short circuit, protective device coordination, and arc flash can be exponential as compared to the use of an IEEE-1584 spreadsheet calculator. EasyPower® simplifies the process, reduces human error and provides a basis from which system changes and modifications can be modeled and the study results updated immediately without the extensive work and risk of error associated with a spreadsheet. EasyPower® also helps with safety program requirements for accurate documentation as it provides reports that become a key part of a corporate arc flash hazard safety program. The EasyPower® ArcFlash program will also be kept up-to-date with the latest industry standards, helping to ensure the most accurate results.

Conclusion

This guide presents the basic steps for performing an arc flash hazard assessment using power analysis software. Users performing arc flash assessments should be aware that reduced short circuit currents could increase arc incident energies for some cases. They should also fully understand the arc let through energies as applied to protective devices, before assigning arc flash boundaries and incident energy ratings to equipment.

Power analysis software that provides complete one-line/analysis integration eliminates the separate steps required by other programs and integrates the short circuit, protective device, and arc hazard functions. This greatly reduces the time and effort to perform the analysis.

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