Practical Solution Guide to Arc Flash Hazards

SECOND EDITION

Conrad St. Pierre
Satish Shrestha, PE
Afshin Majd, PhD, PE
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Mike Koch

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EasyPower, LLC
developers of

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Power made easy.

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FORWARD

EasyPower, LLC is pleased to bring you the Second Edition of the "Practical Solution Guide to Arc Flash Hazards." This edition has been fully updated to reflect the most recent changes in standards and practices. 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 help manage the complex tasks of OSHA and NFPA 70E compliance for arc flash hazards.

Arc flash hazard analysis and the development of safety programs to protect against arc flash hazards is still in its infancy. Research into the arcing phenomena is ongoing as the industry tries to better understand and model arcing faults. Standards and recommended practices are changing constantly to reflect these new understandings and to better protect workers. Personal protective equipment (PPE) is also changing at a rapid pace as new and better technology is developed. EasyPower, LLC 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.

EasyPower, LLC is committed to providing the industry with the most advanced state-of-the-art technology in our EasyPower® software product line. We believe the EasyPower software provides the self-documenting solution capabilities to keep your safety program current and in compliance with OSHA and NFPA 70E® standards. EasyPower, LLC 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.

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.

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Introduction

Our increased dependence on electrical energy has created a lower tolerance for any power outage, no matter how brief. This, in turn, has brought about at least a perceived need for electrical workers to perform maintenance work on energized electrical equipment. In addition to the electrical shock hazard that results from direct contact of live conductors with the body, workers are also exposed to the risk of injury due to accidental initiation of electric arcs. Arc flash injuries can occur without any direct contact with energized parts. This hazard due to arcing faults has existed from the beginning of the electric power industry, but has only recently been addressed as a specific hazard in electrical safety programs and safety codes.

An electric arc or an arcing fault is the flow of electric current through the air from one conductor to another or to ground. Arcs are generally initiated by a flashover caused by some type of conductor that subsequently vaporizes or falls away, leaving an arc. Arcing faults create many hazards, but the greatest risk is burn injuries due to exposure to the heat generated by the arc. This heat can cause serious, even fatal burns, as well as ignite clothing and other nearby material and objects. In addition, electric arcs can produce molten metal droplets, UV radiation, and explosive air pressure waves.

In 2003, when we were approached by many plant engineers, technicians, consultants, electrical contractors, and health and safety managers, we attempted to provide a brief description of the various aspects of arc flash hazards. This book was written to describe these aspects and the ways to address the hazard. It is difficult to talk about arc flash safety without mentioning the name of the pioneer who brought our attention to this topic. Ralph H. Lee published the first paper on arc flash, The Other Electrical Hazard: Electric Arc Blast Burns, in the journal "IEEE Transactions on Industry Applications," (Volume: IA-1   Issue: 3) in May 1982. This paper not only pointed out that arc flash was a deadly phenomenon, but also showed how to calculate the heat energy exposure to workers. In the first two decades after that, progress made by the industry to address arc flash safety was fairly slow. Significant highlights were Doughty et al. papers showing empirical equations for incident energy calculations, and the inclusion of arc flash hazard in the NFPA 70E standard (2000) and the publication of IEEE 1584-2002. Since then, arc flash safety has been given a lot of attention. Every edition of NFPA 70E has had new additions and revisions. Many companies have caught up with arc flash studies, labeling, training, and Personal Protective Equipment (PPE). Arc flash safety was of one the major topics of conferences and professional journals. New findings were reported on how conductor orientation could affect the magnitude of arc flash heat exposure. New technologies were introduced to reduce the magnitude of arc flash.

The second revision of this book includes all major updates in the various standards relating to arc flash. The recently introduced OSHA requirements for arc flash PPE for generation, transmission, and distribution are discussed. Several examples are provided to illustrate arc flash calculations.

Concepts and Definitions For Arc Flash Risk Assessment

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. To deal with the hazard, it is first necessary to understand the phenomena.

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. The 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 a different phase or ground.

- Condensation of vapor and dripping water 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: Tools dropped accidentally can cause a momentary short circuit, producing sparks and initiating arcs.

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

- Failure of the insulating materials.

Electric arcs are also caused by the following:

- Improperly designed or utilized equipment.

- Improper work procedures.
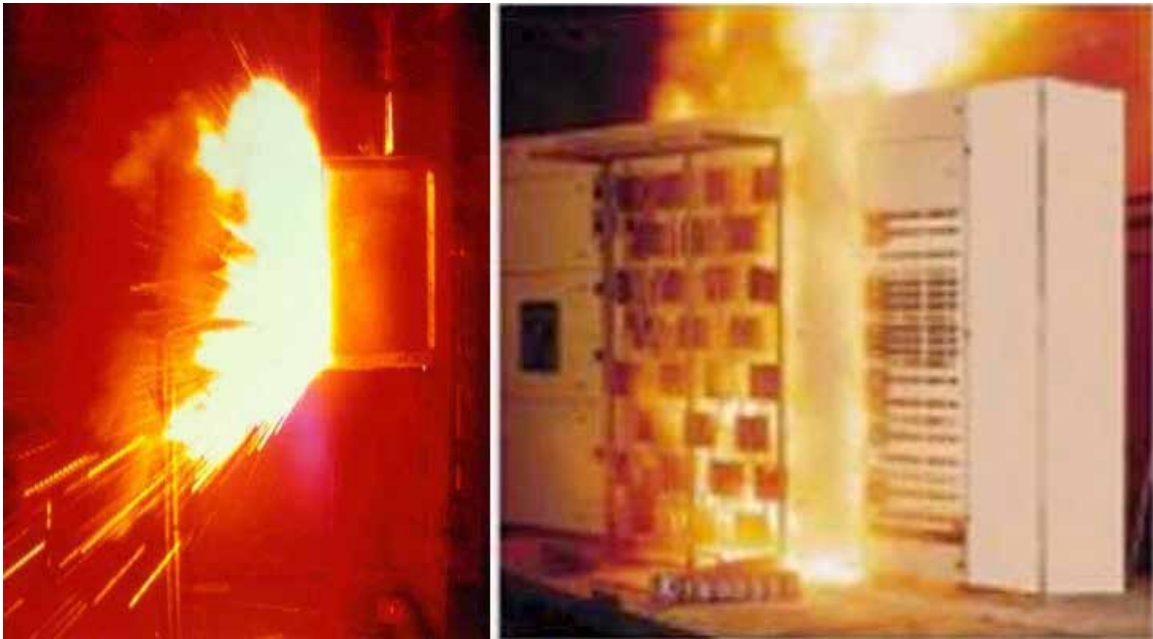
Figure 2.1: (a) Arc Blast in Box;[2] (b) Arcing Fault in an Electrical Panel Board

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 an 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—1,670 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.

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

- Arcs in enclosures, such as in a motor control center (MCC) or switchgear, magnify the blast and energy transmitted as the blast is forced to the open side of the enclosure and towards the worker.

Hazards of Arcing Faults

Figure 2.2: (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 the sound blast. The sound can have a magnitude as high as 140 dB at a distance of 2 feet from the arc.[9]

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.
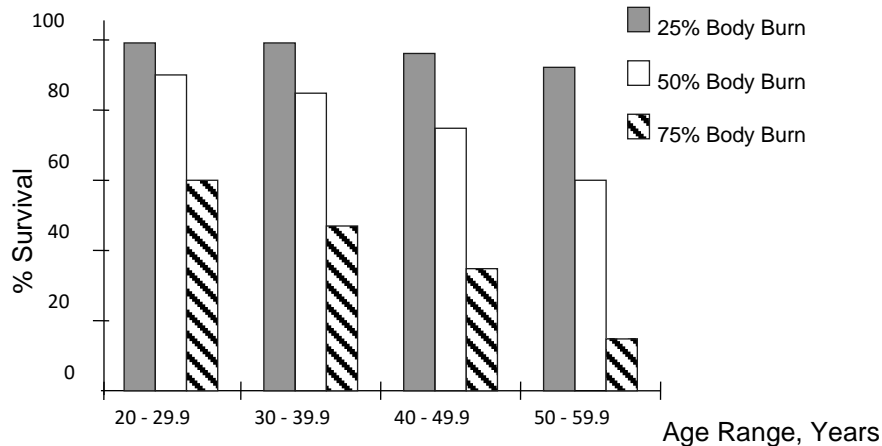
Figure 2.3: Burn Injury Statistics – Probability of Survival (Source: American Burn Association, 1991-1993 Study; Revised March 2002)

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.

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 and 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 Std 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, the need to use force, the available space and safety margins, reach, etc.

- Training, skills, mental and physical agility, coordination with helper.

- Tools used.

- Condition of equipment.

- Maintenance conditions of the equipment.

Developments in Addressing Arc Flash Hazard

Historically, the National Electric Code (NEC®) and other safety codes were primarily concerned with protection from fire, electrocution, and shock hazard—arc flash hazards were not addressed. This changed in 2002, when NEC included 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. 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-2015 includes 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.

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. Terrill, 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."*

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.[11] 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.

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

2. 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.

3. See endnote 1.

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

5. See endnote 1.

6. 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.

7. See endnote 1.

8. See endnote 1.

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

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

11. 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).

Arc Flash Calculation and NFPA 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.

IEEE Std 1584-2002

IEEE 1584-2002 is titled "IEEE Guide for Performing Arc-Flash Hazard Calculations," and provides a methodology for calculating prospective arc flash hazards. Based on test data, the IEEE 1584 committee developed empirical equations to calculate arc flash incident energy for AC systems. It is important to understand that the IEEE 1584 equations are valid only for the conditions for which test data was evaluated. These limitations are summarized in Table 3.1.

Table 3.1: Applicable Conditions for Use of the IEEE 1584 Calculation Method

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
Types of faults	3 phase faults ONLY

Step 1: Estimate of Arcing Current

The IEEE 1584 calculation method has empirical equations for conversion of calculated bolted (zero impedance) faults to estimated arcing fault currents. Due to the resistance of the arc, arcing current will be less than a zero impedance fault at the same location. The lower the system voltage, the greater impact the arc resistance has on the calculated arcing current.

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

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

where

$\log = \log_{10}$

I_a = arcing current (kA)

$K = -0.153$; open configuration

$\quad = -0.097$; box configuration

I_{bf} = bolted fault current for 3-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).

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

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)

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

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)

Step 3: Estimate of Incident Energy

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

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

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

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. This is the same as the Arc Flash Boundary discussed in NFPA 70E.

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

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)

NFPA 70E Annex D

Introduction

Although NFPA 70E is not specific about how incident energy and the arc flash boundary must be calculated, Annex D describes some recognized calculation methods. However, it must be remembered that the Annexes are not a part of the actual NFPA 70E requirements, but are provided for information only.

Ralph Lee Calculation Method (Annex D.2)

The "Ralph Lee" calculation method is based on the original paper published by Ralph Lee regarding arc flash hazards, "The Other Electrical Hazard: Electrical Arc Flash Burns." In this paper, calculation methods were developed based on first principles and

theoretical equations. Refer to the referenced paper for greater detail. In Annex D, the Lee method is used to calculate the arc flash boundary and also to calculate incident energy levels for systems rated above 600 V. For systems rated 600 V or less, Annex D uses the "Doughty Neal Paper" method. The combination of the Ralph Lee Method and the Doughty Neal Paper method described in Annex D are referred to as "NFPA 70E-2015, D2, D3" in the calculation Standard option under Arc Flash Options in EasyPower.

The basis of the Lee method is a determination of the maximum possible arc energy for a given bolted fault current. Based on classic circuit theory, the maximum power can be stated:

P = Max bolted fault MVA x 0.707^2

Based on this assumption, the arc flash boundary distance is calculated based on the following formula:

$D_c = [2.65 \times MVA_{bf} \times t]^{1/2}$

where:

D_c = distance in FEET of the person from arc source (based on 80 deg C skin temperature)

MVA_{bf} = Bolted fault MVA at location

t = time of exposure in seconds

Doughty Neal Paper (Annex D.3)

Annex D references the paper "Predicting Incident Energy to Better Manage the Electrical Arc Hazard on 600 V Power Distribution Systems" by Doughty, et al., and refers to this as the "Doughty Neal Paper." The equations in this paper can be used to calculate the incident energy for systems at 600 V and below. Annex D.3 cautions that "The results of these equations might not represent the worst case in all situations. It is essential that the equations be used only with the limitations indicated in the definitions of variable shown under the equations. The equations must only be used under qualified engineering supervision." Please refer to the original paper and Annex D section D.3 for more information.

The equations used in this method distinguish between arcs in open air and arcs in a box, as does IEEE 1584. The prospective length of the arc gap is also factored into the equations. Fault currents are limited to the range of 16 kA to 50 kA.

For arc in open air:

$$E_{MA} = 5271 \times D_A^{-1.9593} \times t_A \begin{bmatrix} 0.0016F^2 \\ -0.0076F \\ 0.8938 \end{bmatrix}$$

Where

E_{MA} = maximum open arc incident energy, cal/cm²

D_A = distance from arc electrodes (for distances greater than 18 inches)

t_A = arc duration, sec.

F = short circuit current, kA (valid from 16 kA to 50 kA)

For arc in box:

$$E_{MB} = 5271 \times D_B^{-1.9593} \times t_B \begin{bmatrix} 0.0093F^2 \\ -0.3453F \\ 5.9675 \end{bmatrix}$$

Where

E_{MB} = maximum 20 in. cubic box incident energy, cal/cm²

D_B = distance from arc electrodes (for distances greater than 18 inches)

t_A = arc duration, sec.

F = short circuit current, kA (valid from 16 kA to 50 kA voltage)

DC Arc Flash Calculations (Annex D.5)

Section D.5 in Annex D contains information regarding calculation of arc flash incident energy for DC systems. In D.5.1, equations are shown for calculating DC arc flash energy based on the theoretical maximum power transfer approach. These equations are based on a paper by Dan Doan, "Arc Flash Calculations for Exposure to DC Systems" that was published in the *IEEE Transactions on Industry Applications*, Vol 46, No. 6. This method is applicable for DC systems up to 1000 V.

$I_{arc} = 0.5 \times I_{bf}$

$IE_m = 0.01 \times V_{sys} \times I_{arc} \times \dfrac{T_{arc}}{D^2}$

Where:

I_{arc} = arcing fault amperes

I_{bf} = bolted fault amperes

IE_m = estimated DC arc flash incident energy at maximum power point, cal/cm²

V_{sys} = system voltage, volts

T_{arc} = arcing time, sec

D = working distance, cm

For batteries, D.5.3 suggests that the battery bolted fault current be assumed to be 10 times the 1 minute battery rating (to 1.75 V per cell at 25 deg C) if more specific data is not available from the battery manufacturer.

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 Std 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,[1] *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,
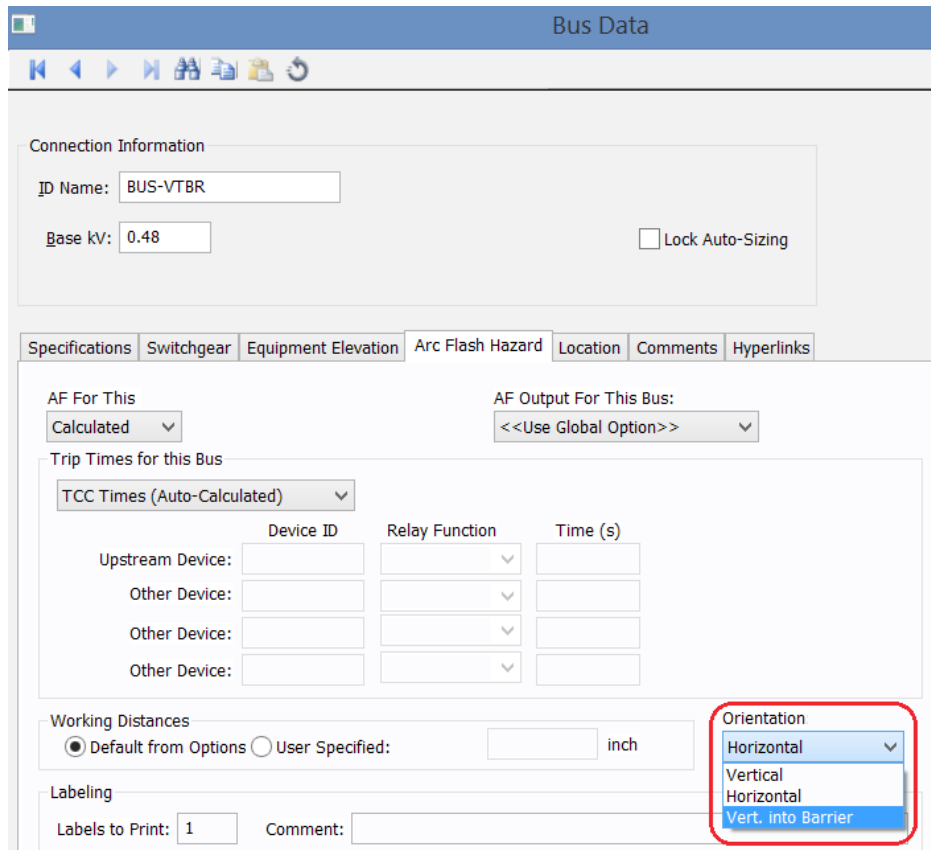
Pressure is in pounds per square foot.

D = distance from arc in feet

I_{arc} = arc current in kA

Electrode Orientation

The IEEE 1584 tests are based on the arcing electrodes in a vertical plane and the calorimeters arranged at 90° to this plane. The test results[2,3,4] indicate that the arc flash hazard is much worse with the electrode horizontal orientation pointing towards the calorimeter or the vertical electrode tips terminated in an insulating barrier instead of in the open air. To account for these conditions, EasyPower enables users to select electrode orientations such as Horizontal or Vertical into Barriers in addition to the default Vertical orientation used in the IEEE 1584 test as shown in the Bus Data dialog box below. The arc flash incident energy calculated with the electrode orientation selected as Horizontal or Vertical into Barriers will be 267% of the incident energy from the default Vertical orientation for low voltage systems and 300% for voltage higher than 1 kV.

Figure 3.1: Setting the Bus Orientation in the Bus Data Dialog Box

Current-limiting Fuses

IEEE 1584-2002 provides an alternative method for calculating arc flash energies for arcing fault cleared by current-limiting fuses. These alternative equations are based on limited testing done for Class L and Class RK1 fuses up to 2000 A from a single fuse manufacturer. Unlike the equations described in Step 4 of the IEEE Std 1584-2002 section earlier in this chapter, the determination of incident energy at an 18" working distance is based solely on the available bolted fault current at the fuse, and does not include factors for determination of arcing fault current, arc time, or arc gap. All testing was done within one specific enclosure size. In addition, these equations are only applicable for available fault currents equal to or greater than the minimum values given for each size range and type of fuse:

        Class L 1601-200 A   22.6 kA minimum

        Class L 601-1600 A   15.7 kA minimum

        Class RK1 401-600 A   8.5 kA minimum

Class RK1 201-400 A   3.16 kA minimum

Class RK1 101-200 A   1.16 kA minimum

Class RK1 1-100 A   0.65 kA minimum

EasyPower is equipped with an option to use the current-limiting fuse equations described in IEEE-1584. However, this option is not the default method for the following reasons:

- The IEEE 1584 tests used to determine the current-limiting fuse equations were based on only one manufacturer's fuses. This would be equivalent to modeling an IAC-53 relay with a Westinghouse CO-8 trip characteristic. It may be in the ballpark, but it is not accurate.

- The tests were very limited in number for each fuse size and were not repeatable for different currents.

- Only a very limited number of fuse types and sizes were tested.

The default method in EasyPower uses the actual time current curve for each specific fuse manufacturer, type, and style to specifically model the melting and clearing time of each fuse. For all fuse clearing times less than 0.01 seconds and less than 50 kA at 480 V, the current-limiting effect will be inherent in the results by the fast clearing time. For lower values of fault current, the current-limiting effect does not play a major role in reducing arc energy.

If the current-limiting fuse equations described in IEEE 1584 are desired, the following steps will set this option in EasyPower.

In the **SC Options** dialog box, do the following:

1. On the **Arc Flash Hazard** tab, click **Advanced**.
2. In the **AF Advanced** dialog box, select the **Include 1584 CL Fuse Calcs** check box.
3. Click **OK** twice to save your changes.
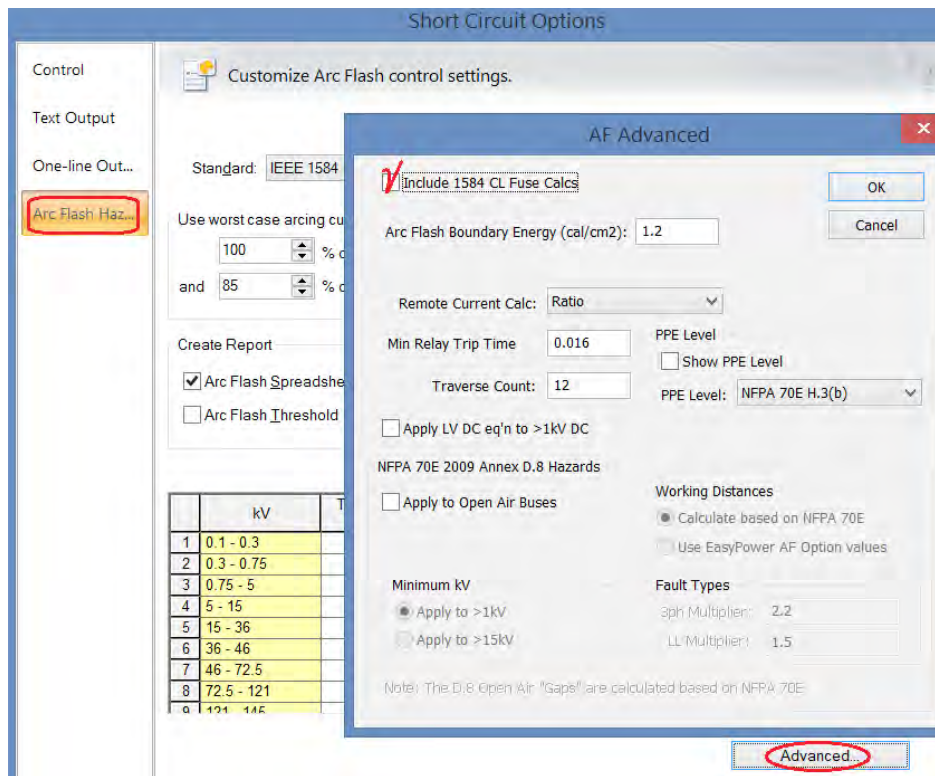
Figure 3.2: Selecting the IEEE 1584-2002 Current-limiting Fuse

Duration of the Arcs

EasyPower determines the duration of the arcs based on the following IEEE 1584b-2011 requirements:

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

- For relays operating in their instantaneous region, allow 16 milliseconds on 60 Hz systems for operation. The default time in EasyPower is 0.016s and the user can modify this time with following steps.

In the **SC Options** dialog box, do the following:

1. On the **Arc Flash Hazard** tab, click **Advanced**.
2. In the **AF Advanced** dialog box, modify the default **Min Relay Trip Time** 0.016.
3. Click **OK** twice to save your changes.
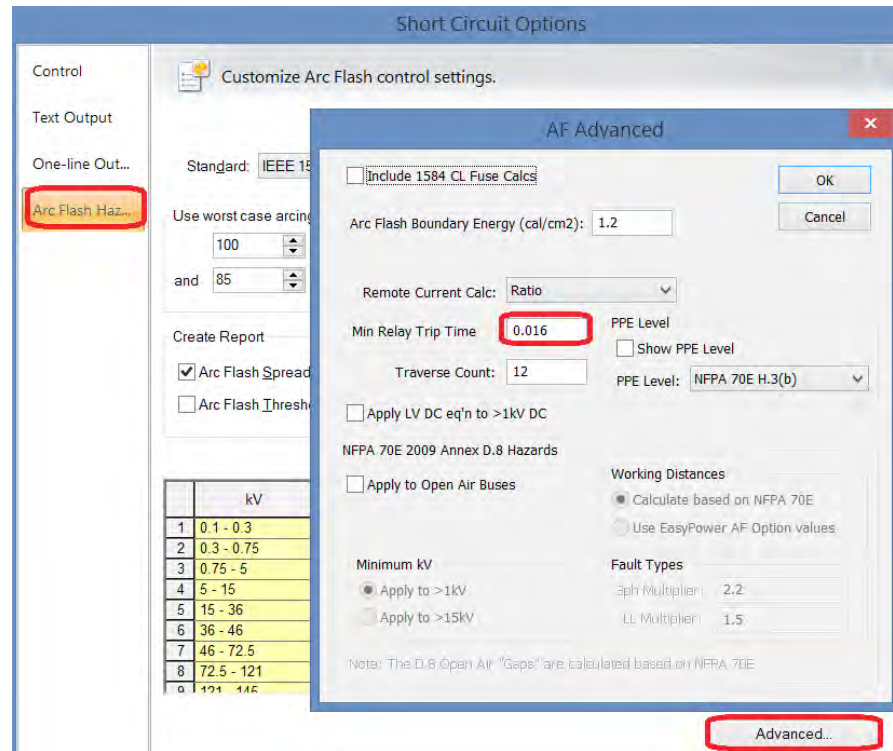
Figure 3.3: Setting the Minimum Relay Trip Time

Estimated Incident Energy for Overhead Open Air Systems

In the 2007 Edition of the NESC (National Electrical Safety Code - ANSI C2), a new rule was added that specifically addresses a worker's exposure to arc flash hazards, and it can be found in Rule No. 410.A.3. Where working on or near energized electrical equipment, the NESC rule states: "Effective as of January 1, 2009, the employer shall ensure that an assessment is performed to determine potential exposure to an electric arc for employees who work on or near energized parts or equipment. If the assessment determines a potential employee exposure greater than 2 cal/cm² exists (see Neal, Bingham, and Doughty [B59]), the employer shall require employees to wear clothing or a clothing system that has an effective arc rating not less than the anticipated level of arc energy. When exposed to an electric arc or flame, clothing made from the following materials shall not be worn: acetate, nylon, polyester, or polypropylene. The effective arc rating of clothing or a clothing system to be worn at voltages 1000 V and above shall be determined using Tables 410-1 and 410-2 or performing an arc-hazard analysis. When an arc hazard analysis is performed, it shall include a calculation of the estimated arc energy based on the available fault current, the duration of the arc (cycles), and the distance from the arc to the employee."

Tables 410-1 and 410-2 in the NESC 2007 Edition were updated to Tables 410-2 and 410-3 in the NESC 2012 Edition. The NFPA 70E 2009 Annex D.8 Tables list the heat flux

rate derived from the ANSI/IEEE C2 (NESC) 410 Tables. To estimate the incident energy exposures for live line work on overhead open air systems 1 kV to 800 kV, multiply the heat flux rate in the D.8 Tables by the maximum clearing time (in seconds). The incident energies estimated from the NFPA 70E 2009 Annex D.8 Tables are the same as from NESC 410 Tables.

The NFPA 70E 2009 Table D.8(2) and NESC 2012 Table 410-3 were calculated based on following conditions:

- Arc gap—calculated by using the phase-to-ground voltage of the circuit and dividing by 10. The dielectric strength of air is taken at 10 kV per inch. See IEEE Std 4-1995.

- Distance from arc—calculated by using the minimum approach distance from NESC Table 441-2 and subtracting two times the assumed arc gap length, and using the following T values: 72.6 kV to 362 kV = 3.0, 362.1 kV to 550 kV = 2.4, 550.1 kV to 800 kV = 2.0.

- EasyPower is equipped with an option to estimate the incident energy exposures for live line work on overhead open air systems 1 kV to 800 kV based on the NFPA 70E 2009 Annex D.8 Tables, which are the same as Tables 410-2 and 410-3 in the NESC 2012 Edition.

The following are the steps needed in EasyPower to calculate the incident energy for an open air AC system rated at 1 to 800kV:

1. In the **Bus Data** dialog box, set the **Bus Type** (equipment type) to **Open Air**.
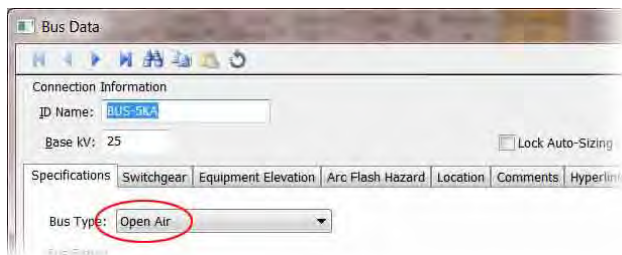
Figure 3.4: Setting the Bus Type to Open Air

2. In the **SC Options** dialog box, do the following:
   a) On the **Arc Flash Hazard** tab, click **Advanced**.
   b) In the **AF Advanced** dialog box, under **NFPA 70E Annex D.8 Hazards,** select the **Apply to Open Air Buses** check box.
   c) Under **Minimum kV**, select either **Apply to >1kV** or **Apply to >15 kV**.
   d) Click **OK** twice to save your changes.
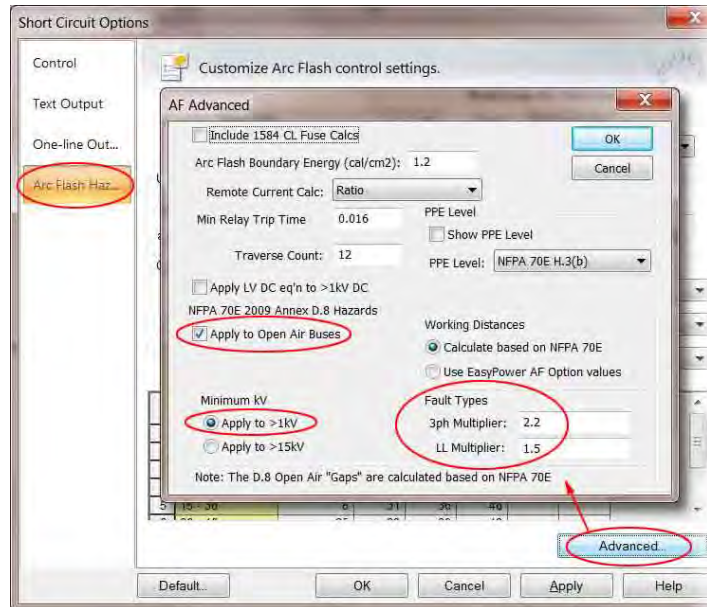
Figure 3.5: Options for Arc Flash Calculations on Open Air Buses

3. On the one-line, click **Line to Ground**. EasyPower normally determines the arcing time based on the protective devices used in the system. If 3-phase or line-to-line fault simulations are performed, the incident energy is equal to 2.2 or 1.5 times that of the line-to-ground fault. The 2.2 or 1.5 multipliers can be changed in the **AF Advanced** dialog box, under **Fault Types**.

4. Trip times for each bus can be defined in their data dialog box in lieu of a protective device.
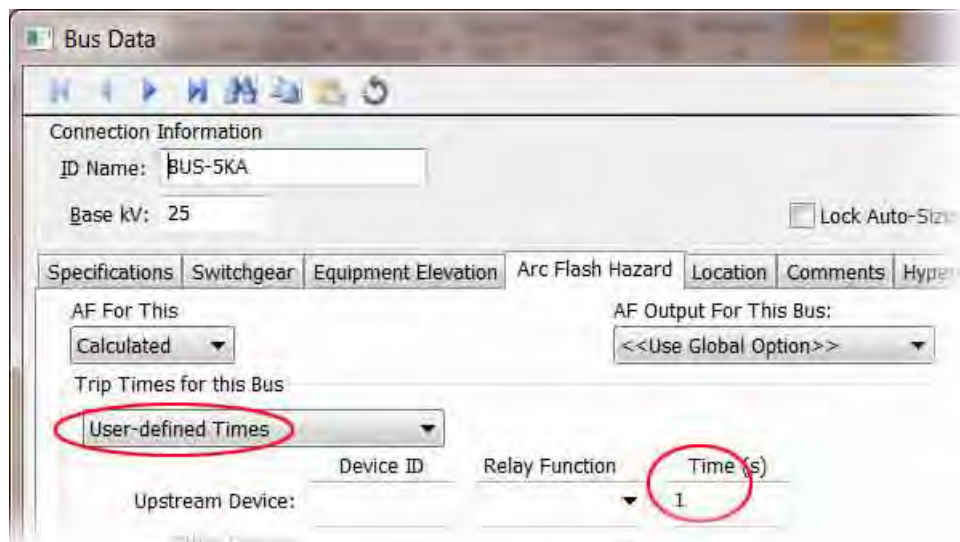
Figure 3.6 Setting User-Defined Arc Time for a Bus

Example: In the following example, a 25kV open air system has been simulated for the incident energy calculations both in EasyPower and ArcPro.

It should be noted that NFPA 2009 D.8 tables list the heat flux rate, which are derived from the ANSI/IEEE C2 (NESC) 410 tables. To obtain the incident energy exposures for an arc flash in an overhead open air system rated at 1 to 800 kV, multiply the heat flux rate in the D.8 tables by the maximum clearing time (in seconds).

The following table indicates that EasyPower outputs match the NFPA D.8 table values, as well as ArcPro results.

Table 3.3: EasyPower Outputs Match the NFPA D.8 Table Values and ArcPro Results

Line-to-Ground Bolted Fault Current (kA)	Arcing Gap		Working Distance	Heat flux Cal/cm²/s		1-second Incident Energy (Cal/cm²)		
	(mm)	(inches)	(inches)	NFPA Table D.8(1)	ArcPro	NFPA Table D.8(1)	ArcPro	EasyPower
5	101.6	4	15	8.7	8.7	8.7	8.7	8.7
10	101.6	4	15	20.8	20.8	20.8	20.8	20.8
15	101.6	4	15	35.6	35.6	35.6	35.6	35.6
20	101.6	4	15	52.8	52.8	52.8	52.8	52.8

The EasyPower system one-line diagram, arc flash calculation results, and reports are shown in the following figures.
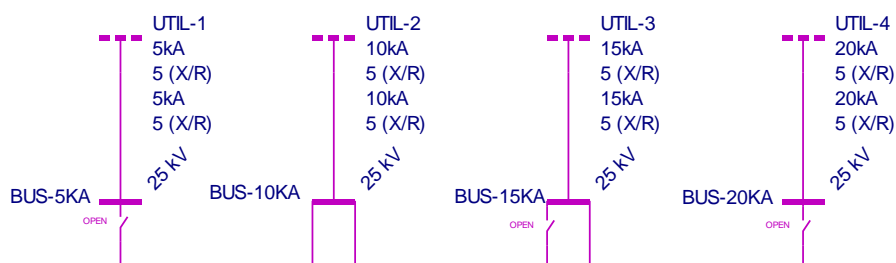
Figure 3.7: 25 kV System
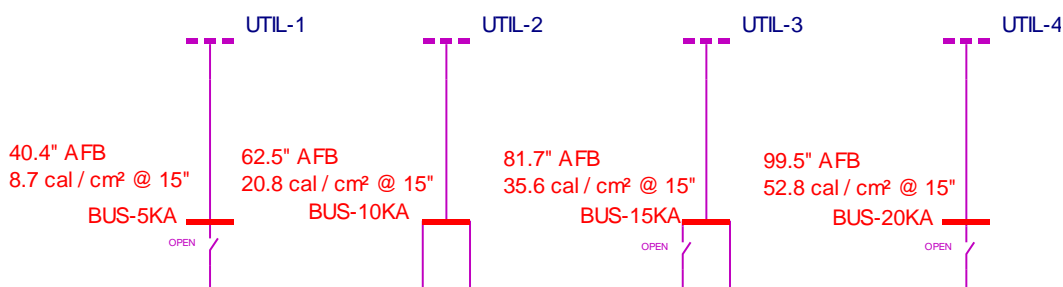
Figure 3.8: Calculation Results for Line-to-Ground Arcing Faults with One Second Arcing Time

Figure 3.4 EasyPower Output Table

Arc Fault Bus Name	Arc Fault Bus kV	Equip Type	Gnd	Arc Gap (mm)	Bus Bolted Fault (kA)	Bus Arc Fault (kA)	Arc Time (sec)	Est Arc Flash Boundary (inches)	Working Distance (inches)	Incident Energy (cal/cm2)
BUS-5KA	25	Open Air	X	101.6	5	5	1	40.4	15	8.7
BUS-10KA	25	Open Air	X	101.6	10	10	1	62.5	15	20.8
BUS-15KA	25	Open Air	X	101.6	15	15	1	81.7	15	35.6
BUS-20KA	25	Open Air	X	101.6	20	20	1	99.5	15	52.8

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

2. Stokes, A.D. and Sweeting, D.K. "Electric Arcing Burn Hazards" IEEE PCIC Conference Record, 2004. Paper PCIC-2004-39, 9pp.

3. R. Wilkins, M. Allison and M. Lang "Effect of Electrode Orientation in Arc Flash Testing" 2005 Industry Applications Conference, October 2005

4. R. Wilkins, M. Lang and M. Allison "Effect of Insulating Barriers in Arc Flash Testing" 53rd Annual Technical Conference of the IEEE PCIC, September 2006. Paper No. PCIC-2006-6

Practical Steps to Arc Flash Calculations

CHAPTER
04

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.

Introduction

Several methods for arc flash calculations were described in Chapter 3. In this chapter, we look at the practical steps for the arc flash calculations.

The following steps are involved in detailed arc flash study.

1. Identify all locations and equipment for arc flash hazard assessment.

2. Collect Data:

   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, and 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 one-line diagram of the system.

4. Perform a short circuit study:

   a. Calculate bolted (available) 3-phase fault current for each piece of equipment.

   b. Calculate current for every contributing branch and load.

5. Determine expected arc current:

   a. Calculate arc current.

   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 arc flash boundary for the equipment.

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

It is important to understand the steps required to calculate the arc flash incident energy and arc flash boundary. The use of EasyPower software allows for easy calculation of arc flash incident energies and arc flash boundaries and documentation of the analysis with reports, one-line diagrams, and arc flash labels.

Step 1 – Identify All Locations and Equipment for Arc Flash Hazard Assessment

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. This comes from the IEEE 1584-2002 recommendations. 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.

Since 2002, additional testing has demonstrated that the IEEE 1584-2002 recommendation in the paragraph above may not be conservative in all cases. On the EasyPower website (easypower.com) in the Arc Flash Resource Center is a document titled "Calculating Arc Flash Energies and PPE for Systems <250V" that can help answer some questions regarding this gray area. The document discusses some of the newer testing data along with giving options to make sure your workers are properly protected for energized work at this level. NFPA 70E-2015 Table 130.7(C)(15)(A)(a) also may also be used to determine whether an arc flash incident energy should be calculated for a particular equipment type based on the tasks to be performed.

Step 2 – Collect Data

Refer to Chapter 7 – Data Collection for additional information describing the data collection process.

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 the utility, generators, transformers, cables, transmission lines, motors, etc. The nameplate 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 have an extensive library of manufacturer's 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[1, 2, 3] 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	

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 the time-current characteristics (TCC) for these devices from the manufacturers. **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.

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 an Arc Flash Hazard Study

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

*Data required for the IEEE 1584 method

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.

Determine All Possible Operating Conditions

Make note of all possible connections (system operating modes) using diagrams and tables. The circuit breaker, switch, or fuse statuses 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 arc flash hazard. Figure 4.1 shows the available fault currents for two scenarios of connections: (a) everything connected and (b) the 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

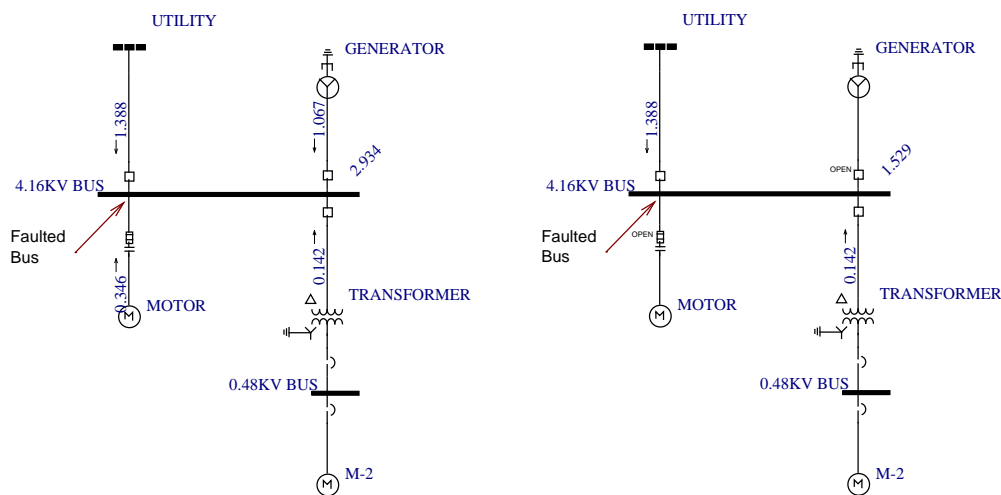| Equipment Connected	Normal Operation	Co-generation	Maintenance Schedule A	Maintenance Schedule B
Utility	ON	ON	OFF	ON
Generator	OFF	ON	ON	OFF
Motor	ON	ON	ON	OFF
M-2	ON	ON	ON	ON

Figure 4.1: EasyPower® Example of Connected Equipment for Two Possible Cases

Step 3 – Prepare a One-line Diagram of the System

One-line (single-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 the 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 EasyPower software requires the 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.

Step 4 – Perform a Short Circuit Study

A complete tutorial on performing short circuit studies is not provided here, but additional considerations related to arc flash hazards when performing short circuit studies are described briefly in the sections that follow. The EasyPower software short circuit module will calculate the bolted fault and arcing fault currents that are applied in the arc flash hazard equations. Steps 4 and 5 in this chapter describe the different currents calculated by the program. As a user of the software, it is important to understand the different currents used in the arc flash calculations and why they are necessary. This will enable you to understand the implications of your design decisions and also help when trying to mitigate high arc flash hazards.

Only 3-phase faults are considered when performing arc flash hazard analysis. 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 single-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 arc flash hazard analysis, 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 arc flash hazard determinations, short circuit calculations should be conservative, but not overly conservative.

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 that can be operated open or closed.

- Large motors or process sections not in operation.

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

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 can be a 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.

Step 5 – Determine Expected Arc Current

Calculate Arc Current

Calculate arc current for every required equipment or bus using one of the empirical formulas 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.

Consider a Range of Arc Current

Tolerance Due to Random Variation based on IEEE 1584

To cover the variance that can occur in arcs, IEEE procedure suggests the following for voltages below 1000 V:

1. Calculate the expected bolted fault condition.

2. Calculate the arcing current at 100% of the IEEE 1584 estimate for the above condition.

3. Calculate the arcing current at 85% of the IEEE 1584 estimate for the above condition.

4. At these two 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.

The default settings in EasyPower's arc flash options apply the IEEE recommendation of calculations at 85% and 100% of the arcing current. Only the worst-case result is shown in the analysis. For the other calculations, it may be necessary to use the program's Scenario Manager to create different scenarios with maximum and minimum expected bolted fault conditions.

Calculate Branch Currents Contributing to the Arc Current

This is done using the branch current contributions to the bolted fault current obtained in the prior step (Step 4, Calculate Contributing Branch Currents section). To calculate the contributing currents to the arc fault, use equation (4.1).

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

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, but 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 has low harmonic content. Therefore, the linear relation (4.1) is a reasonable approximation.

Step 6 – Estimate 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 the 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.

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 a single line curve: Find the tolerance for the trip time within the TCC data or the product literature. 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 the 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.
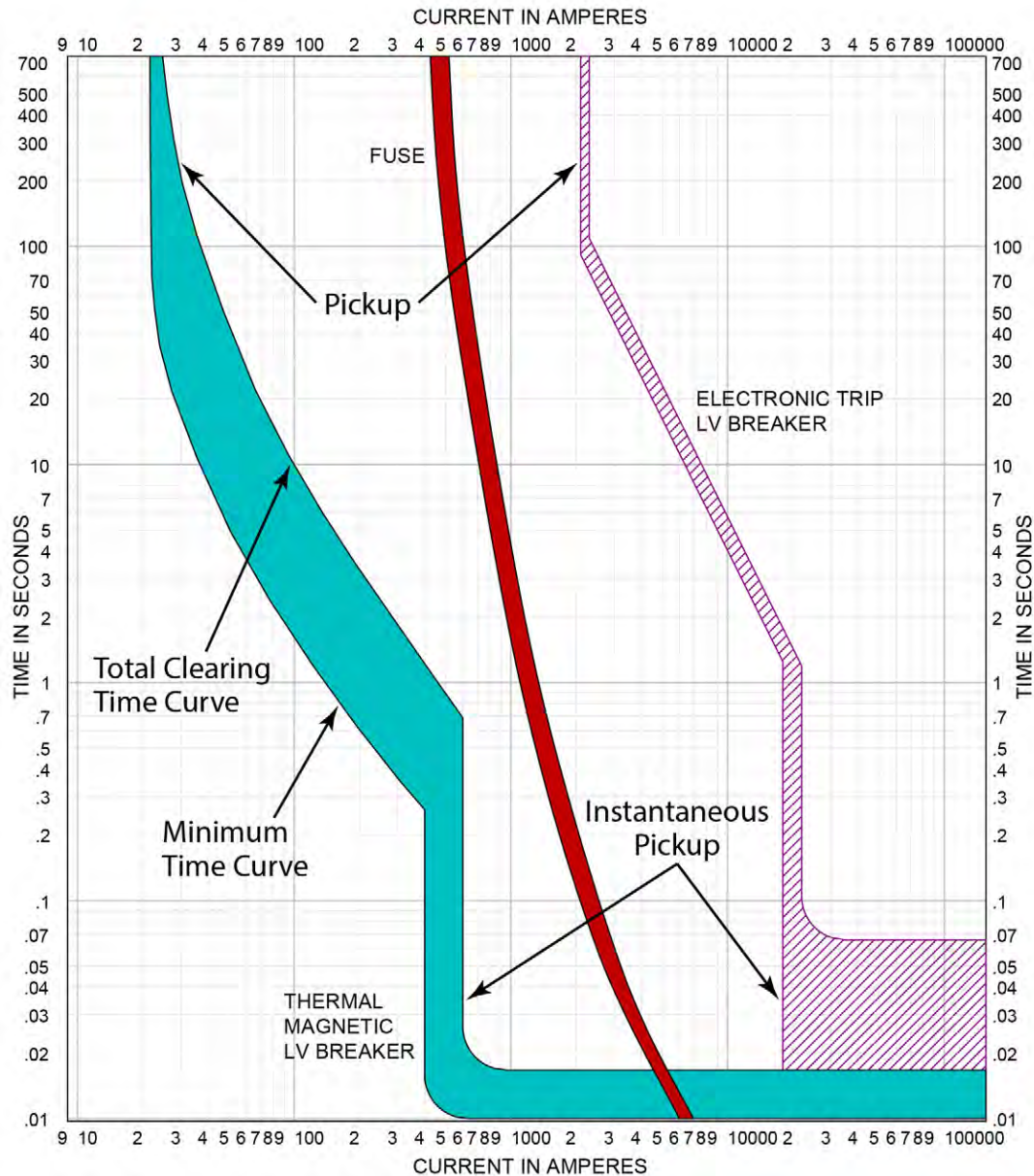
Figure 4.2: Example of TCC Plot with Tolerance Band

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.

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.

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 the operation of protective devices.

The EasyPower arc flash Integrated method can be used to calculate arc flash incident energies for equipment served from multiple feeds. The method of calculation accumulates the energy over time while taking into account the changing fault currents as the different protective devices trip or open at different times. The Integrated method is discussed in Appendix B.
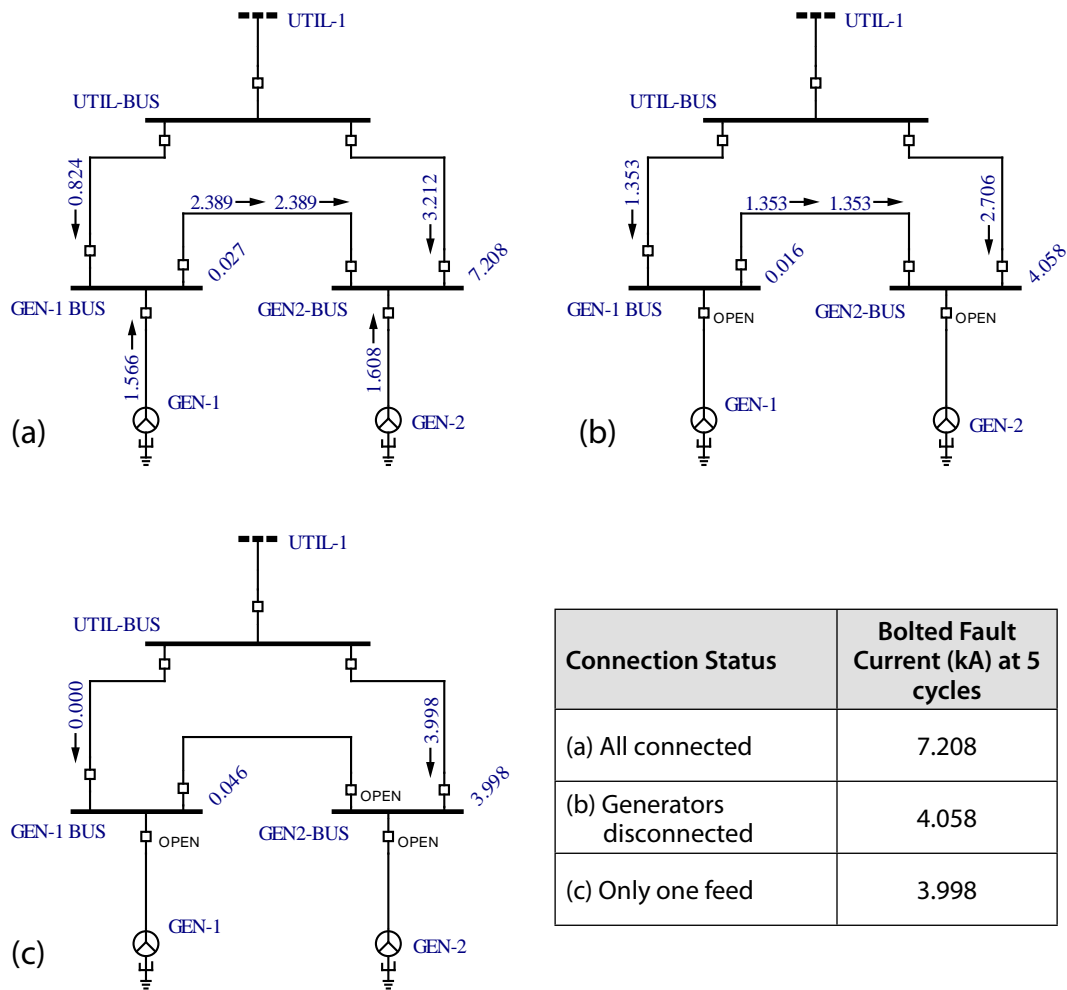
Figure 4.3: Example Showing Multiple Source Fed Bus Fault and Series of Operations with Fault Current Changing with Breaker Operation

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

Step 7 – Estimate 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, the distance from the arc, and the gap between electrodes

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:

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

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

- Upper bound of arc current due to random variations and its associated trip time.

- Multiple feed scenarios:
    - Evaluate incident energy for each type of possible connection as noted in Step 4.
    - Evaluate incident energy for arc current changing through the series of breaker operations, as described in step 6.

Step 8 – Determine the Arc Flash Boundary

The arc flash boundary is the distance at which persons exposed to arc flash, without appropriate PPE, will obtain second degree burns that are curable. The arc flash boundary is a function of the arc flash incident energy. The higher the arc flash energy, the farther away the boundary will be.

Step 9 – 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:

- It makes it easy for workers to access the necessary details and drawings. This is necessary for safety planning.
- It provides compliance with OSHA and NFPA.
- It makes it easy to implement changes in assessments when power system changes are made or when the standards are revised.
- In the event 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 like EasyPower helps to maintain compliance with the many aspects of NFPA 70E arc flash requirements and can greatly simplify a safety program.

Documentation in Reports

The assessment report should include the following details:

- The name of person performing the assessment.
- The date of assessment.
- All data collected and used in the assessment, including protective device settings.
- Assumptions used in the absence of data.

- The method of hazard assessment used—the standard and the revision year.
- If software was used, the name of the software and the version.
- The results—incident energy and arc flash boundary for every equipment.
- 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 the:

- Safety coordinator
- Safety division/department
- Foremen and electricians
- Electrical engineer
- Affiliated contractors

Documentation in One-Line Diagrams

Figure 4.4 shows an example EasyPower one-line diagram. This is the low voltage 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 on all the exposed conductor parts. In this example, the line side of the main breaker 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 the switchgear main breaker. This would provide the workers with the knowledge of risk at each equipment.

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

1. The arc flash hazard assessment results on every equipment that poses a risk.
2. Specify the arc flash boundary.
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 the true working condition. The closer the distance, the more the incident energy, and higher the risk.
4. 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 to communicate this with workers.

5. 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.
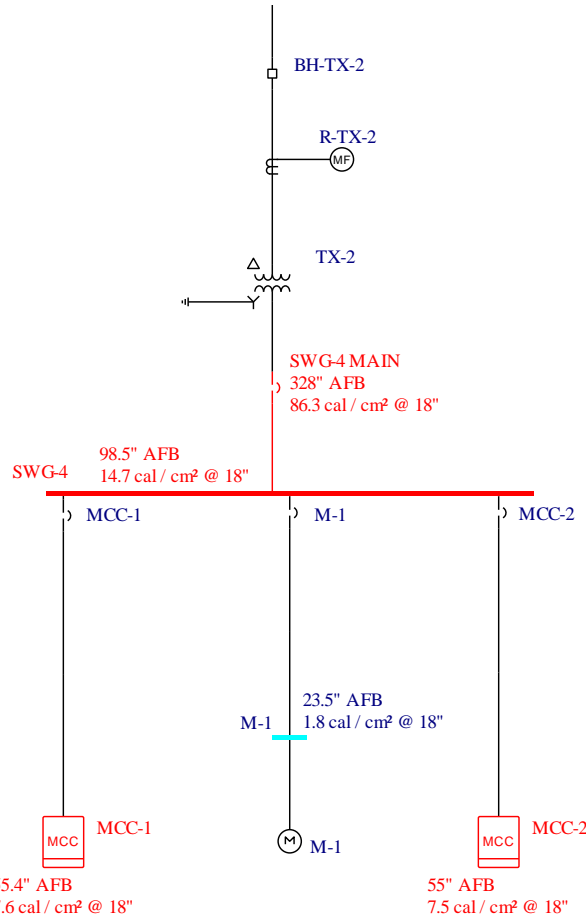
Figure 4.4: Example of Arc Flash Assessment Results on an EasyPower One-line Diagram

6. 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.

Arc Flash Labeling

Arc flash labels are to be placed on equipment to provide warning of the potential arc flash hazard present during energized work. Arc flash labels should be located in a place that is easily visible and readable from some distance. An example arc flash label is shown in Figure 4.5. NFPA 70E-2015[4] states "that the label contain all of the following:

1. Nominal voltage

2. Arc flash boundary

3. At least one of the following:

    a. Available incident energy and the corresponding working distance, or arc flash PPE category in Table 130.7(C)(15)(A)(b) or Table 130.7(C)(15)(B) for the equipment, but not for both.

    b. Minimum arc rating of clothing.

    c. Site-specific level of PPE.

The method of calculating and the data to support the information for the label shall be documented."

Note: Since the example label was obtained using the EasyPower software arc flash calculations, only the available incident energy is shown without reference to a PPE level. In the NFPA Article 130.5(C)(1) Informational Note:[5] "For information on selection of arc-rated clothing and other PPE, see Table H.3(b) in Informative Annex H." The example label shown below refers to the table for PPE requirements.

> ⚠ **WARNING**
>
> **Arc Flash and Shock Risk Assessment**
> **Appropriate PPE Required**
>
> | | |
> |---|---|
> | **14.7** | cal/cm²at 18 Inches - **Arc Flash Incident Energy** |
> | 8' - 2" | Arc Flash Boundary |
> | | Protective Clothing and PPE -- Refer to NFPA 70E-2015 Table H.3(b) |
> | 0.48 | kV Shock Hazard when cover is removed |
> | 3' - 6" | Limited Approach |
> | 1' - 0" | Restricted Approach - Class 00 Voltage Gloves |
>
> Equipment Name: SWG-4 (Fed by: SWG-4 MAIN)
> Date: October 16, 2015 - Calculation Method: IEEE 1584

Figure 4.5: Example of Arc Flash Warning Label Printed from EasyPower

For more information on labeling, refer to "Arc Flash Labeling Do's and Don'ts" in Appendix C.

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

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

3. William D. Stevenson, Jr., *Elements of Power System Analysis*, McGraw-Hill.

4. NFPA 70E, "Standard for Electrical Safety in the Workplace," 2015 Edition

5. See endnote 4.

Reducing Arc Flash Risks

Arc flash incidents can be reduced by following procedures correctly, the 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 so 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.

Exposure to arc flash can be limited in three ways:

1. Avoiding the occurrence of arc flash incidents.

2. Reducing the level of arc energy released.

3. The proper use of personal protective equipment (PPE).

Arc flash incidents can be reduced by following procedures correctly, the 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 so 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 mentioned above. PPE is discussed in Chapter 6.

Avoiding Arc Flash Incidents

Arc flash incidents can be avoided by understanding their causes and taking steps to reduce the risk of initiating an arcing fault. The various causes of arc flash discussed in Chapter 1 are summarized below. The mitigation measures are described in the following sections. This book is not intended to provide complete safety information and training requirements related to electrical safety. The information below is simply a brief overview of some common causes of arc flash incidents how to mitigate these risks.

Summary of most common causes of arc flash incidents:

- Dust, impurities, and corrosion at contact surfaces producing heat, loosening contacts, and creating sparks.

- Sparks produced during racking of breakers, replacement of fuses, or 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 or bolts, or metal parts.

Preventive Maintenance

Preventive maintenance practices are employed in most companies that require high reliability of electrical power supply or process continuity. Preventive maintenance also provides for a safer workplace. Enhance maintenance procedures when carrying out inspections, performing preventive maintenance, or performing breakdown maintenance, by including procedures that address arc flash hazards. This reduces the overall cost of implementing an arc flash program. The following are some of the common causes of arc flash incidents and suggested mitigation measures that could be employed.

- Seal unused openings into equipment. Rodents and birds entering panels and switchgear are common initiators of arcing faults. These can lead to short circuits that often result in arc flash[1]. This risk can be prevented by closing all open areas of equipment with wire net or sealant so that rodents and birds cannot enter.

- Use corrosion-resistant terminals. Corrosion can lead to the 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 reduces corrosion.

- 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 the discoloration of 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. Proper arc rated PPE should be used by workers involved in thermography.

- 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 it be exposed. Insulation prevents arcing. For example, if a worker drops an uninsulated spanner that touches the bare bus bars of two phases, a short circuit will occur. However, this does not happen if the spanner or the bus bar is insulated.

- Make sure relays and breakers operate properly. Arc flash incident energy calculations are based on the proper operation of the upstream protective device. If this upstream device should fail to operate properly, the arc energy released during an arcing fault could be many times the predicted value. Companies with good maintenance practices carry out routine inspection and testing of circuit breakers and relays. The frequency of testing varies depending on the type of equipment, service conditions, and equipment age. Consult the NETA recommendations and manufacturers' recommendations to develop a testing schedule. Verify that all protective devices are being operated within their short

circuit ratings. If a circuit breaker or fuse is subject to more fault current than it is rated to interrupt, it cannot be relied upon to safely clear a downstream fault. In addition, the device itself could fail and create an arcing fault when attempting to clear a high magnitude fault.

- Pitting of contacts can occur when breakers and fuses are operated. For devices with visible contacts, replace contacts when excessive pitting is noticed.

- When a protective device trips or a fuse melts, make sure that the cause of the fault has found and cleared before re-energizing the circuit. While it is common practice to try to immediately re-energize a circuit after a fault since many trips are "nuisance" trips, this is a potentially dangerous practice that should be discouraged. Closing back into a fault can produce sparks that could lead to arc flash.

- Wire harnesses 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 or MCC.

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

Working on Energized Equipment

1. It is ALWAYS preferable to work on de-energized equipment, regardless of the magnitude of the arc flash risk. When work on live equipment is unavoidable, then in most cases, justification and written authorization is required in the form of an Energized Work Permit.

2. Use insulated tools. A dropped tool can cause momentary faults, sparks, and arcs. Insulated tools 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. A slip while tightening or loosening screws, nuts, or 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 insulating property of air and allow an arc to strike through. Spraying directly on a live conductor can also provide a conducting path that results in electric shock.

Reducing Incident Energy

The incident energy exposure can be reduced by system design or operating procedures. Several ways to reduce the possible incident energy on an existing system include:

- Reducing the fault current magnitude
- Reducing the exposure time
- Remote operation of circuit breakers
- Remote racking of circuit breakers

Reducing the Fault Current Magnitude

Reducing the available fault current decreases the arcing current. Assuming that the fault duration does not increase, the resulting incident energy exposure will be reduced. In existing systems, reducing the fault current magnitude is generally difficult. Some options for reducing the magnitude of arcing current include:

- Modifying the system configuration to reduce available fault current such as through the use of smaller kVA transformers and eliminating parallel operation of transformers on double-ended substations.
- Application of current-limiting fuses/breakers.
- Use of current-limiting reactors.

System Configuration

For any location in an industrial system, the fault current magnitude is most greatly influenced by the capacity and impedance of the upstream transformer. Reducing the kVA rating of a transformer directly reduces the maximum possible downstream fault current. This reduction of fault current can lead to a reduced arc flash level provided the fault clearing time does not increase significantly. A point will be reached where further reduction in transformer size will actually cause an increase in incident energy downstream due to increased fault clearing times.

Double-ended substations (Main-Tie-Main configurations) with a normally closed tie (Figure 5.1) are 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.*
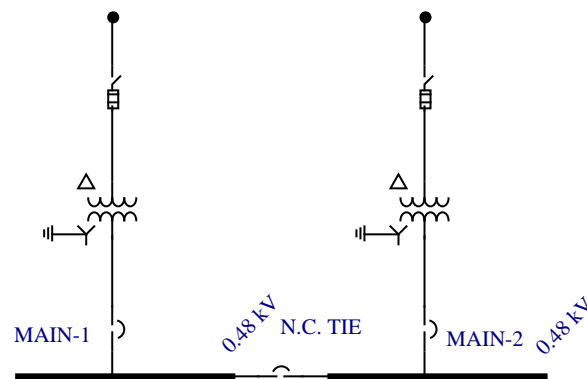
Figure 5.1: Double-End Load Center Configuration
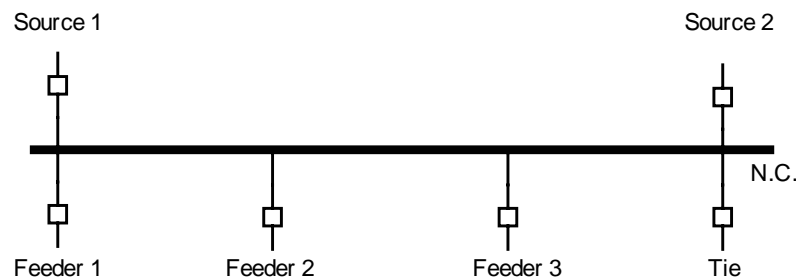
Figure 5.2: Dual Sources

Current-Limiting Fuses/Breakers

Current-limiting fuses/breakers can reduce the maximum "let-through" current for fault current that is in the current-limiting range of the fuse. A fuse is considered to be current-limiting if it clears a fault before the first current peak occurs, generally within ¼ cycle. In addition to limiting the maximum fault current in this case, the fuses clear the fault extremely rapidly resulting in low arc flash incident energy downstream of the fuse. However, if the available fault current is such that the fuse is not in the current-limiting range, then the fuse does not provide any reduction in arc flash incident energy when compared to a molded case circuit breaker. Special current-limiting circuit breakers are also available and function in a similar manner to current-limiting fuses.

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 lower interrupting ratings. 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.

Reducing Arcing Time

For existing systems, reducing the duration of an arc is the most practical method of reducing the incident energy. The arc duration is a function of the time-current characteristics of the upstream device that must clear the fault. 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.

- Perform or update a protective device coordination study to reduce protective device operating times.
- Implement maintenance mode settings for low voltage breakers and protective relays.
- Implement Zone Selective Interlocking for low voltage switchgear.
- Implement "Fast Bus Tripping" schemes for medium voltage switchgear.
- Use of bus and transformer differential protection to combine selectivity with instantaneous operation.
- Retrofit time-overcurrent relays with a delayed instantaneous trip (definite-time) element if needed.
- Use of optical sensors to rapidly clear faults in the event of arc flash within an equipment enclosure.
- Installation of remote feeder breakers to reduce arc flash levels for group-mounted low voltage switchboards and panelboards.

Perform Protective Device Coordination Study

Many industrial and commercial power systems have never had a comprehensive protective device coordination study and even where studies have been done, arc flash levels were generally not a concern. Incident energy is primarily a function of the arc current magnitude and the arc duration. There are limited options for reducing current significantly, especially on existing systems. The main tool available for reducing arc flash energy is to reduce the arc time. When coordinating inverse time type devices such as overcurrent relays, circuit breakers and fuses, selectivity is achieved by making each upstream device slower than all of the downstream devices that it must coordinate with. While this slower operation may provide adequate equipment protection, it results

in longer arc times and higher arc energy. Protective device coordination is generally a compromise between protection (fast operation) and selectivity (slower operation), and these two goals are quite often directly conflicting. In the past, coordination settings were based on equipment protection boundaries and arc flash levels were not a consideration. Often, significant reduction in incident energy is possible without sacrificing coordination by simply lowering device settings. To ensure that overcurrent devices in series properly coordinate with each other, it is often necessary to allow a safety margin between the two time-current curves. This is especially true for overcurrent relays and medium voltage circuit breakers. This safety factor is referred to as the Coordination Time Interval or CTI. Traditionally, when coordinating between two overcurrent relays, a CTI of 0.3 to 0.4 sec was used. This was based on the accuracy and operating characteristics of electro-mechanical induction disk overcurrent relays. With modern digital relays, this CTI can be reduce to the range of 0.2 to 0.25 seconds. This reduction can significantly reduce the incident energy levels.

Maintenance Mode Settings

As discussed in the previous section, to achieve selectivity, overcurrent devices must be coordinated so that upstream devices are slower than downstream devices. For main buses in switchgear, this means that the overcurrent device that is protecting the main bus must be slower than all of the downstream devices that it is expected to coordinate with. This can result in very long clearing times for a fault on the main bus, and this in turn results in high incident energy, exceeding 40 cal/cm2 in many cases. One approach to reducing these high arc flash energy levels is to speed up the upstream device only when work is being done on the equipment. This is typically referred to as a "maintenance mode" setting and is manually initiated prior to any maintenance or inspection activity near the equipment. In maintenance mode, a low-set instantaneous trip function is used to provide for sensitive high-speed fault clearing for any fault that may occur. This can reduce the incident energy level by a considerable amount. The trade-off is that while the device is set to the maintenance mode, it will no longer coordinate with downstream protective devices and any fault downstream can result in a wider outage than is necessary. While use of a properly installed and tested maintenance mode setting can provide significant arc flash reduction, it suffers from three major weaknesses:

- Lack of coordination while in maintenance mode

- Requires manual initiation of maintenance mode

- Require manual switching off of maintenance mode after work is completed.

The main advantage of the maintenance mode approach is that it is the least costly technique to implement in most cases, especially for existing systems.

For low voltage power circuit breakers, most new trip units are available with a maintenance mode option. When set to maintenance mode, a low-pickup instantaneous

trip function is added to the normal device functions. Per the 2011 National Electrical Code, any protective that does not have an instantaneous trip function in normal service must be provided with a maintenance mode setting option. For older trip units lacking this feature, new trip units from a variety of manufacturers can be retrofit to the existing circuit breakers.

For medium voltage equipment, most modern digital relays can be programmed and configured to provide for a maintenance mode setting that is manually set via a front-panel pushbutton or a separate selector switch via a discrete input. As with the low voltage devices, the maintenance mode setting enables a sensitive instantaneous trip element (ANSI Device Function Code 50) that provides for rapid clearing of a downstream fault while in maintenance mode. Unlike the low voltage breaker trip units, this maintenance mode function generally must be specially programmed and configured in the relay.

For any type of maintenance mode setting, it is important that the worker is provided positive feedback that the trip unit or relay is definitely in maintenance mode. This can be done using an LED on the device or a custom LCD message.

The final consideration regarding use of the maintenance mode is how the protected equipment should be labeled. Normally, the incident energy level on an arc flash label is based on the worst-case situation that can be reasonably expected. Since the maintenance mode must be manually initiated, it is probably reasonable to assume that a worker might not remember to place the device in maintenance mode, especially if contractors are working on site. In this case, the label should reflect the incident energy based on the normal system conditions with the maintenance mode switched OFF. The Energized Work Permit could be used to specify the use of the maintenance mode setting and then reflect the lower incident energy level on this specific Work Permit.   **If a decision is made to base the arc flash label data on the maintenance mode being switched ON, it is imperative that this be clearly indicated on the arc flash label.**

For low voltage trip units and relays defined in the EasyPower library as having maintenance mode options, EasyPower provides a convenient method for switching any device into maintenance mode to assess the impact on the downstream arc flash energy.

The time-current curves below show the impact of implementing a maintenance mode setting for a transformer primary protection relay:

CURRENT IN AMPERES X 100 AT 480 VOLTS
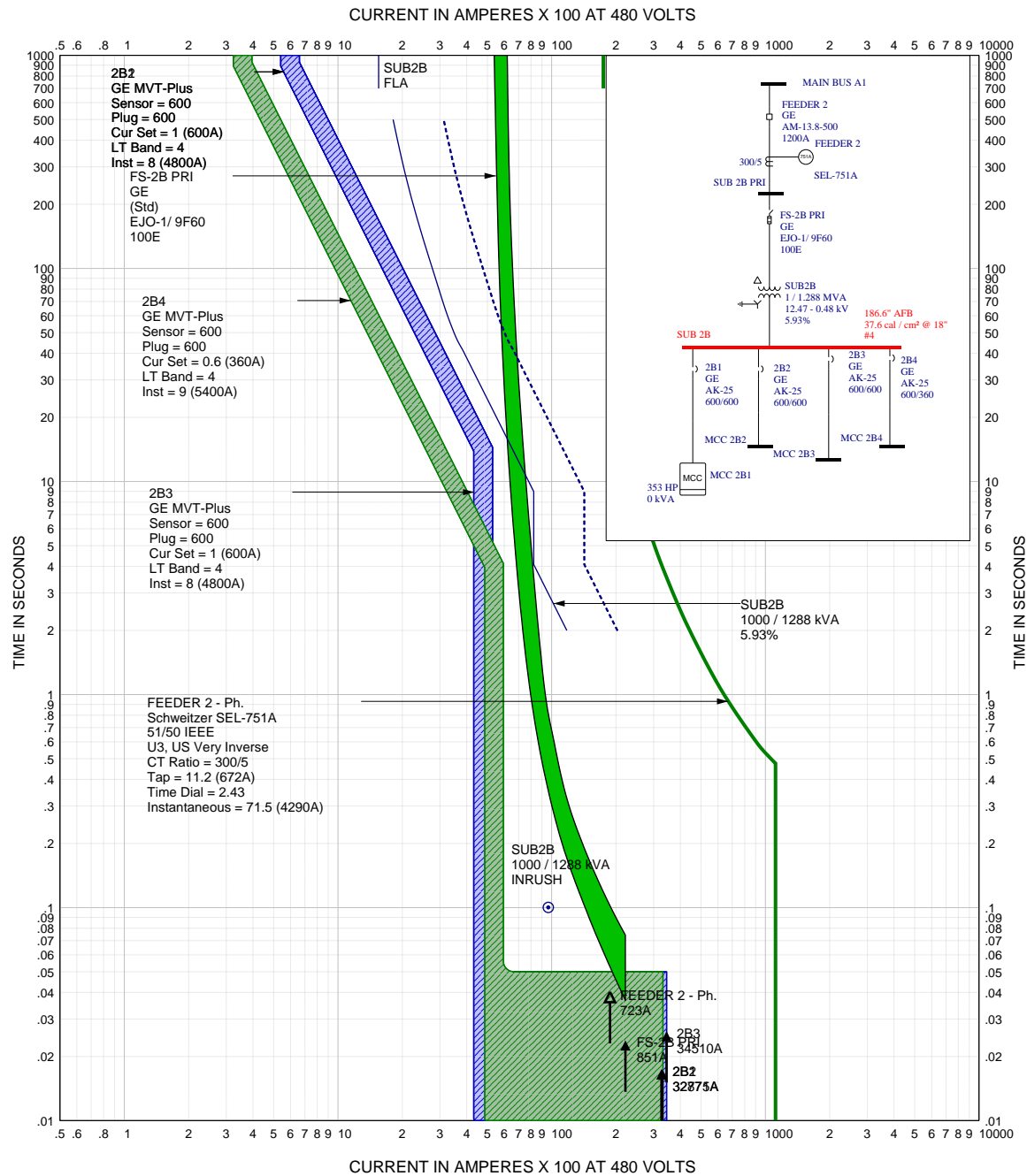
Figure 5.3: Feeder 2 Relay Normal Settings – Arc Flash at Sub 2B Bus – 37.4 cal/cm²
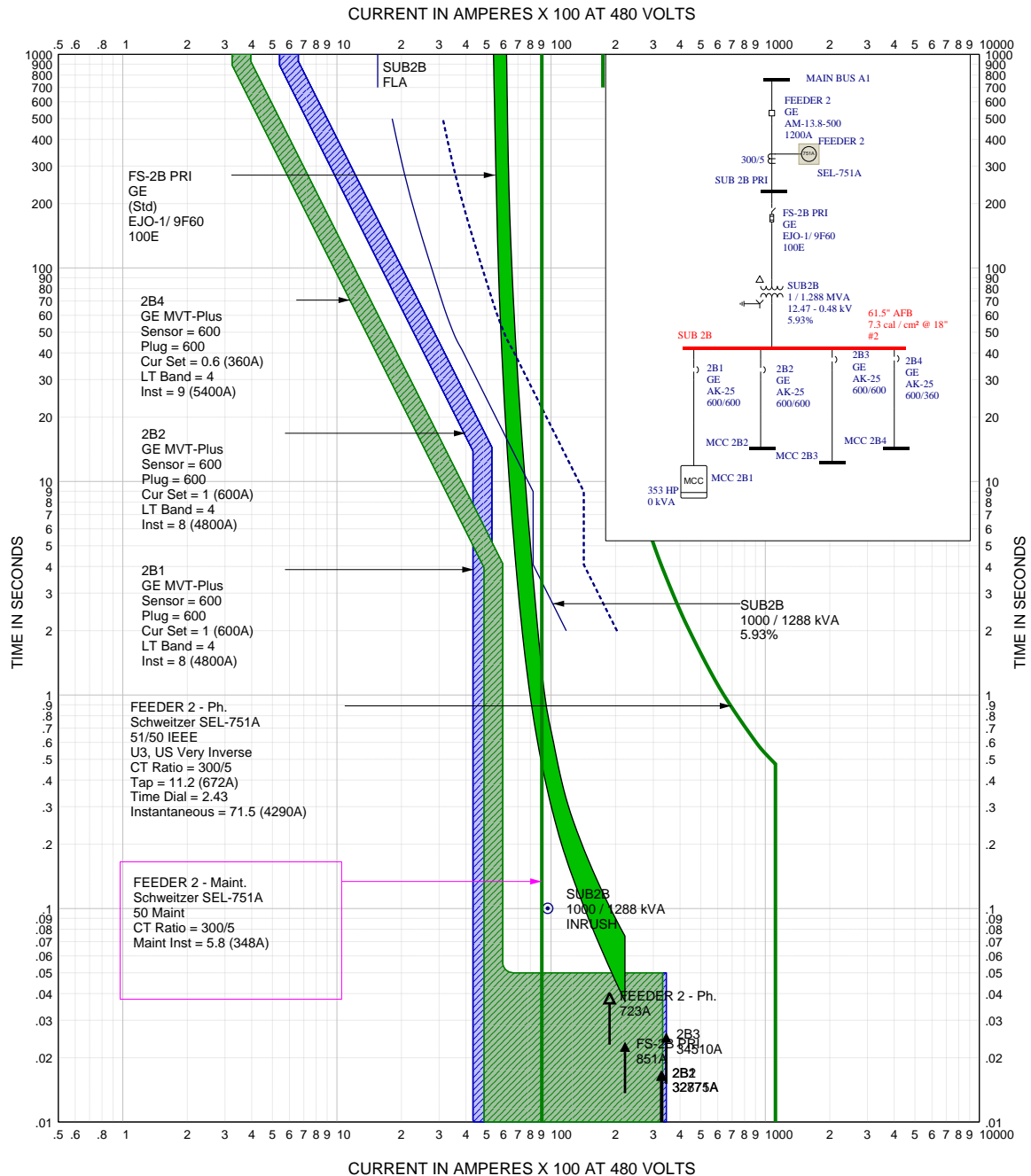
Figure 5.4: Feeder 2 Relay in Maintenance Mode – Arc Flash at Sub 2B – 7.3 cal/cm²

Zone Selective Interlocking

For low voltage power circuit breakers, it has long been an option to provide a signaling system between downstream and upstream trip units to increase fault clearing time for bus faults that must be cleared by the main breaker. This system is called "Zone Selective Interlocking" or ZSI. To be selective with the downstream feeder breakers, the main and tie breakers must be set slower than the slowest feeder breaker for normal operation. This can result in relatively long clearing times and this translates to high

incident energy levels. A ZSI system provides a communications path between the feeder breakers and the main (and tie) breakers so that the upstream trip unit receives a "restraining signal" indicating that a downstream trip device has also detected the fault. When the upstream device receives this signal, it operates on its normal operating curve that coordinates with the downstream devices. However, if the fault is on the main bus, none of the feeder breaker trip units will detect this fault and no restraining signal will be received by the main breaker trip unit. If no restraining signal is received, the main trip unit will operate on a very fast Short-Time trip function with the minimal time delay required to allow the signal processing to occur. This faster tripping time results in significantly lower arc flash levels for faults occurring on the main bus. Arc flash levels will be comparable to what can be achieved through the use of a maintenance mode switch, but in the case of a ZSI system, the system is always in service so no operator action is required to switch it on or off. In addition, the ZSI system provides full selectivity, unlike the maintenance mode.

ZSI is limited to low voltage power circuit breakers trip units and cannot be applied to molded case circuit breakers. For medium-voltage systems, an approach similar to ZSI can be used. It is referred to as Fast Bus Tripping and is described in the next section.

EasyPower provides built-in support for ZSI systems provided the trip unit is properly defined in the EasyPower library. When the ZSI system is properly defined and enabled in EasyPower, the program correctly calculates the downstream arc flash based on the operation of the restraining signal.

In the example system shown below, the main breaker and the two feeder breakers are equipped with Zone Selective Interlocking (ZSI). For a fault on the Main Switchboard bus, the main breaker does not receive a restraining signal from either of the feeder breakers and therefore operates on its "fast" unrestrained time current curve. This results in much faster fault clearing and greatly reduced arc incident energy. Unlike the maintenance mode approach, ZSI is fully automatic and provides complete selectivity at all times between the main breaker and the feeder breakers.
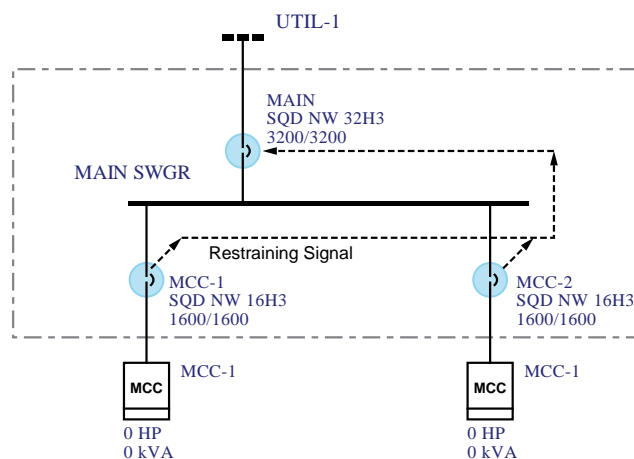
Figure 5.5: Zone Selective Interlocking
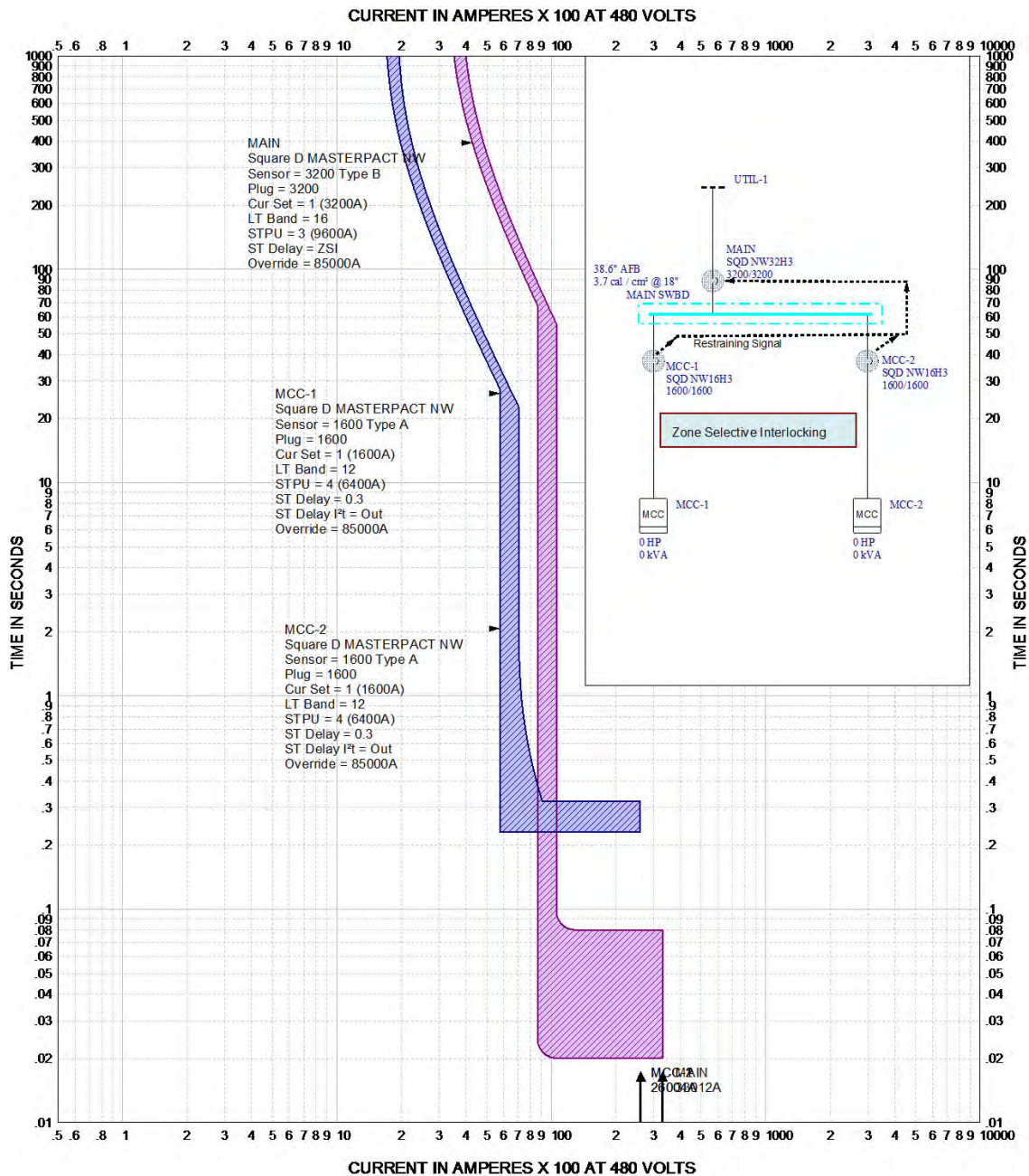
Figure 5.6: ZSI Time Current Curves

Fast Bus Tripping

The same concept described above for low voltage power circuit breakers can also be applied to overcurrent relays used for the protection of medium and high voltage systems. This is generally referred to as "Fast Bus Tripping." It is relatively easy to implement if digital relays are used. For this method to be effective, it must be applied to all sources and feeders on the bus. Using digital relays, normally output contacts

from every feeder relay are connected to a discrete input on the main breaker relay. The output contacts are configured (as part of the relay programming) to close whenever any overcurrent element picks up. As with the ZSI system, this acts as a restraining signal to the upstream relay and causes it to operate on its normal "slow" response curve to allow the downstream relay time to clear the fault. If none of the downstream relays detect the fault, then a low-set instantaneous trip function with a very short time delay (approximately 1 cycle) in the main breaker relay quickly clears the fault.

Fast bus tripping can be fairly easily retrofit into existing switchgear and provide nearly as much arc flash reduction as the bus differential relaying described below.

Differential Relaying

Differential relaying works on a fundamentally different concept than standard overcurrent relaying. As shown in Figure 5.7 below, a differential relay monitors the sum of all current entering and leaving a bus in each phase. Under normal operating conditions, the sum of all of the currents entering a bus should be zero. If the sum of these currents is not zero, or very close to it, it indicates current is going somewhere it should not be—a fault condition. Note that if the differential relay detects a fault condition, the fault must be within the zone defined by the location of the current transformers. This is known as the differential zone. For a bus differential fault, there is no need to wait on some other device to operate, as is the case with overcurrent relaying. The relay can operate extremely quickly, typically within a cycle, to issue a trip signal to the lockout relay which in turn trips all the breakers within the differential zone.

Differential relaying can also be applied to other critical equipment and systems such as transformers, generators and large motors. The original impetus for differential relaying was improved equipment protection and reduced damage, but it also provides for significantly reduced arc flash energy levels due to the high speed fault clearing it achieves. Also, it can be designed to incorporate the source (main) breakers in the differential zone of protection. This solves one of the thornier issues in arc flash reduction since the main breaker cubicle in a metal-clad switchgear lineup often has very high incident energy levels.

The major downside to bus differential relaying is that it is difficult to retrofit into existing switchgear. The traditional high-impedance bus differential relay requires dedicated and matched current transformers for each breaker position. However for new installations, bus differential protection is highly recommended.
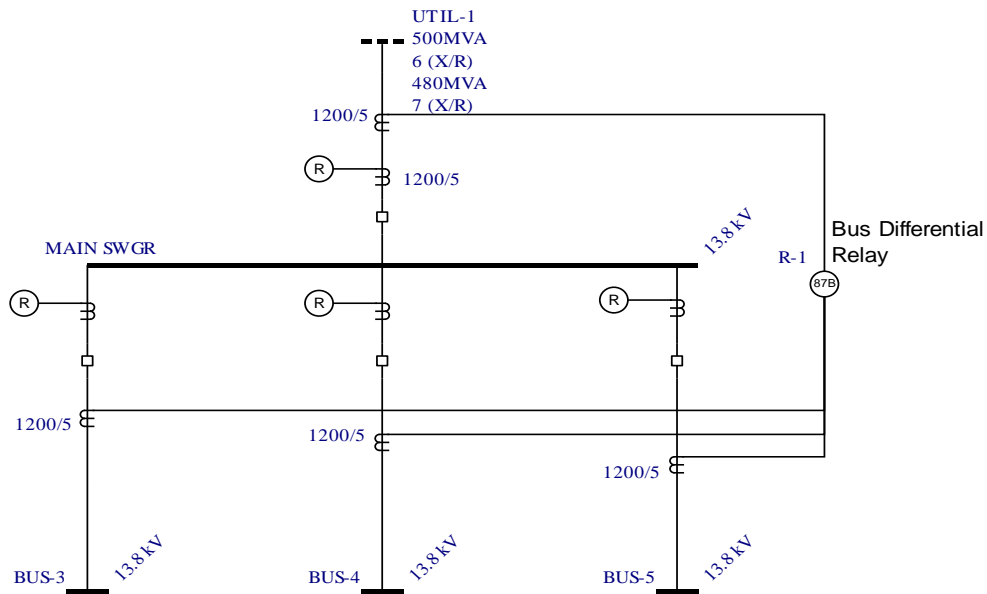
Figure 5.7: Typical Bus Differential Relaying System

Upgrade Relays and Settings for Unit Substation Transformer Primary Protection

For larger industrial facilities that take service at medium voltage, unit substations provided power transformation to a lower voltage (480 or 600 V) and distribution switchgear. For the low voltage main breaker (or for the entire low voltage bus if no main breaker is present), arc flash energy is generally higher than desired since a fault in this portion of the system must be cleared by the transformer primary protection. Assuming there is an upstream medium voltage breaker that can be tripped, arc flash levels on the low side can often be improved by upgrading the overcurrent relaying on the primary side and implementing a protection scheme more focused on reducing arc flash through faster clearing times.

Figure 5.8 below shows a typical relay curve for transformer primary protection. This extremely inverse curve provides reasonable transformer protection and coordinates with the downstream 480 V main breaker. However, for faults in the 480 V main breaker section, the clearing time will be quite long.

By adding a "definite time" function in addition to the inverse time function, the relay curve can be made to much more closely match the 480 V main breaker trip unit TCC, and provide much faster tripping for a 480 V fault. Figure 5.9 shows the revised TCC. Arc flash incident energy at the main breaker has been reduced from 98 cal/cm^2 to 22 cal/cm^2 by the addition of the definite time overcurrent function to the primary relay.

CURRENT IN AMPERES X 100 AT 480 VOLTS
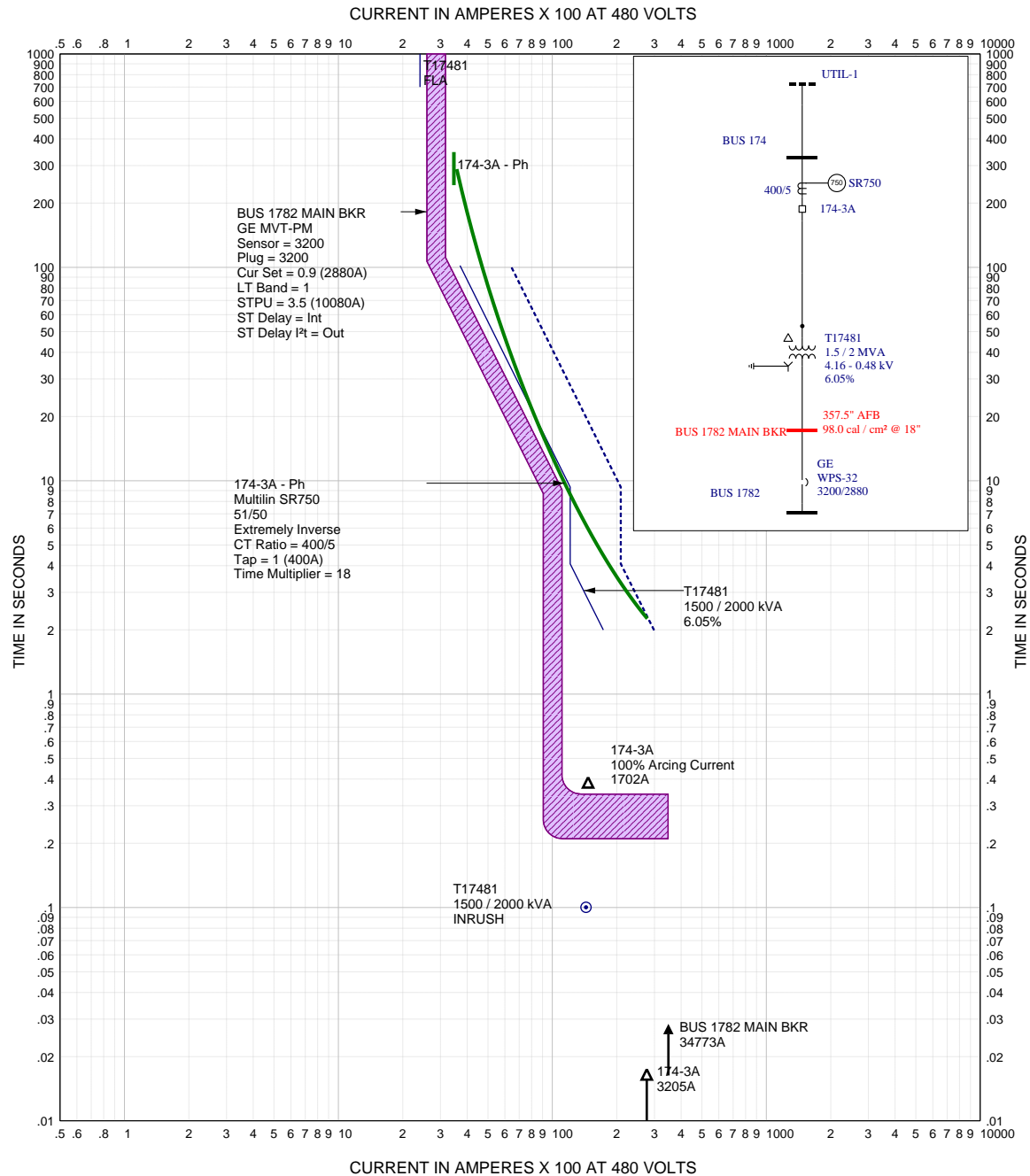
Figure 5.8: Typical Time Overcurrent Curve for Transformer Primary Relay

CURRENT IN AMPERES X 100 AT 480 VOLTS
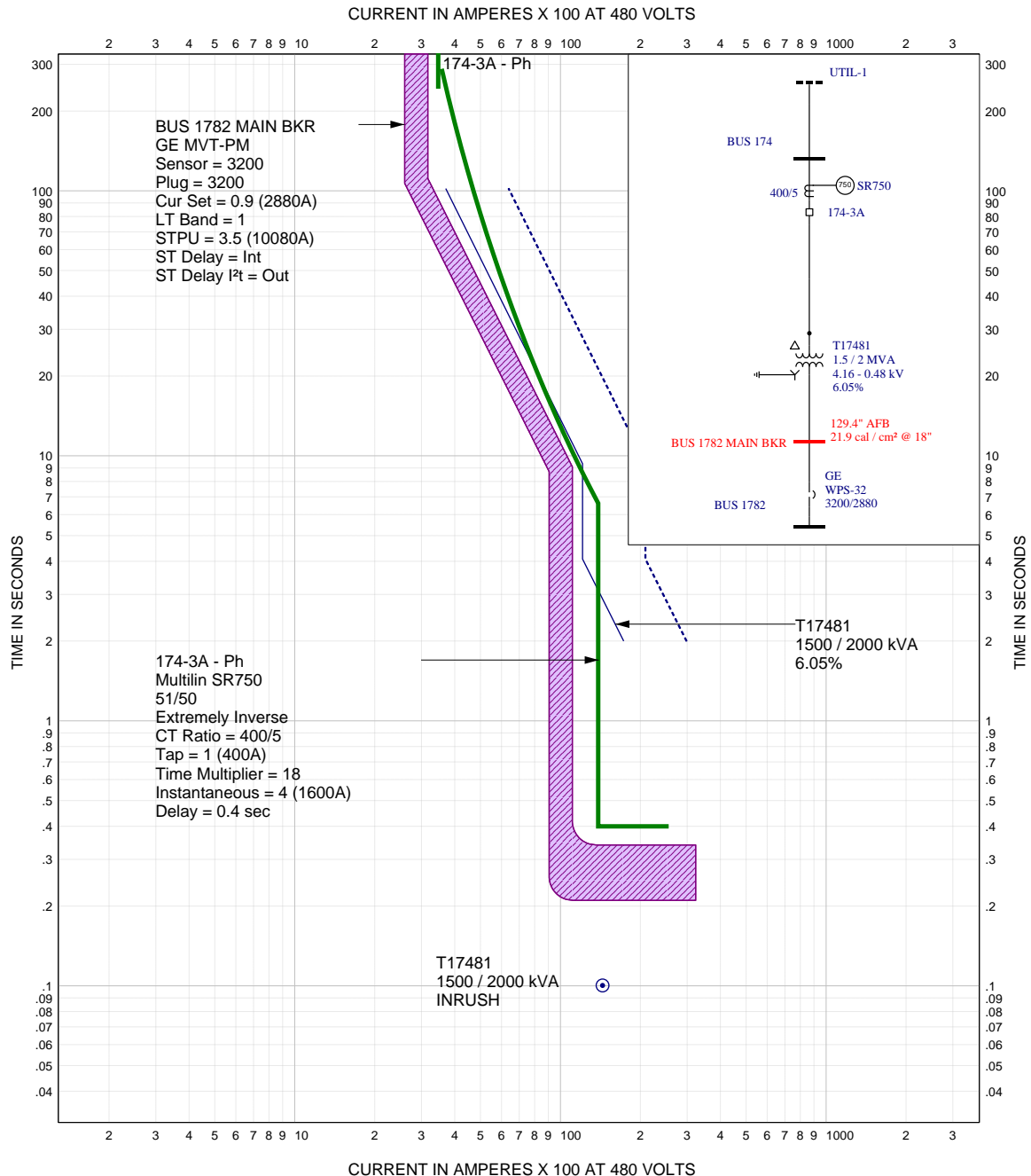
Figure 5.9: Typical Time Overcurrent Curve for Transformer Primary Relay (Revised)

Install Optical Arc Detection Relays

ABB and SEL offer an arc flash detection system using light sensing fiber optic cable that is installed inside of the equipment to be protected. The sensor detects the flash of light and the arc detection relay output contact trips the upstream circuit breakers. Per the manufacturer's data, the response time for these systems is in the range of ¼ to ½ cycle. This puts this system on par with differential relays for speed of operation. For new equipment, the sensors should be laid out and installed by the equipment manufacturer

to ensure reliable operation. In addition to the light sensors, current transformer inputs are required to supervise the optical sensing. This is to avoid nuisance tripping due to stray light entering the equipment enclosure.

Install Remote Circuit Breakers or Fuses to Improve Main Breaker and Bus Arc Flash Levels

In many cases, arc flash levels at main switchgear, service entrance panels and their associated main breakers will be quite high because fault clearing depends on the operation of a primary fuse or relay. In many installations, the incident energy at the main switchboard may exceed 40 cal/cm^2. In these situations, owners may determine it is not safe to allow any operation of circuit breakers or switches in the main equipment while it is energized. To mitigate this situation, a separate circuit breaker or fused switch can be installed upstream of the main switchboard. This device protects anyone working on the main equipment but is remote so that it can be included in the arc time determination since there is minimal risk of arc propagation in this situation. Of course, the incident energy at this new remote device will also be very high, but this approach would provide a lower energy level at the main switchboard and allow operation of the breakers and switches in the main board.

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 switchgear can be retrofitted with remote control switches.

New microprocessor relays can be programmed to manually supervise the closing of a breaker using a "punch and run" time, which 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 that the following three items are shown before withdrawal: the mechanical indicator shows the breaker is 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. These remote racking systems provide a motor to rack the breaker in or out with a remote control unit so that the operator can be a safe distance from the breaker as it is racked.

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1.   Reference from page 3 (item #1)

Personal Protective Equipment (PPE)

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.

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 from arc flash is arc-rated clothing. Arc-rated clothing is tested for performance under exposure to electric arc. This is different from flame-resistant clothing. Arc-rated clothing is also flame-resistant.

NFPA 70E

NFPA 70E-2015 provides arc flash PPE related requirements in sections 130.5(C) and 130.7(C). Workers must use adequate PPE on various parts of the body suitable for the work to be performed. Various standards pertaining to care, testing, and use of PPE are outlined in this section. Refer to the standards for details. Some of the main requirements are as follows:

- All employees within the arc flash boundary are required to wear arc flash PPE if it is determined that PPE is required based on the standard.

- PPE should cover all other clothing that can be ignited.

- PPE should not restrict visibility and movement.

- Non-conductive protective head wear 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.

- Hearing protection is required.

- Body protection is required using arc-rated clothing when the estimated incident energy at the body may cause a second degree (curable) burn (1.2 cal/cm^2).

- Heavy duty leather or arc-rated gloves are required to protect the hand.

- If incident energy exceeds 4 cal/cm^2, heavy duty boots are required to protect the feet.

Selection of Arc Flash PPE

NFPA 70E-2015 provides two different methods of selecting PPE for arc flash. Section 130.5(C) states that any one of these methods may be used on the same piece of equipment, but not both methods at once. These two distinct methods are:

- Incident Energy Analysis method

- Arc Flash PPE Category method

Incident Energy Analysis Method

As per section 130.5(C)(2), arc-rated clothing and other PPE shall be selected based on the calculated incident energy in cal/cm^2 at the working distance specific to the task to be performed. Incident energy analysis calculation details are described in Chapter 3. The working distance can vary with the tasks being performed. If a worker needs to perform task at a distance closer than the working distance used to estimate the incident energy, then additional PPE shall be used.

Since it may not be clear to many electrical workers how much extra PPE is required for closer working distances, a practical approach would be to consider the closest working distance amongst various tasks and use that analysis for labeling purpose. This way the label will display the worst possible incident energy, and PPE selected will be adequate based on the worst case incident energy.

Another practical approach is to carry out incident energy analysis as part of the job planning. Commercial software such as EasyPower easily allows creating work permits based on the task. The work permit can include the working distance that would be applicable to the task at hand. The updated incident energy calculation will be included in the work permit. This PPE will be job specific and any confusion can be eliminated.

Using the calculated incident energy, PPE can be determined by looking up Table H.3(b) in Informative Annex H. However this table is provided as guidance only and is not part of the requirement. Table H.3(b) has 3 levels of protective clothing and PPE based on the incident energy exposure:

- Less than or equal to 1.2 cal/cm^2

- 1.2 to 12 cal/cm^2

- Greater than 12 cal/cm^2

For details on this table refer to the standard. What this table specifies is the type of clothing required and that the arc rating of the clothing must be greater than or equal to the calculated incident energy. For example, if the incident energy for a particular task on an equipment is 4 cal/cm^2, you can use 4 cal/cm2 rated clothing and it is not necessary to use 12 cal/cm^2 rated clothing. However the types of clothing mentioned in this table in the second level (1.2 to 12 cal/cm^2) are recommended. To simplify the

process of selecting PPE, some companies use the upper limit of the range for choosing the arc rating of clothing. In this case, the arc rating of the clothing would be at least 12 cal/cm² for the second category and at least 40 cal/cm² for the last level.

Arc Flash PPE Category Method

As per section 130.5(C)(3), when the PPE Category method is used, we need to follow sections 130.7(C)(15) and 130.7(C)(16) to select arc flash PPE. This method is used in lieu of incident energy analysis. There are some conditions that need to be met in order to use the PPE Category method.

This method is a three-part process for alternating current (AC) systems:

Step 1: As per 130.7(C)(15)(A), first identify if arc flash PPE is required for the task to be performed using Table 130.7(C)(15)(A)(a) Arc Flash Hazard Identification for Alternating Current (AC) and Direct Current (DC). The information needed to use this table includes:

1. Equipment type
2. Task to be performed
3. Condition of equipment including:
    a. Was it properly installed?
    b. Was it properly maintained?
    c. Are doors closed and secure?
    d. Are equipment covers in place and secure?
    e. Any evidence of impending failure?

The results of this table determine whether arc flash PPE is required.

Note: If the task to be performed is not mentioned in Table 130.7(C)(15)(A)(a), this method cannot be used and PPE selection should be based on incident energy calculations.

Step 2: As per 130.7(C)(15)(A), if it is determined based on Table 130.7(C)(15)(A)(a) that arc flash PPE is required for the task to be performed, then determine the PPE category using Table 130.7(C)(15)(A)(b) Arc Flash Hazard PPE Categories for Alternating Current (AC) Systems. The PPE Category ranges from 1 to 4. This table also provides the arc flash boundary. The necessary information to use this table are:

- Equipment type including voltage
- Maximum short circuit current for this equipment
- Maximum time to clear the fault (based on upstream trip device)
- Working distance

Note: Table 130.7(C)(15)(A)(b) can only be used if the following conditions are met.

- Fault current at the equipment does not exceed the values in the table.

- The trip time for the upstream trip device is not longer than the fault clearing times specified in this table.

- The working distance for the task is not less than what is specified in this table.

If these conditions are not met, the incident energy analysis method should be used instead.

Step 3: As per section 130.7(C)(16), after determining the arc flash PPE category from Table 130.7(C)(15)(A)(b), determine the arc-rated clothing and other PPE using Table 130.7(C)(16). Each PPE Category has a list of PPE to protect various parts of the body. Refer to the standard for the details. The minimum arc rating of arc rated PPE required for each category are provided in the table below:

Table 6.1: Minimum Arc Rating for Each of the PPE Categories

PPE Category	Minimum Arc Rating (cal/cm^2)
1	4
2	8
3	25
4	40

Data Collection for an Arc Flash Hazard Study

Data collection is an important part of an arc flash risk assessment. An improperly modeled system leads to inaccurate arc flash hazard estimates. Considerable time and effort is required to collect data for modeling the system. Any previous records of equipment, layout and as-built drawings, existing one-lines or test sheets may be used to improve the data collection process and reduce the man hours required.

Introduction

Prior to beginning the data collection process for an arc flash risk assessment study, a few questions need to be answered:

1. How large is the facility? (The number of substations at different voltage levels.)
2. How many levels into the system will data be collected?
3. How much time until the study needs to be completed?
4. How many people are collecting data?
5. How much data is already available?

Based on the answers to these questions, the arc flash risk assessment may need to be broken up into different phases. It might be better to collect data and build the one-line model from the medium and high voltage distribution downstream to the individual low voltage substations, collecting data for each feeder serving a switchboard, MCC and panelboard. Typically, arc flash incident energies are higher at these locations than in other low voltage equipment further downstream in the system. The required time for data collection and system modeling increases exponentially as you work further downstream in the system. After the intermediate study has been completed, then additional data may be collected and added to the EasyPower model to perform the arc flash risk assessment.

Until the study has been completed for the entire system, the tables in NFPA 70E-2015 Article 130.7(C)(15) are recommended as a guide to provide adequate protection to qualified workers.

Some of these decisions will hinge on whether the data collector is a member of plant personnel, a contracted individual who is normally on-site, or a consultant or contracted individual who has traveled to the site.

If you are new to data collection, it is recommended that you perform a small portion of the review process first to estimate the amount of time for the entire data collection process. Depending on the type of system (industrial, commercial, utility, etc.), different amounts of time are required to collect data per substation. Depending on how much data is to be collected, it may take as little as 2 hours to up to 2 or 3 days. If all feeders are required from each MCC and panelboard, the time required could be 1-2 weeks, depending on how many distribution points are served from each equipment.

If you are creating a one-line diagram of an electrical system for the first time, the following steps are recommended:

1. Create a conceptual map of the key components including transformers, sources, switchgear/switchboards, and distribution points (MCCs, panels, etc.). A simple hand drawing will do for a start. Plant engineers and electricians typically have

knowledge of the layout of the system. Consultants can obtain information from plant personnel to create this rough map.

2. Based on the conceptual map, prepare and plan for site inspection. Data collection forms or templates are very helpful in keeping track of details, organizing information, and saving time. (A few example templates are included in the Data Collection Template section, later in this chapter.) Coordinate with the plant personnel for the site visit. In some cases, it may not be possible to obtain the required data if it becomes necessary to open some equipment covers, which may require shutdown and interfere with the plant operation. The information may be obtained later during scheduled maintenance.

3. Use a digital camera if possible. The pictures often reveal more information than what you record in your notes. If you have difficulty understanding any of the equipment data, you can obtain help from experienced people using the picture.

4. Most equipment have nameplates that show the equipment ratings. Note the details from the nameplates.

5. For equipment with adjustable settings, note the range of available settings and the current setting. The status of switching devices should also be noted (open or closed).

6. Create a one-line diagram showing all the equipment such as utility connections, transformers, cables, switches, circuit breakers, fuses, loads, switchgear, etc. Make sure that their interconnection is correctly represented in the drawing. Mark each equipment with the ID names and the relevant data. Commercial power system software like EasyPower has the ability to create one-line diagrams, store all the necessary equipment data, and perform arc flash hazard analysis. ID names are also important for placing arc flash labels in the appropriate locations after the equipment incident energy has been determined.

7. The more knowledge the electrician (plant personnel) has of the facility, the better the final model will be. You may need to consult with a few different plant individuals before you understand or gather data you need.

8. If you have information from previous studies with recommended settings or drawings, be sure to verify the data. For one, the facility may not have been updated after the previous study, maintenance may have replaced fuses with units with higher current ratings, or the instantaneous may have been adjusted due to nuisance tripping.

9. Before beginning data collection, understand the purpose of the data collection. What kind of study are you performing?

10. If you are new to data collection, do not jump all over the facility. Finish one substation or distribution point before starting the next. Also, collect data for a small section, then review the data to make sure you have not missed anything. As you gain experience collecting data, you should constantly ask yourself the

question, "Have I collected all the required data?" A good practice is to model the collected data in EasyPower after you collect data for the first substation or distribution point. That way, if you are missing any data, you can collect the missing information before proceeding. Use the experience you've gained as you proceed to other areas of the facility.

This book describes data collection for an arc flash study, but if other studies will be performed in the future using the one-line, you may want to consider collecting additional information while performing this study. The data to be collected as described in this chapter will allow for short circuit analysis, protective device coordination, and arc flash studies.

Items Useful for Data Collection

Take the following with you while you collect power system data:

- A signed work permit.

- PPE for arc flash protection. Since the arc flash risk assessment has not been performed yet, use the tables in NFPA 70E-2015 Article 130.7(C)(15) to select the appropriate PPE. A minimum Arc Flash PPE Category of 2 is recommended.

- A non-metallic writing instrument (pencil, pen, eraser).

- Paper. If drawings exist, make initial one-line drawings with the data provided, then make changes to these drawings.

- Facility drawings.

- Templates for protective device settings.

- Tables of protective device settings (such as relay setting sheets).

- A flashlight. Make sure the cover is non-metallic.

- A mirror with non-metallic handle, so that you can view difficult locations.

- A camera.

- Keys, screwdrivers, or other tools for an electrician to open or remove equipment doors and covers.

- A laptop or tablet for entering information directly into EasyPower.

Safety Tips for Data Collection

Follow these safety tips when collecting data:

- Whenever possible, perform data collection on de-energized equipment.

- Stand aside while the equipment door or front cover is being opened. Persons other than the one opening the front cover should maintain a distance of 10 feet.

- Use a "come back later" policy. Some nameplates or equipment settings may be at locations that are difficult to reach. If the equipment is energized and all the necessary information cannot be obtained, perform data collection during a scheduled shutdown. Do not push yourself to take unnecessary risks to complete your task all at once. Remember that you are performing this data collection as part of a safety program for hazard assessment.

- Electrical hazards such as shock and arc flash are not the only hazards that exist during data collection. Follow all site safety policies regarding the use of ladders and lifts for work above the floor and use fall protection as required. If necessary, shutdown and lockout conveyors or other moving equipment.

- Watch for water, moisture, ice, and other similar hazards. This should be taken care of as part of regular maintenance. If you spot these conditions on energized equipment, request for shutdown and maintenance.

- Watch for loose screws, bolts, or other metallic parts.

- Do not lean objects on the equipment.

- Make sure there are no missing screws. When you remove screws or nuts and bolts for inspection, it is possible to miss putting them back. Keep track of what is removed.

- Count your tools. Leaving tools in electrical equipment is not uncommon. This could be dangerous. Make sure you count your tools when your work is complete. This reinforces visual inspection.

- Make sure equipment is safe to open. If you are new to a specific type of equipment, ask someone who knows for additional information. It is very easy to open equipment with interlocks and unknowingly shutdown processes.

Estimations and Assumptions

During data collection, there are typically an assortment of estimations or assumptions that may have to be made due to any number of reasons. Some of the reasons might be: you must wait for plant shutdown to open a cabinet due to inherent risks; a nameplate is missing; the text has been rubbed off or painted over; there are additional hazards created by shutting equipment down (chemicals, life-saving equipment, hospital, melter, etc.); or you are unable to obtain data from the utility.

Be sure to document all assumptions you've made to ensure that future review of the system will be understood. This documentation allows you or anyone else to understand where the data came from and why those decisions were made.

Items that may need to be assumed or estimated:

- For missing or unreadable nameplates, review existing drawings or data sheets to obtain information. If drawings or data sheets are unavailable, base your assumptions on similar equipment installed close by or at the same time as the equipment you are documenting.

- Length. It can be difficult to determine cable, busway and transmission line length due to walls, high ceilings, difficulty tracking conduit, or cable tray. It is recommended distances are within 5-10% of the actual length. The impact of cable impedance and length have increased importance on calculations as the voltage level decreases. For example, ignoring a 50 foot conductor at 13.8 kV may not affect calculations, while ignoring a 50 foot conductor 480 V or 208 V may greatly affect calculations.

- For molded case circuit breakers (MCCBs) with an unknown instantaneous setting, set it to the maximum available setting.

- For MCCs and panelboards, arc flash labeling is not always applicable at each feeder served from the MCC or panelboard. This may be due to an absence of a way to disconnect the equipment served by the MCC or panelboard. In these cases, it may only be necessary to collect data to provide for short circuit and coordination analysis. The limited recommended data is described below:

  o Main breaker/fuse.
  o Largest feeder breaker/fuse and load/motor information.
  o Protective device and conductor information for any equipment that needs to be modeled for arc flash analysis, such as a sub-panel or sub-MCC.
  o Group total <50hp motor horsepower.
  o Group total >50hp motor horsepower.

  A template showing the recommended MCC information is shown in the Data Collection Template section.

- For busduct, like MCCs and panelboards, it may take a lot of time to collect data for all the feeder equipment served. If time or access to bus plugs are an issue, consider collecting feeder data for an assortment of bus plug sizes along the length of the bus duct. For example, if a bus plug is 200 feet in length, you might consider collecting data at the beginning (0 feet), middle (100 feet) and end (200 feet), for different bus plug sizes (30A, 100A, 200A). Then in the EasyPower software, model a bus at each of the three bus duct locations and add the generic feeder data for each of the bus plug sizes at each bus. An example is shown in the

following figure. As long as the conductor length is similar, using the generic arc flash incident energy should be sufficient. If the length is much longer, then these cases should be modeled individually. Also, it is recommended that any bus plugs 400A or larger should be modeled individually.
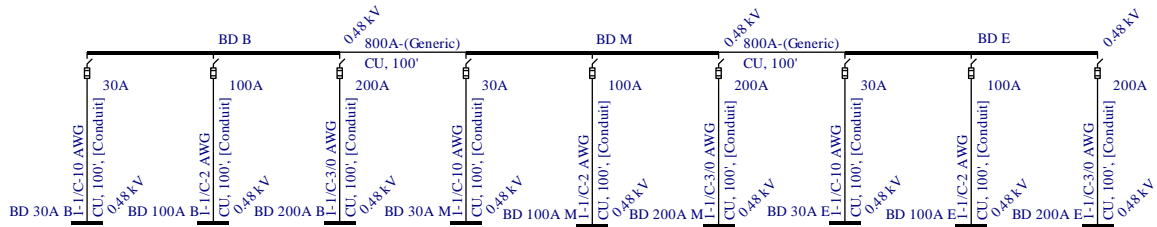
Figure 7.1: Generic Bus Duct Example

- There are books and papers from manufacturers available that provide typical data for equipment. A book that has quality data that can be used as estimations is *A Practical Guide to Short-Circuit Calculations* by Conrad St. Pierre. The book can be purchased from the EasyPower.com website.

Data Collection Templates

In this section, templates are provided for a substation and an MCC that show the type of data collection that is required. These templates may be used directly or as a guide for creating your own templates. It also may be more convenient for you to create spreadsheets instead of using one-lines. Based on this author's experience, it is usually easier to write legibly in a spreadsheet than on a one-line. This is especially true if the data is being collected for a different person to create the one-line model in the software.

The third template is for data collection of low voltage power circuit breakers with associated trip units. The template includes all of the different device types and settings that are required to properly model the breaker and trip units in the EasyPower software. For other types of protective devices, data collection templates may be created based on the software requirements.

Substation Data Collection Template

SUBSTATION DATA - SUB:

PRIMARY

PRIM BKR

PRIMARY FEEDER:

Cond/Phase:
Cond Size:
Cond Matl:
Length:

Rcwy Size:
Rcwy Type:

FUSED SWITCH:

Fuse Type:
Fuse Size:

Switch Amps:
Short Ckt:
C&L:

TRANS PRI

FS-1

TRANSFORMER DATA

kVA:
Voltages:
Taps:

Impedance:

Winding Config:
Secondary Grounding:
Cooling:
Temp Rise:

XFMR

Main Breaker Data

Breaker Mfg: =
Breaker Type: =
Trip Type: =
LTPU: =
LTD: =
STPU:=
STD: =
INST: =

SUB-MAIN

0.48 kV

SECONDARY FEEDER:

Cond/Phase:
Cond Size:
Cond Matl:
Length:

Rcwy Size
Rcwy Type

SUBSTATION

SUB-1   SUB-2   SUB-3

Feeder Breaker Data

Breaker Mfg: =
Breaker Type: =
Trip Type: =
LTPU: =
LTD: =
STPU:=
STD: =

0.48 kV

PANEL PNL-1

0 kVA

MCC Data Collection Template

MCC DATA -- MCC:

Substation:

SUB-1

FEEDER DATA:

Cond/Phase:
Cond Size:
Cond Matl:
Length:

Rcwy Size:
Rcwy Type:

MCC LOAD DATA:
Constant-Speed Motors:
    Total Motor > 50 hp:
    Total Motor < 50 hp:

Total AFD Load:

Total Non-motor Load:

Meter Data:

Main Breaker Data:

Manuf:
Type:
Frame:
Amp Rating:
Inst Setting:

Interrupting Rating:

MCC-MAIN

MCC   0.48 KV

MCC-1   MCC-4

M-1   M-2   M-3   L-1   L-2

LARGEST MOTOR:
(Constant-Speed)

Name:
HP:
Bkr Type:
Frame:
Trip:
Short Circuit:
Inst. Trip:

Smallest Breaker Data:
(Lowest I.C.)

Manuf:
Type:
Frame:
Amp Rating:
Inst Setting:

Interrupting Rating:

LARGEST FEEDER:

Name:
Load:
Bkr Type:
Frame:
Trip:
Short Circuit:
Inst. Trip:

Low Voltage Breaker with Trip Unit Template

Breaker ID	Breaker Mfr/Type	Frame Size / Sensor	Trip Unit Mfr/Type	Plug Rating	Long Pickup	Long Time Delay	Short Pickup	Short Time Delay	I²T	Inst. Pickup	Ground Pickup	Ground Time Delay	Interupting Rating	Comments

Equipment Name Plates and EasyPower Data

In this section, you will see how to use name plates to collect data as well as where it will be placed in EasyPower power system software, for later arc flash analyis.

Solid State Trip (Example A)

Solid State Trip (Example B)

Thermal Magnetic Breaker (Example A)

Compact® NSF250N Circuit Breaker

Thermal Magnetic Breaker (Example B)

Low Voltage Fuse (Example A)

Low Voltage Fuse (Example B)

Generator (Example A)

Model	S4
Power Factor	0.8
kVA	512
kW	410
RPM	1800

Reactances Class H / 480 V   - Time constants (ms)

		VS2	S4	S5	M7	M8	L9	L9 (6w.)
Kcc	Short-circuit ratio	0,36	0,36	0,32	0,40	0,31	0,35	0,36
Xd	Direct axis synchro. reactance unsaturated	349	335	373	319	376	344	338
Xq	Quadra axis synchro. reactance unsaturated	209	201	223	191	225	206	203
T'do	Open circuit time constant	1738	1855	1855	1930	1958	1997	1997
X'd	Direct axis transient reactance saturated	20,1	18	20,1	16,5	19,2	17,2	16,9
T'd	Short circuit transient time constant	100	100	100	100	100	100	100
X"d	Direct axis subtransient reactance saturated	14,1	12,6	14	11,6	13,4	11,8	12,1
T"d	Subtransient time constant	10	10	10	10	10	10	10
X"q	Quadra. axis subtransient reactance saturated	19,1	16,9	18,8	15,3	17,8	15,6	15,8
Xo	Zero sequence reactance unsaturated	0,1	0,4	0,1	0,1	0,9	0,9	0,4
X2	Negative sequence reactance saturated	16,6	14,8	16,5	13,5	15,6	13,7	14
Ta	Armature time constant	15	15	15	15	15	15	15

Generator (Example B)

Press **Calculate** for X/R value

Multiply Per Unit Reactances by 100 for Percent values.

Transformer (Example A)

Press **Calculate** for Z0% and X/R Ratio values

Transformer (Example B)

Medium Voltage/High Voltage Breaker

Modeling and Arc Flash Analysis in EasyPower®

An up-to-date one-line diagram is the essential basis for all system studies. The one-line describes the electrical power system equipment, layout, and connections. Creating a one-line diagram in EasyPower from the data collected in the field is fast and easy, and facilitates accurate analysis.

EasyPower is a powerful computer software program you can use to quickly model and analyze industrial, utility, and commercial electric power systems. It supports both AC and DC modeling. You can create one-lines and perform analyses such as short circuit, arc flash, and coordination. The program includes a comprehensive equipment library for all major manufacturers.

Here, we will describe briefly how you can use EasyPower to create a one-line and perform an arc flash hazard analysis.

Creating a One-line

The Session Window

The program opens in a session window. The upper area, called the ribbon, contains several tabs, including **Home**, **Insert**, and **Tools**. On the left is an **Equipment Palette** that you use to select the equipment for your one-line. The bottom of the window displays a status bar for information about your system settings. The main area of the window is where you build your one-line. In our example, the snap-to-grid feature is turned on, which helps to keep the equipment aligned.
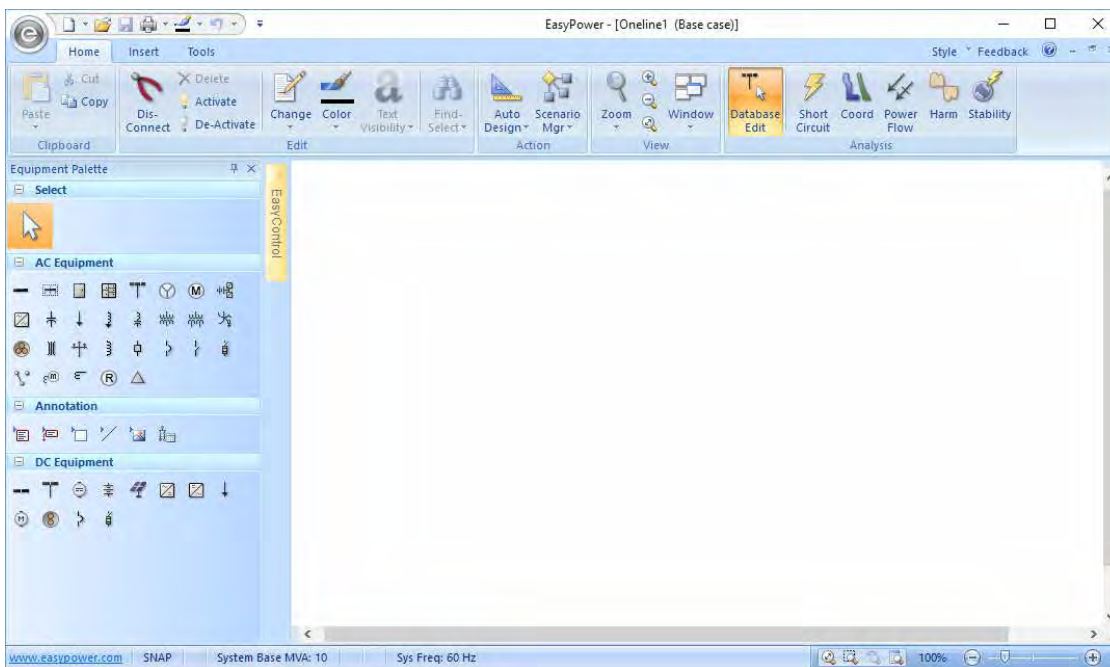

Figure 8.1: The EasyPower Session Window

The program opens in the **Database Edit** focus. This is where you will build your one-line and record your equipment data. Additional analysis options include **Short Circuit**, **Coordination**, **Power Flow**, **Harmonics**, and **Dynamic Stability**. The options available depend on those you've purchased.
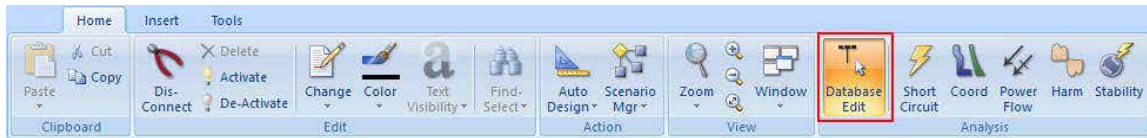
Figure 8.2: Home Tab Including Analysis Options

The **Equipment Palette** displays the AC and DC equipment you can select for your one-line. You can also insert notes, boxes, lines, pictures, and schedules. Click the pointer arrow when you need to put EasyPower into select mode.
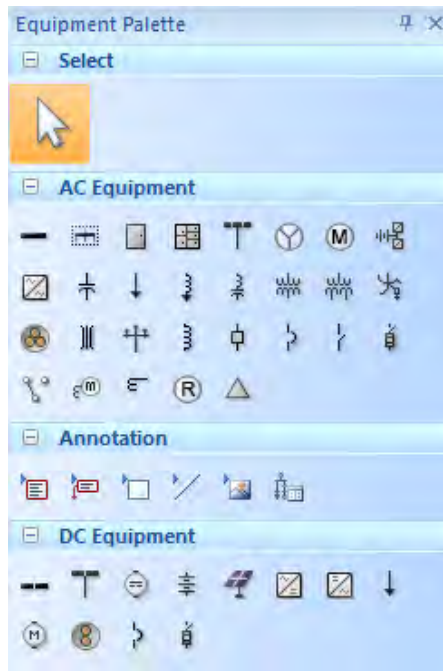

Figure 8.3: The Equipment Palette

You can hover the pointer over the equipment symbols to see the names of the equipment until you become familiar with the symbols.
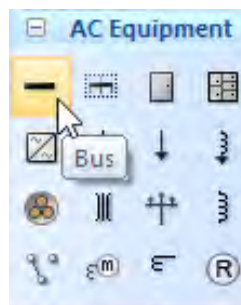

Figure 8.4: Displaying the Equipment Name

Adding Equipment to the One-line

To add equipment to the one-line, select the equipment from the **Equipment Palette** and then click on the one-line in the location where you want to add the equipment. A common equipment item is a "bus." The bus is used as the connection point for equipment.

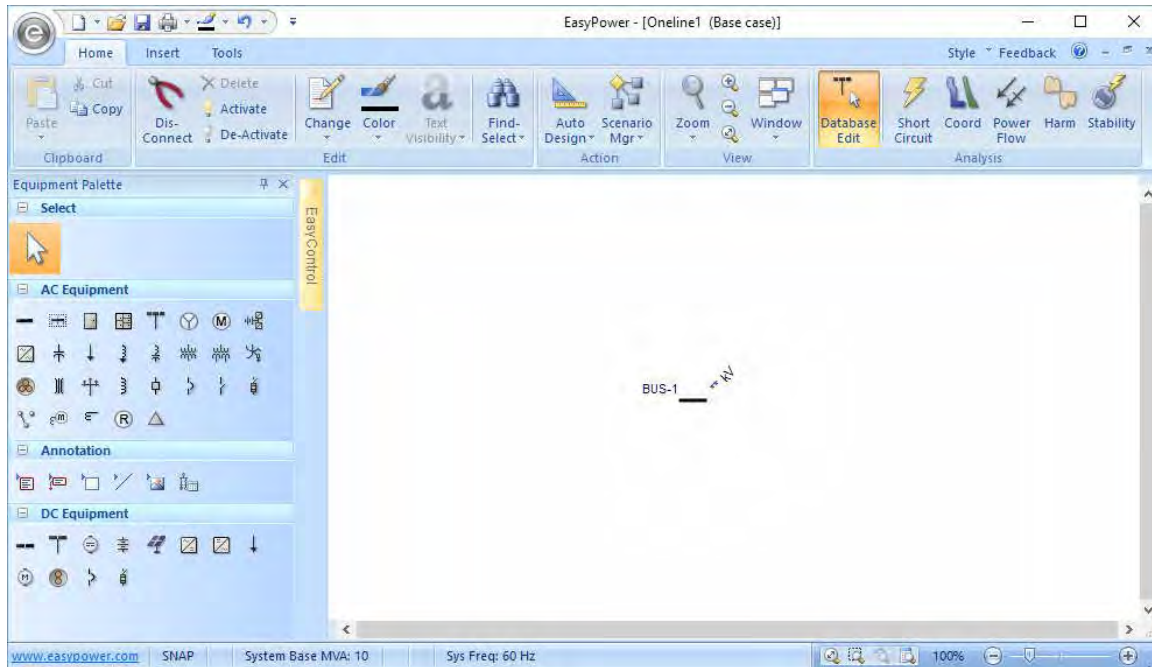Here, we have selected a bus and placed it on the one-line.

Figure 8.5: Bus Placed on One-line

We can move the bus by dragging it. If we want to make the bus larger, we can drag it by the edge until we reach the size we want.

Figure 8.6: Resizing a Bus

To enter information about the bus, we double-click on it to open the **Bus Data** dialog box. Fields with a red exclamation mark are required. Notice that for a bus, the **Base kV** is required. We can change the bus name and enter the specifications for the bus here.

Figure 8.7: Bus Data Dialog Box

The bus we are creating is for connecting the utility. Here you can see we've changed the bus name to UTILITY and set the Base kV for the bus to 13.8 kV.

Figure 8.8: Changing Bus Information

Adding a Utility

Next, we'll add the utility to the one-line. The utility is red because it is not yet connected to the bus.
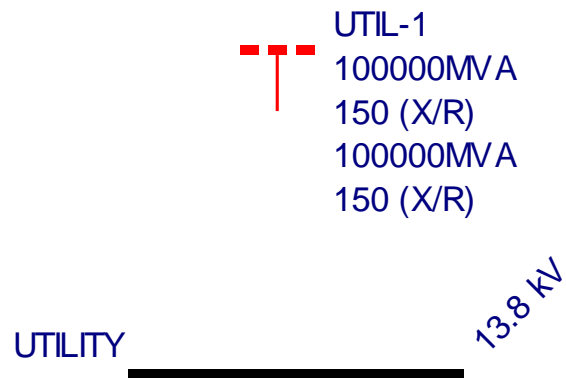

Figure 8.9: Adding the Utility

To connect the utility, we drag the utility down until its leader line connects with the bus. When it is connected, the utility color changes from red to black.
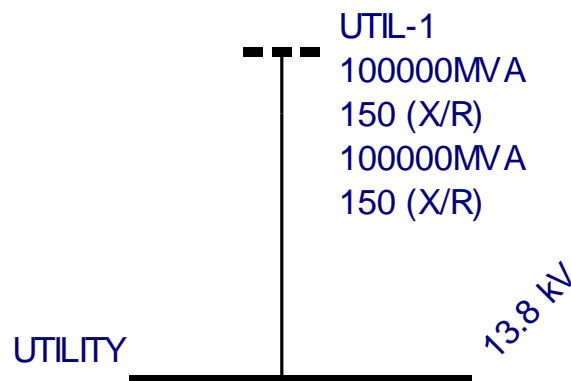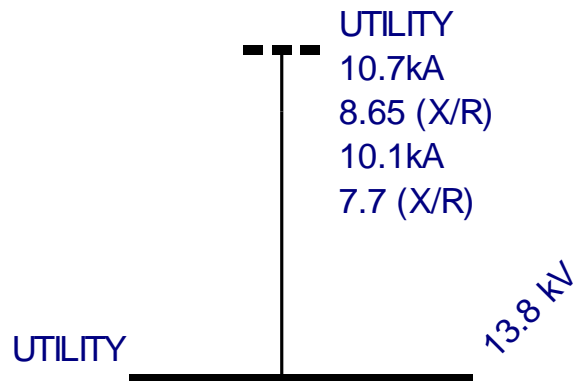

Figure 8.10: Connecting the Utility

By double-clicking on the utility, we can change the default information for the utility to the actual specifications.

Figure 8.11: Changing the Utility Information

After we click **OK** to save and close the **Utility Data** dialog box, the updated utility information appears on the one-line.

Figure 8.12: Updated Utility Information Displayed on the One-line

Adding a Fused Switch

We can add a fused switch below the UTILITY bus by dragging the fused switch from the **Equipment Palette** and placing it below the UTILITY bus. We can double-click on the fused switch to add the data.
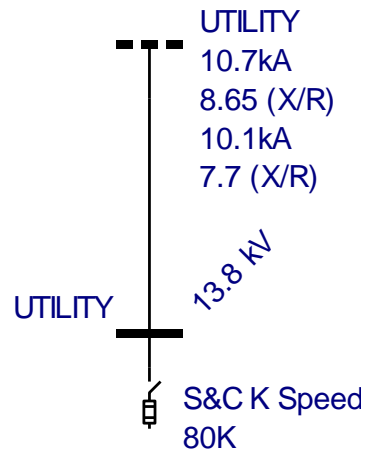
UTILITY
10.7kA
8.65 (X/R)
10.1kA
7.7 (X/R)

13.8 kV

UTILITY

S&C K Speed
80K

Figure 8.13: Adding a Fused Switch

Adding a Transformer

Next, we'll add a transformer and attach it to the fused switch. The lower "leader line" of the transformer is not connected, so it appears with a red highlight.
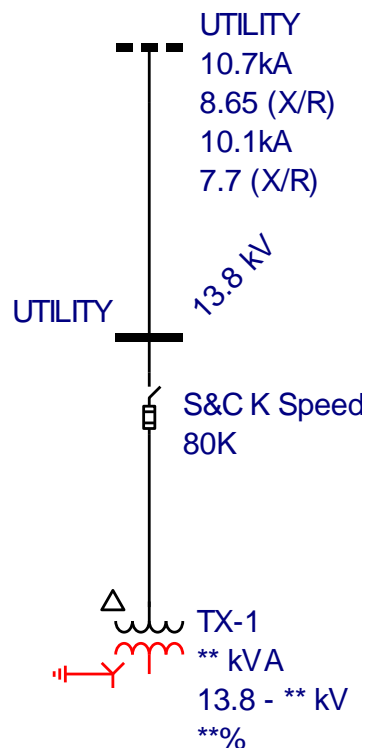
UTILITY
10.7kA
8.65 (X/R)
10.1kA
7.7 (X/R)

13.8 kV

UTILITY

S&C K Speed
80K

TX-1
** kVA
13.8 - ** kV
**%

Figure 8.14 Adding a Transformer

Next, we'll add a new bus below the transformer, and then drag the leader line of the transformer down to connect the bus. After entering the bus Base kV, we can double-click on the transformer to enter the transformer data.
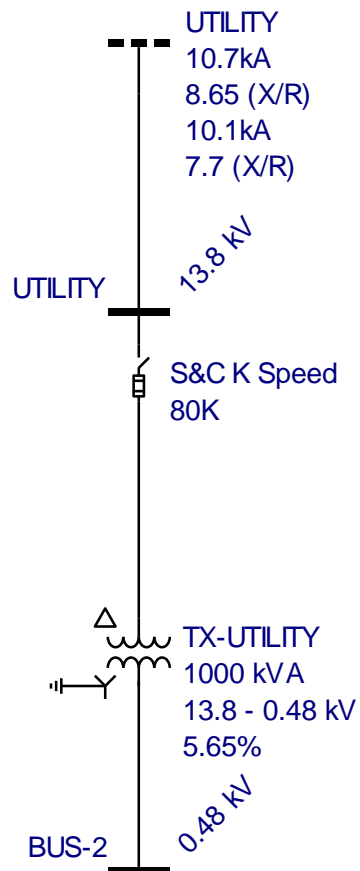

UTILITY
10.7kA
8.65 (X/R)
10.1kA
7.7 (X/R)

13.8 kV

UTILITY

S&C K Speed
80K

TX-UTILITY
1000 kVA
13.8 - 0.48 kV
5.65%

0.48 kV

BUS-2

Figure 8.15: Transformer and Bus Information Entered

Adding a Bus as a Switchgear

Next, we'll add a bus with a bus type of **Switchgear** to the one-line. We will resize it as we did the first bus to allow room for feeders.
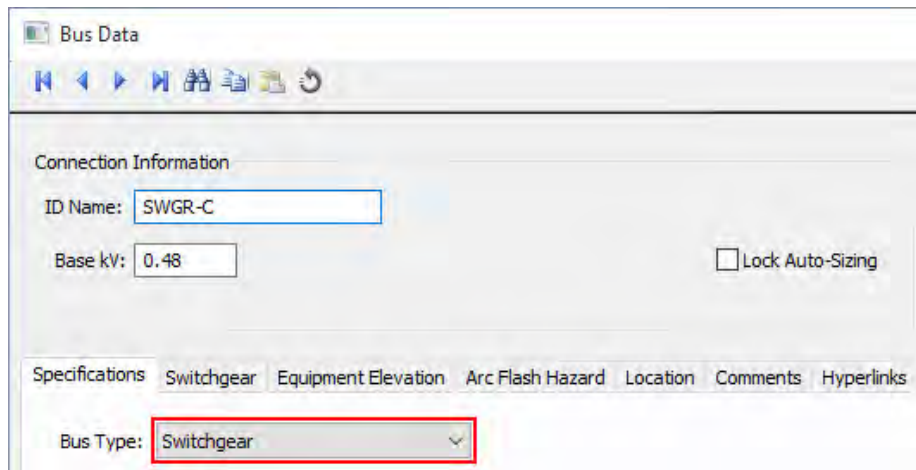

Figure 8.16: Bus Type of Switchgear

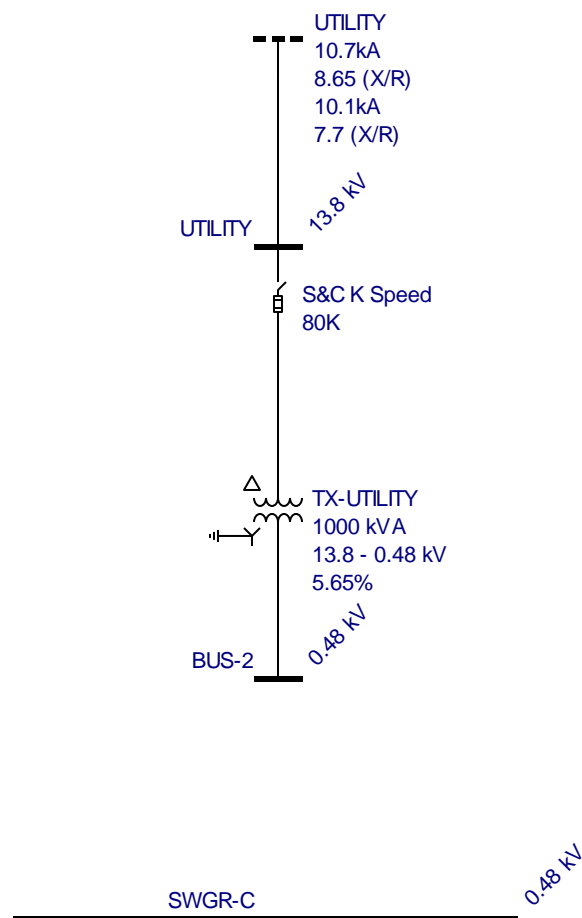

Figure 8.17: Adding a Switchgear Bus

Adding a Cable

We want to add a cable between BUS-2 and the SWGR-C. We select the cable from the **Equipment Palette**, click on BUS-2, and then drag the other end of the cable to the bus. Afterwards we can double-click on the cable to enter its data, such as the number of phases, cable length, and impedance values.

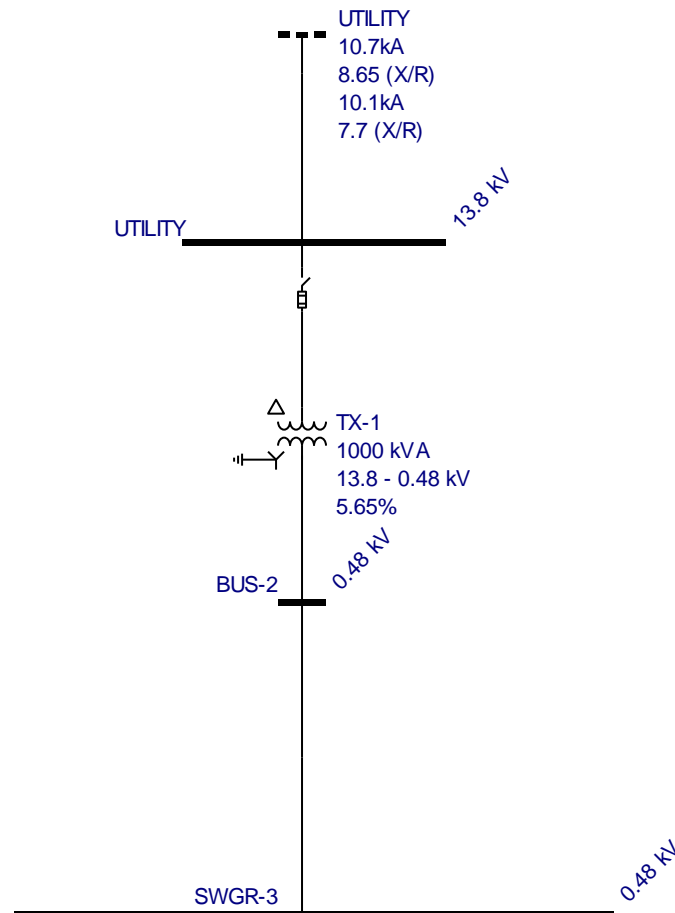*Figure 8.18: Adding a Cable*

Adding Additional Equipment

We can add equipment such as MCCs, panels, or motors below the switchgear bus. MCCs and panels are connected by a cable; motors are connected directly to a bus by attaching the leader line.

As we did with the other equipment, we can double-click on each equipment item to enter its information.
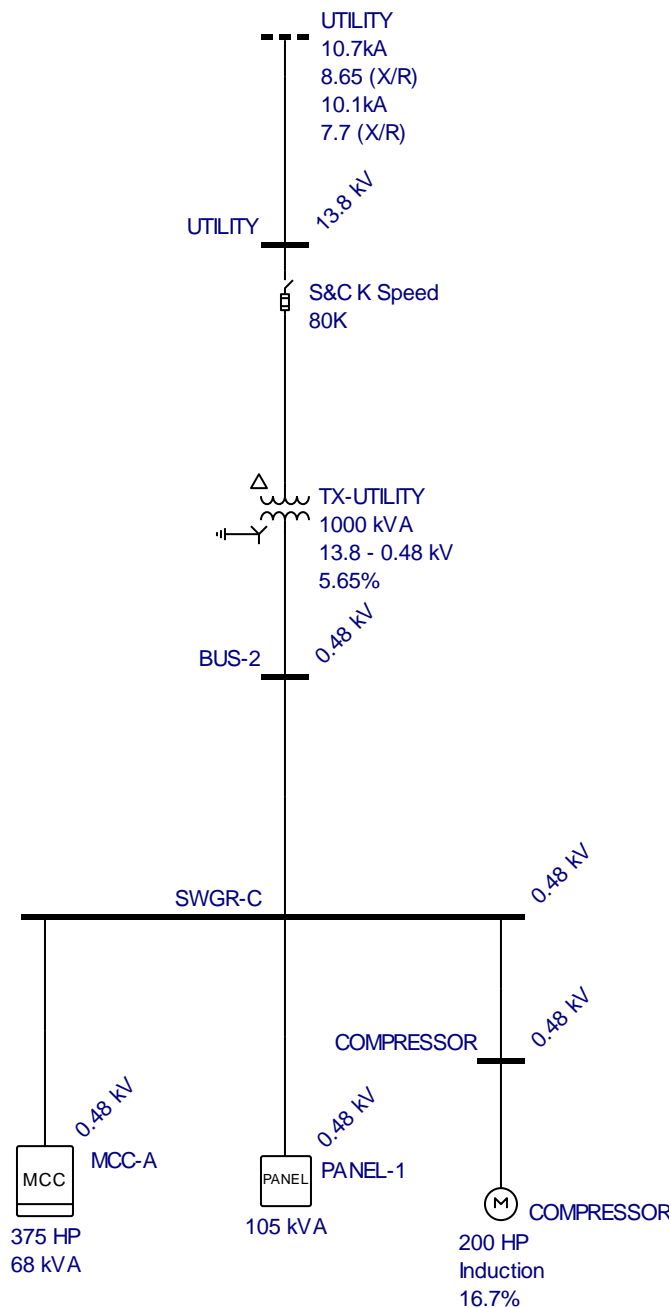
Figure 8.19: Adding an MCC, Panel, and Motor

Adding Breakers

We can add breakers to the one-line by clicking the **LV Breaker** symbol on the **Equipment Palette**, and then clicking on the places where we want the breakers added.

UTILITY
10.7kA
8.65 (X/R)
10.1kA
7.7 (X/R)

UTILITY   13.8 kV

S&C K Speed
80K

TX-UTILITY
1000 kVA
13.8 - 0.48 kV
5.65%

BUS-2   0.48 kV

SWGR-C   0.48 kV

COMPRESSOR   0.48 kV

0.48 kV   0.48 kV

MCC   MCC-A
375 HP
68 kVA

PANEL   PANEL-1
105 kVA

COMPRESSOR
200 HP
Induction
16.7%
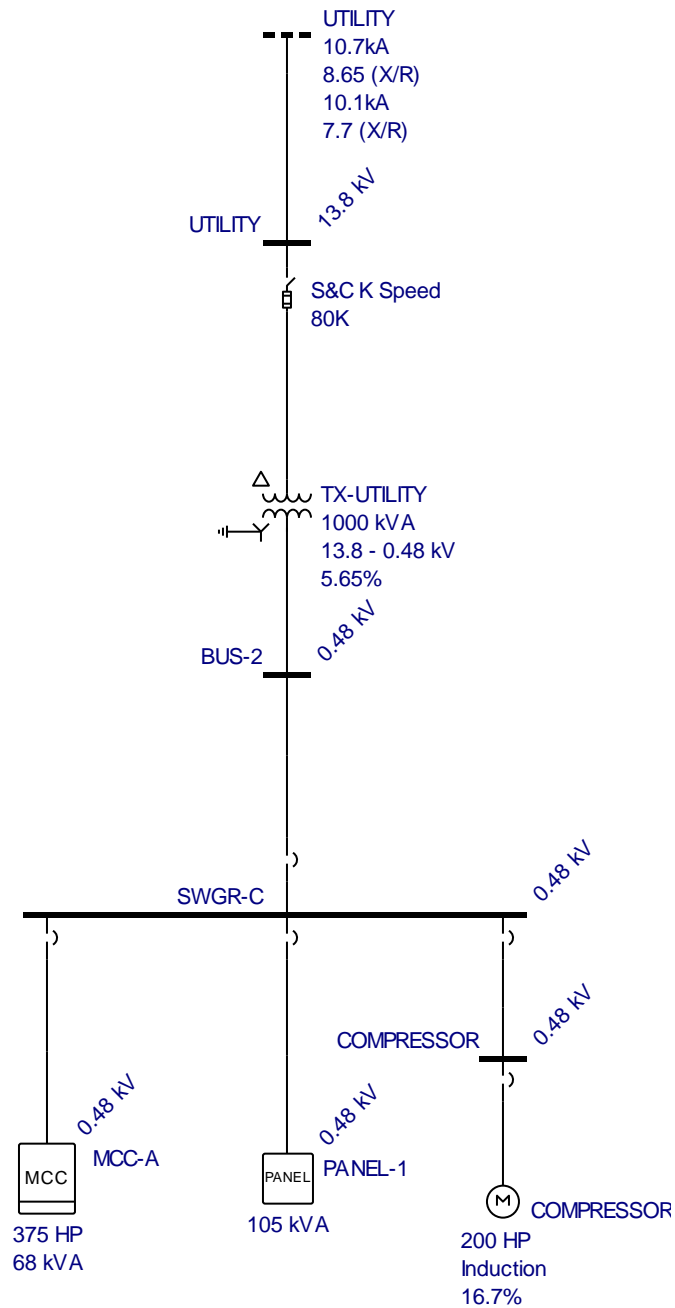
Figure 8.20: Adding Breakers

We can then double-click on each breaker to enter the breaker information.

Figure 8.21: Entering Breaker Information

Saving the One-line

When we have the one-line we want, we can save the file. After all of the equipment is added and the relevant information is entered, we can start performing analysis of our power system.
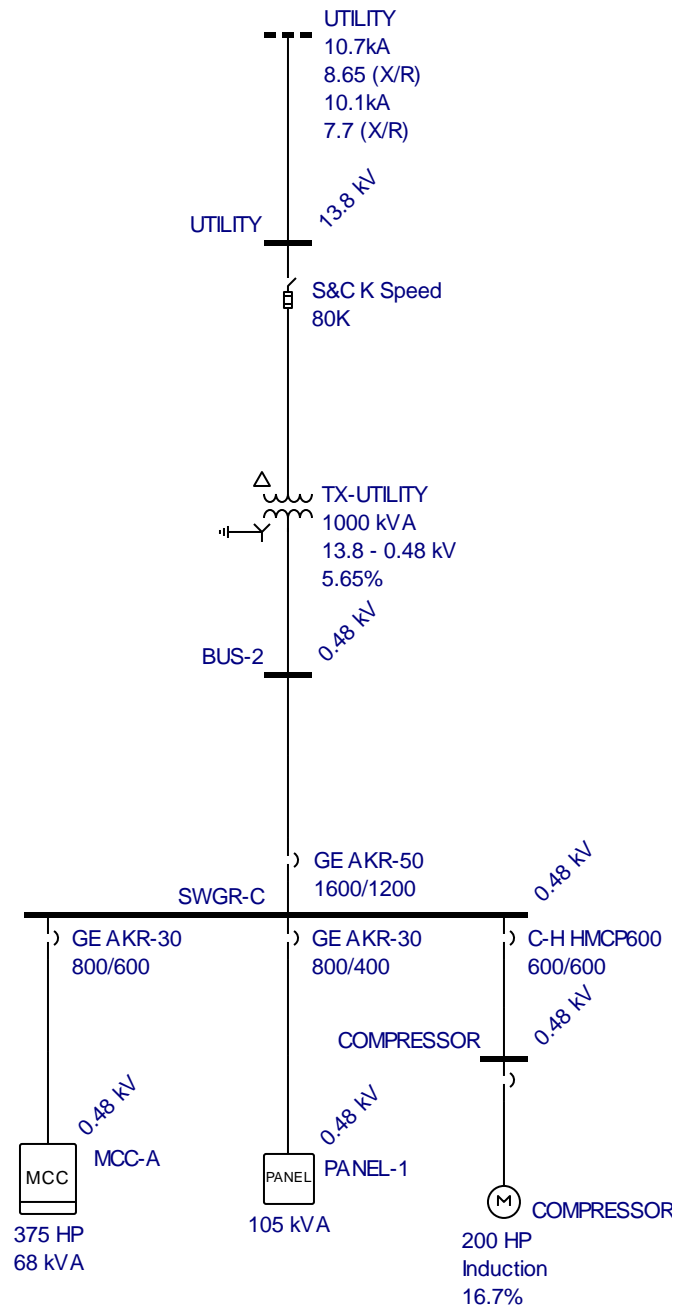
Figure 8.22: Completed One-line

Performing an Arc Flash Hazard Analysis

In this section, we'll demonstrate how to perform an arc flash hazard analysis in EasyPower, using the *Protection-1.dez* sample one-line file included with the software.
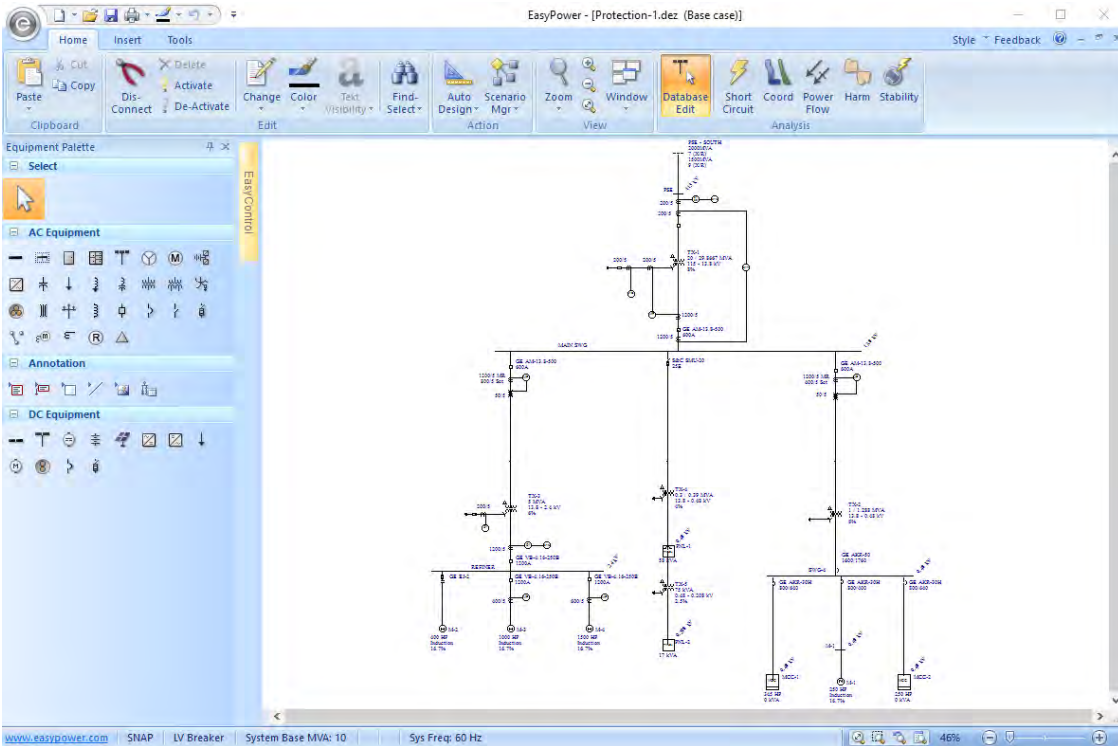
Figure 8.23: Protection-1.dez Sample One-line

Performing the Analysis

To perform an arc flash analysis, we must be in the **Short Circuit** focus. After clicking **Short Circuit** on the **Home** tab, the **Short Circuit** tab is displayed. The options for short circuit analysis appear in the ribbon area.
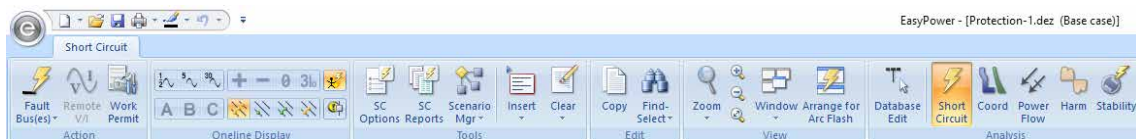
Figure 8.24: Short Circuit Tab

Note that the **Arc Flash** button is already selected. We'll click **Fault Bus(es)** to start the analysis.

Figure 8.25: Arc Flash and Fault Bus(es) Buttons on the Short Circuit Tab

The program displays the arc flash boundaries (AFB) and incident energies.

TX-2

328" AFB
86.3 cal / cm² @ 18"
SWG-4

23.5" AFB
1.8 cal / cm² @ 18"

M-1

MCC-1
MCC
55.4" AFB
7.6 cal / cm² @ 18"

M-1

MCC-2
MCC
55" AFB
7.5 cal / cm² @ 18"
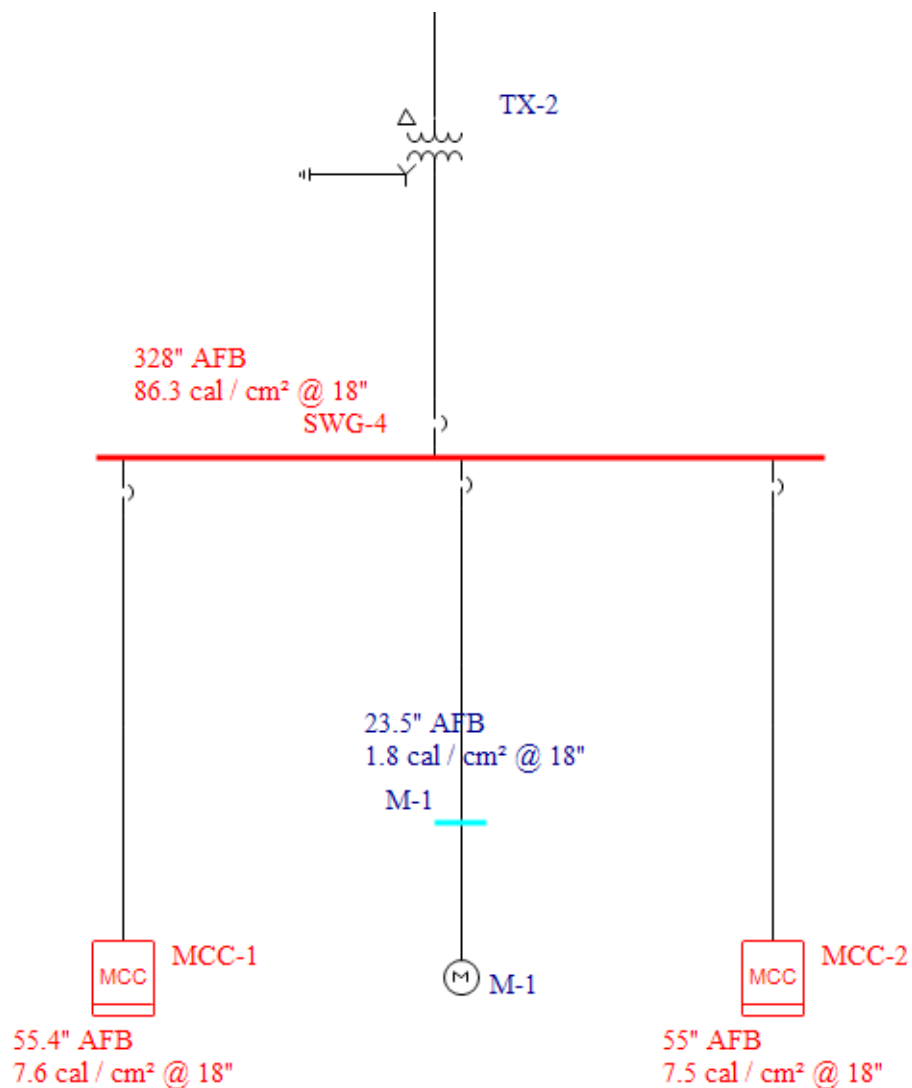
Figure 8.26: Arc Flash Results on the One-line

We can change the information displayed based on the short circuit options. To open the options, we click **SC Options** on the **Short Circuit** tab, and then click the **Arc Flash Hazard** tab. We'll change the **Worst-Case Arc Flash Hazards Output** to **Both (Incl & Excl Main)**, and then click **OK** to save the change.

Figure 8.27: Short Circuit Options – Arc Flash Hazard Tab

Displaying Detailed Output and the Arc Flash Spreadsheet

Now, we'll double-click SWG-4 to fault the bus, and then click **Arrange for Arc Flash** to view the Arc Flash Hazard report.

This displays a detailed set of arc flash results for the arcing fault. The results on the downstream feeder breakers represent the hazards one would incur when working just downstream of those breakers.
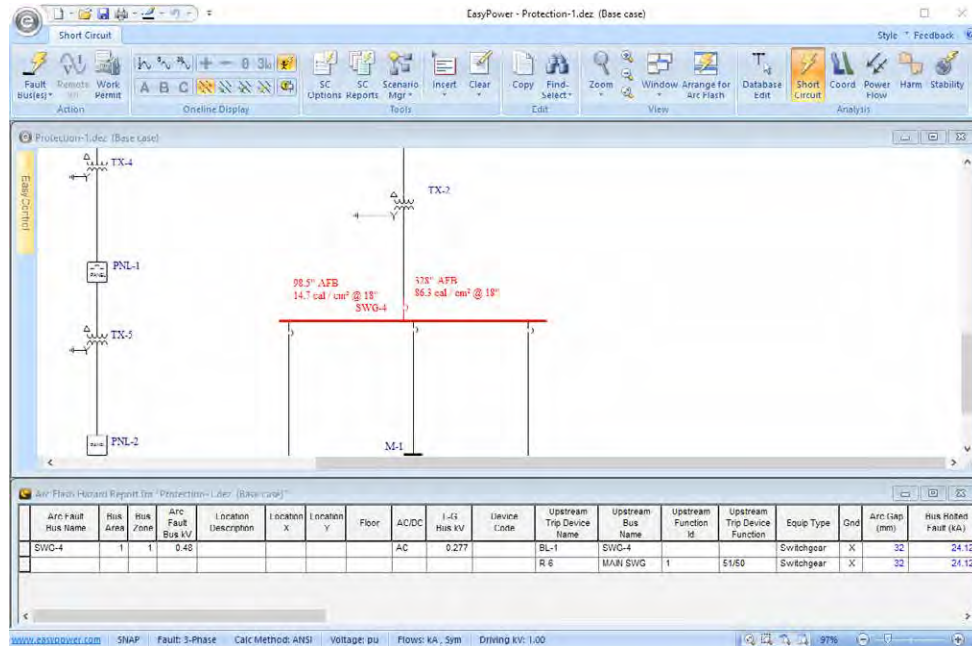
Figure 8.28: Arc Flash Results with the Arc Flash Hazard Report Displayed

Printing Arc Flash Hazard Labels

We can print arc flash hazard labels directly from the Arc Flash Hazard report. First, we select the report window, and then click **Label**.
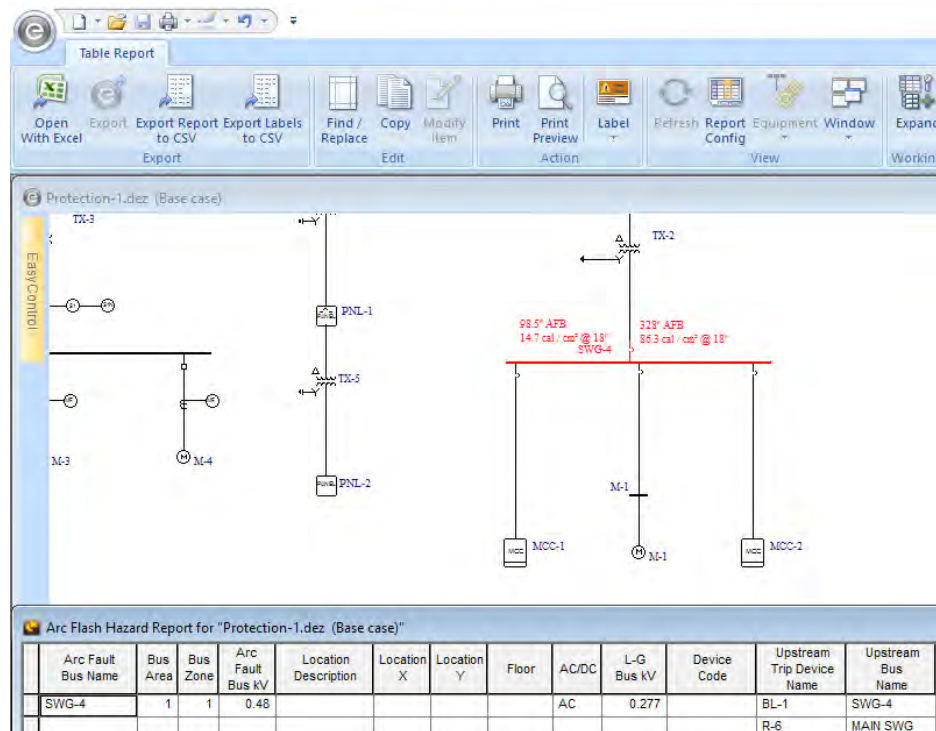
Figure 8.29: Printing Arc Flash Hazard Labels

A preview of the label appears. We can select different templates and layouts, select the devices for which we want to print labels, and also add comments that will appear on all the labels. When we have the label we want, we can print it.
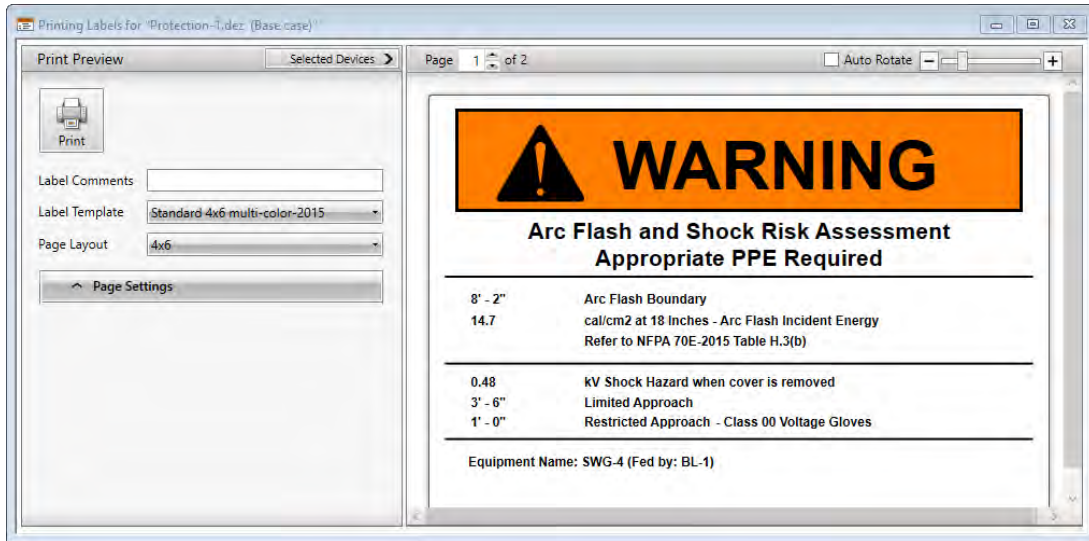
Figure 8.30: Printing an Arc Flash Label

Additional Features

In addition to performing arc flash analysis and printing labels, you can also create Energized Work Permits, perform coordination integration, and specify user-defined trip times for the bus.

Download a Demo

You can download a free trial version of the EasyPower software from:
www.easypower.com/products/EasyPower/EasyPower_demo.php

You can learn more about EasyPower by visiting our website at:
www.easypower.com

APPENDICES

Appendix A

Arcing Current and Incident Energy Graphical Representation
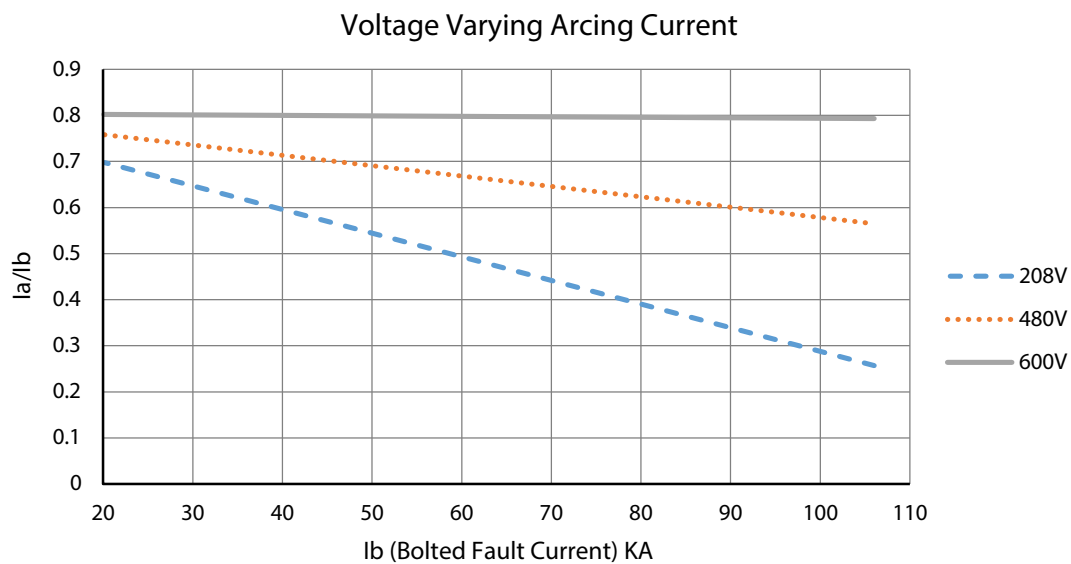
Figure A.1 Arcing Current Variance Due to Change in Voltage

Effect of Changes to Gap Space in Arcing Current Equation
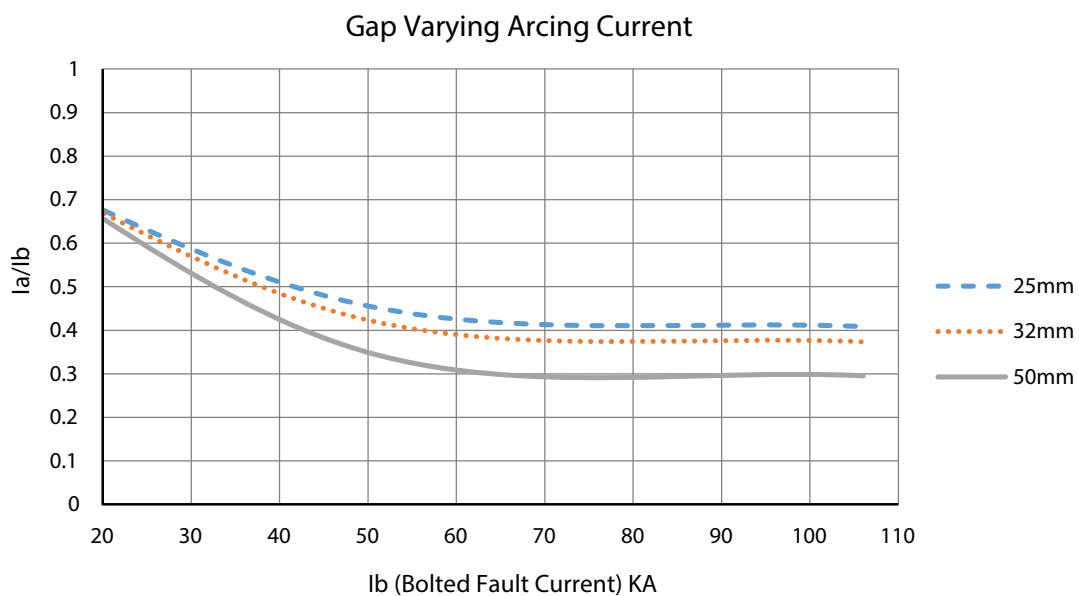
Figure A.2 Arcing Current Variance Due to Change in Gap Distance

Incident Energy for Different Bolted Fault Currents in Open Configuration

Open Configuration Incident Energy vs. Bolted
Fault Current at 480V, 32mm Gap
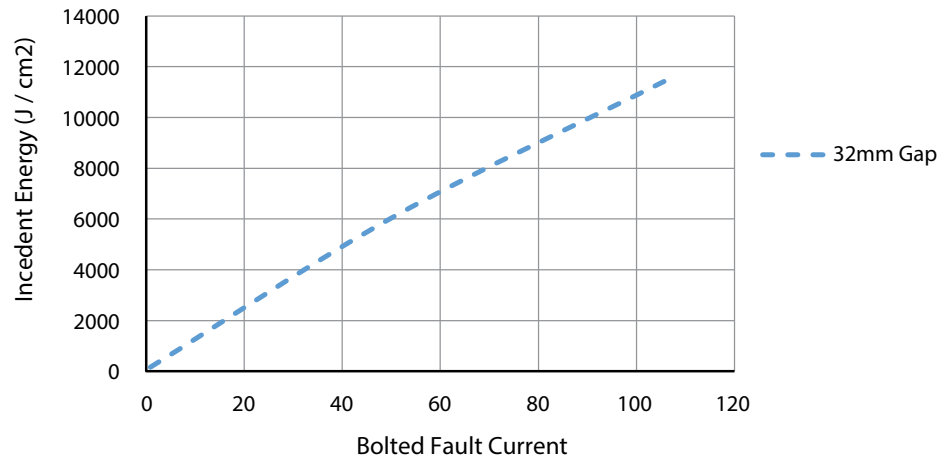
Figure A.3 Incident Energy at 32 mm Gap in an Open Configuration

Incident Energy for Different Bolted Fault Currents in Box Configuration

Box Incident Energy vs. Bolted Fault Current
at 480V, 32mm Gap
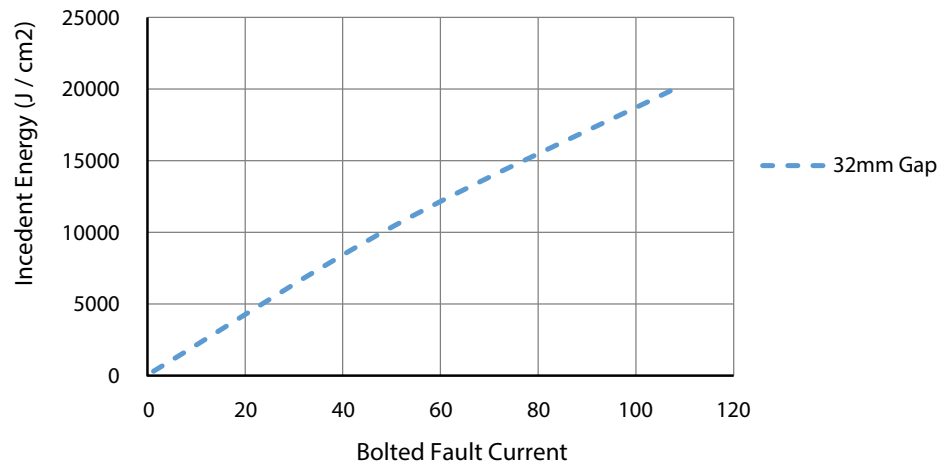
Figure A.4 Incident Energy at 32 mm Gap in a Box Configuration

Appendix B

Evaluating Arc-Flash Hazard for Time-Varying Currents

In radial distribution circuits fed by a utility network, with few or no motors and with no generators connected nearby, the arc currents are pretty much constant if the random fluctuation in arc is neglected. This is true in most commercial power systems, utility distributions, and some small industrial plants. For such conditions, the arc-flash hazard calculation method outlined in the published standards would be adequate. The trip time of any protective device can easily be obtained by looking at a time-current curve (TCC). Time-current curves give the trip time for constant fault currents or overloads. As long as the fault current remains constant, we would need to deal with a single bolted fault current, arc current, and arc duration, and therefore the calculation would be straightforward.

In other types of power systems, the fault current does not remain constant in the following cases:

- Fault close to a generator

- Fault close to large motors

- Fault on equipment fed by multiple sources

Calculating the time-varying values of fault currents can be time consuming. Also, because time-current curves are based on constant currents, obtaining trip times of protective devices add another level of complexity for time-varying currents. Therefore, accurate prediction of arc flash incident energies becomes extremely involved.

This topic discusses the various types of time-varying fault currents, the way protective devices operate in response to time-varying currents, and some effective methods to calculate reasonably accurate arc flash incident energies for time-varying currents. EasyPower software calculates arc flash hazards for time-varying fault currents through two methods: Dynamic Simulations and the "Integrated" method. The name "Integrated" comes from the fact that incident energy is integrated (or accumulated over time). IEEE Std 1584-2002 equations are used for arc flash hazard calculations in the examples presented here.

Transient Fault Currents

Generators

If an arc flash occurs near a generator, the generator initially contributes a large AC current, which reduces to a lower steady state value after several cycles. If the excitation system of the generator does not increase the field excitation, this is true. This is the transient behavior of generators. In most cases, the excitation system ramps up the field current and this in turn increases the output short circuit current.
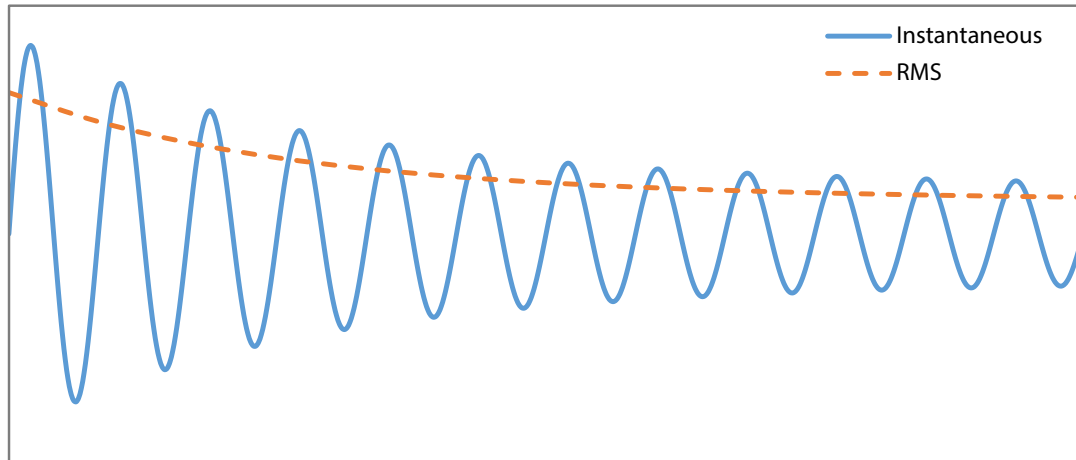
Figure B.1: AC Component of Fault Current Close to a Generator

Figure B.1 shows the AC component of the transient fault current close to a generator. The RMS value is represented by the dotted line. The RMS value of the bolted fault current is required to calculate the arc current.

Motors

When a fault occurs upstream to a motor, the motor contributes short circuit current for a few cycles, as shown in Figure B.2. Only the AC component of a phase is shown here.
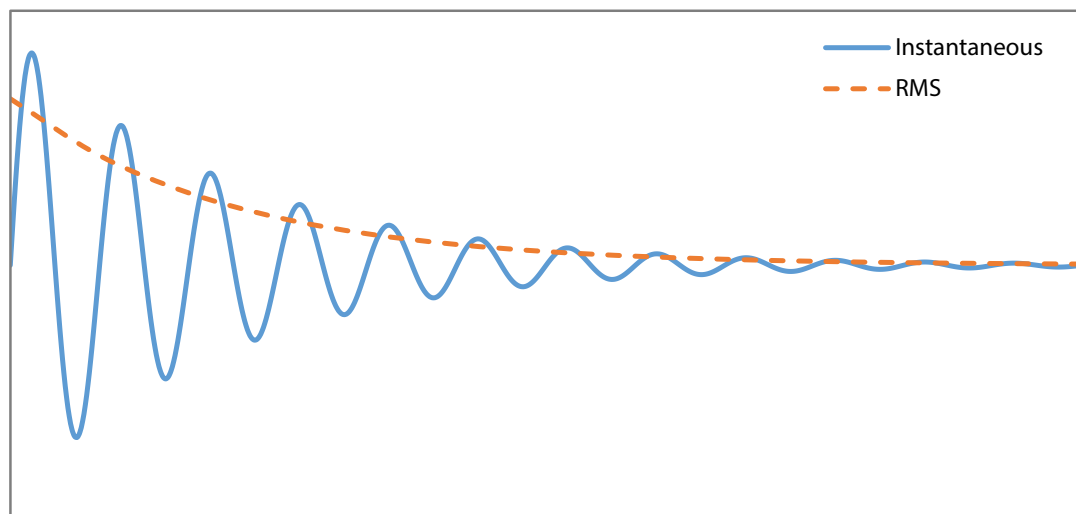
Figure B.2: Contribution of Short Circuit AC Currents from a Motor

Equipment Fed by Multiple Sources

Figure B.3 shows an example of a medium voltage switchgear fed from the utility transformer and a generator in a co-generation scheme.
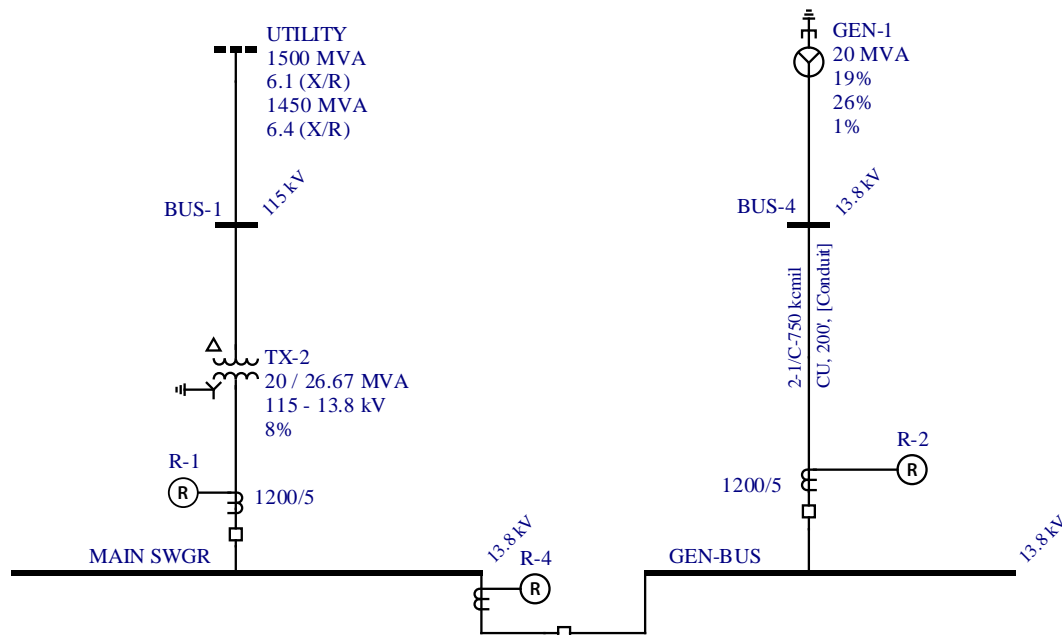
Figure B.3: Example System with Co-generation

If a fault were to occur on the bus MAIN SWGR, current would come from both sources. In this example, the tie-breaker relay R-4 would trip first, to isolate the generator from the fault. Next, the relay R-1 would trip, isolating the utility from the fault. Figure B.4 below shows the AC RMS component of the fault current at the bus as a function of time. Downstream motor contributions have been ignored in this example for the sake of simplicity. This plot was obtained through the Dynamic Stability simulation feature of the EasyPower software. Fault is initiated at zero seconds. Initially, both sources feed to the fault. At almost 0.5 seconds, the tie-breaker interrupts the current from the generator. At close to 0.8 seconds, the utility breaker clears the fault.

Calculating the arc flash incident energy for this example requires breaking up the entire fault duration into small time steps, calculating the trip times for time-varying currents seen by the relays, calculating the incident energy for each time step, and integrating the energy over time until the fault is cleared. This process is similar to a time-domain simulation.
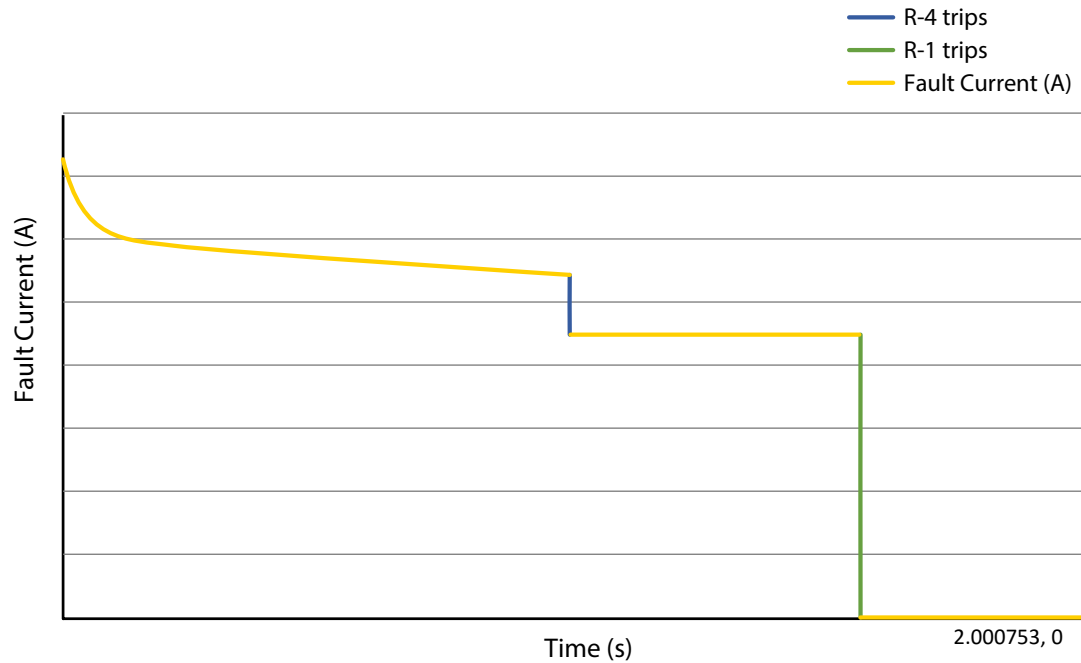
Figure B.4: Plot of Fault Current Over Time for the Co-gen System Example
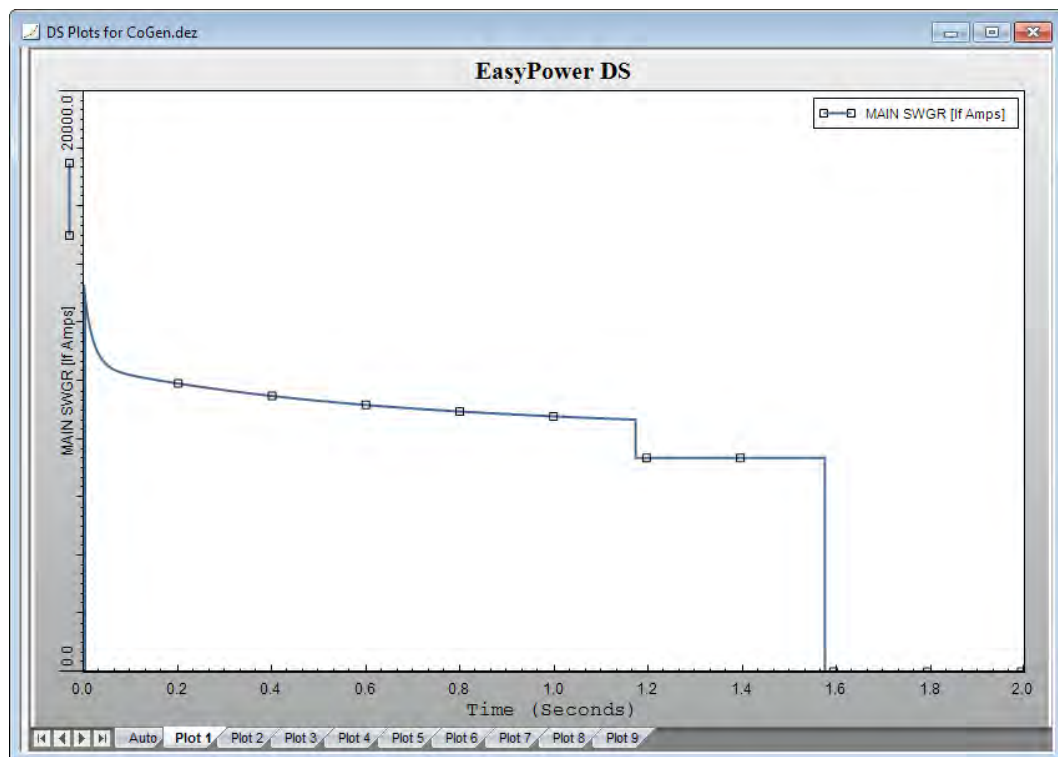
Figure B.5: Example Showing the Effect of a Common Branch and Multiple Sources
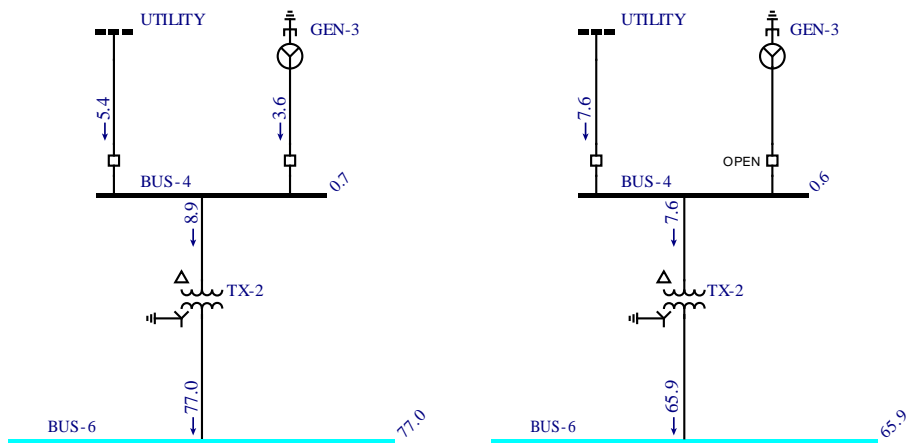
Figure B.6: Example Showing the Effect of a Common Branch and Multiple Sources

Effect of a common branch: When multiple sources feed to a common branch, the impedance of the branch causes the current contribution from the different sources to affect one another. The presence of other sources lowers the current contribution of any source. Figures B.5 and B.6 shows two sources, a utility and a generator, feeding a transformer. A fault occurs on the secondary side of the transformer. Two cases are presented here: one with generator connected and the other with generator breaker tripped. In this example, the utility provides 5.4 kA when the generator is connected. When the generator breaker opens, the utility current increases to 7.6 kA. Therefore, the relay on the utility breaker sees a time-varying current. To accurately evaluate the trip time of the utility relay, a realistic simulation is necessary.

Protective Devices

Most protective devices have a "memory" variable that makes the device trip when the variable exceeds a threshold value. The "memory" variable integrates over time. For example, when a fault current passes through a fuse, heat energy is accumulated in proportion with the I^2T value (square of current integrated over time).[1] The fuse melts when a certain melting temperature is reached. The melting I^2T value at various fault currents can be calculated from a TCC. When the calculated accumulated I^2T in a circuit exceeds the I^2T value from a TCC, the fuse melts. This method can be used to calculate the fuse melting time in the case of time-varying currents. Low voltage circuit breakers with inverse-time characteristic curves exhibit a similar behavior. Induction disc relays trip when the disc rotates and triggers a switch. The "memory" variable in this case is the rotation (or travel) of the disc, which is a function of the relay current integrated over time. Definite time and instantaneous trip functions are constant trip times, independent of the current.

In calculating the trip time of any protective device it is necessary to take into account the effect of time-varying currents on the behavior of the device.

ANSI Short Circuit Calculations

ANSI/IEEE C37.010-1979 standard describes procedures to calculate short-circuit currents at various intervals.[2] The intervals are:

- Momentary: This is also referred to as first cycle (or ½-cycle). The generator contribution to the fault is highest at this time interval. The momentary current is used to evaluate the short circuit duty of fuses, low voltage breakers, and the close and latch duty of high voltage breakers.

- Interrupting Time: This is the time at which a high voltage breaker's contact separates. This is 1–7 cycles after the fault is initiated.

Most faults are cleared within a few cycles for instantaneous trip. Relays with time delays typically trip in less than a second. Low voltage breaker short time delays trip in half a second or less. Apart from the momentary and interrupting time intervals, a third time interval called delayed time (or 30-cycle) is also considered.[3]

- Delayed Time: The motor contributions have decayed in this time and the generators may contribute a fraction of its transient current. This is also referred to as 30-cycle current.

For short circuit duty calculations, the asymmetrical currents (which include the transient DC component) are also considered in momentary and interrupting time fault currents. However, for arc flash hazard calculations, only the AC component is considered because the highly resistive arc fault will have negligible DC component.

Although a dynamic simulation or transient simulation software can calculate the continuously changing fault currents over time, there are no published standards on these methods. The ANSI/IEEE C37 standards are the primary short circuit calculation methods accepted by the industry. Therefore, we feel the need to calculate arc flash hazards using the momentary and interrupting time current described in the standards and the 30-cycle current.

Accuracy of Single Current Calculations

Spreadsheet calculations, hand calculations, or traditional calculation methods in arc flash hazard assessment use a single fault current. The momentary current is the most widely used since this would be the highest. The calculated hazard level using this approximation could be lower or higher than the actual hazard. Both the fault current and the trip time of protective devices play significant roles. Here are two examples:

- **Case 1**: Figure C.6 shows a fault at MCC-2. The momentary current, interrupting

time current, and the 30-cycle currents are shown on the one-line drawing. The upstream fuse on the main switchboard is expected to clear the fault. The fuse will see a momentary current of 24.1 kA, an interrupting time (5-cycle) current of 20.9 kA and a 30-cycle current of 18.6 kA. This decay in current is due to the motors.
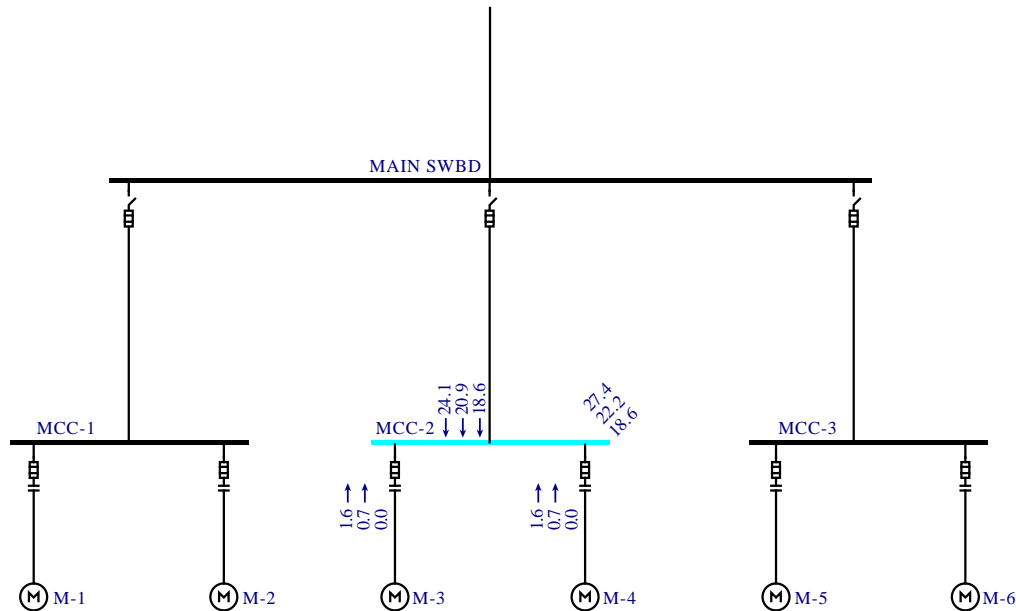
Figure B.7: Example System with Motors Contributing to a Fault

If the momentary current is used, the melting time of the fuse calculated from the TCC for a typical Class L 800A fuse will be about 0.083 seconds. As a result, the arc flash incident energy at 18 inches at MCC-2 will be 3.7 cal/cm^2, which falls in the NFPA 70E PPE category 1. Since fuses have inverse time-current characteristics, smaller currents will yield longer melting times. For a decreasing current, we can expect the melting time to be longer and hence the incident energy will be higher than 3.7 cal/cm^2. If we consider the time-varying nature of the current, the fuse will melt in about 0.34 seconds. The actual incident energy will be about 11.5 cal/cm^2. This requires PPE category 3. There is a great difference in the results of the two methods of calculations.

- **Case 2**: Refer to the system in Figure B.3 for a fault at MAIN SWGR bus and the plot of fault current in Figure B.4. The utility sees a constant AC current and the utility relay is the last device to trip. The trip time will remain constant. If the momentary currents are used for arc flash hazard calculations, the incident energy at 18 inches will be 28.8 cal/cm^2. This requires a PPE category 4. If the time-varying currents were considered, the incident energy would be 21.7 cal/cm^2, which is PPE category 3. Thus, we can see that a simple calculation using just the momentary current would result in excessive PPE.

The two cases described above show opposite effects of using the momentary current in lieu of time-varying current considerations. The first case shows less hazard than the

actual hazard. The second case shows greater hazard. Without studying very closely the current variations and protective device characteristics it would be difficult to predict if the momentary current method would yield higher or lower hazard results than the actual hazard. A detailed simulation would be necessary accurately calculate the hazard.

The Integrated Method

The Integrated method uses a stepped time domain simulation of arc faults. Simulations are carried out in small successive time steps. For each time step, the calculations are made for bolted fault current at the faulted bus, the arc current at the fault, and the arc current through the protective devices. Incident energy is calculated for this time step and added to the incident energy accumulated up to the previous time step. Protective devices are evaluated for trip conditions. The memory variables for trip devices are integrated using the through current and information from the TCC. When a trip condition is found to exist at the end of the time step, the device is switched opened to interrupt the current. For relay controlled breakers, the breakers are opened with an additional delay equal to the rated opening time of the breakers after the relay has tripped. The simulation is run until the fault current reduces to zero. The arc flash boundary is calculated from the total accumulated energy.

The bolted fault currents are calculated using the ANSI/IEEE C37.010 standard. The momentary currents are used up to the first cycle. From 2-8 cycles, the interrupting time currents are used. Thereafter, the 30-cycle currents are used. This is a close approximation using the available standards and practices in short circuit calculations.

Conclusions

- Time-varying fault currents coming from generators, motors and switching action in multi-source (or parallel feed systems) are difficult to calculate through spreadsheets and hand calculations. Evaluation of trip devices for time-varying currents is also complex. Therefore, accurate determination of arc flash hazard for time-varying fault currents is a challenge.

- Using only the momentary currents in arc flash hazard calculations can give inaccurate results when the fault current does not remain constant.

- The Integrated method runs time domain simulations, accumulating the arc flash incident energy over time. Evaluation of currents, protective device operation, and incident energy on successive small time steps improves the accuracy of calculations. This is the most accurate method known so far that follows the ANSI/IEEE C37 standard and IEEE Std 141.

Appendix C

This is an insert of a brochure with the same title that is included to help you better understand arc flash labeling.

Arc Flash Hazard Labeling Do's and Don'ts

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Email: sales@easypower.com

www.EasyPower.com

Overview

With industry adopting NFPA 70E, and Canada's Z462 as the consensus electrical safety standard, North American facilities and many of their counterparts worldwide are performing arc flash hazard studies to label their electrical equipment for safety. The requirement for arc flash hazard labeling is found in the National Electrical Code, Article 110.16 for new equipment, NFPA 70E-2015 Article 130.3(D) for existing equipment, and OSHA 1910.335(b)(1) for general safety hazards.

There are as many different ways to label equipment as there are engineers and electricians in industry. Unfortunately, many of the methods being used are incorrect and may actually decrease worker safety, while increasing your company's liability should an accident occur. This article supplies a safe-approach reference developed through years of experience working with engineers and electricians on their arc flash hazard projects. The viewpoints expressed in this paper are provided as a guide to industry, recognizing that the NEC, NFPA, and OSHA set the standards but do not cover the myriad of questions associated with labeling the different types of electrical equipment in industry.

Common Terms: AFH (arc flash hazard), NFPA 70E (National Fire Protection Association – Standard for Electrical Safety in the Workplace), OSHA (Occupational Safety and Health Administration), CSA Z462 (Canadian Standards Association - Standard for Electrical Safety in the Workplace), PPE (Personal Protective Equipment), NEC (National Electrical Code), ANSI (American National Standards Institute).

Don't Label for Energized Work – Do Label to Warn of Hazards

In the majority of facilities hoping to obtain NFPA 70E compliance, the most prevalent mistake we see is performing an AFH study for the sole purpose of labeling equipment. Following the study, the plant continues the same day–to-day operations, only now the electricians wear PPE as labeled on the equipment.

Two myths need to be dispelled: 1) Arc flash hazard labeling alone does not provide 70E or OSHA compliance and 2) Labeling does not eliminate the requirement for work permits, safety programs, or training and planning when working on energized equipment. What this means in simplified terms is that a facility cannot perform energized work based solely on the fact that the equipment is labeled and the worker is wearing the appropriate PPE as designated on the label.

> Labels should not be used to "assess" a hazard, select PPE categories, or perform energized work based on the information provided on the label.

Arc Flash Hazard labels should be applied to warn personnel of a potential hazard. Labels should not be used to "assess" a hazard, select categories, or perform energized work based on the information provided on the label. These tasks are part of the planning, documentation and work permit process required by NFPA 70E 130.2. Arc Flash hazard information such as PPE category, incident energy, and boundary information shown on many labels should only be used as a cross-check with the information provided in the work permit process.

Label Worst Case

NFPA 70E, 2015 Article 130.5(D) requires AFH labels to show the incident energy or the required PPE category for that equipment, and the arc flash boundary and the voltage. Most labels being applied today list both, along with a host of other items such as AFH boundaries, approach boundaries, glove requirements, etc. Whatever options you select, the listed incident energy or PPE should be the "worst" case for that equipment. The 2015 edition of NFPA 70E specifically states that you cannot show both the incident energy and the PPE Category.

Many companies choose to label switchgear, for instance, with a working distance of 24-36 inches. They do this based on the assumption that the only work being done on the equipment is racking out the breaker. However, that is not a realistic assumption. What happens if the breaker racking mechanism sticks and the electrician positions himself/herself closer to fix the mechanism? What if there are other work tasks that crop up requiring a closer working distance?

Other factors contribute to "worst" case results such as generators being turned on/off, motors being turned off or on during a shutdown condition, etc. These variables must be considered in a "worst" case calculation.

> *AFH labeling with values less than "worst" case requirements will increase your company's liability, should there be an arc flash accident.*

AFH labeling with values less than "worst" case requirements will increase your company's liability, should there be an arc flash accident. The attorneys working for the injured parties will easily prove that a higher incident energy existed at a standard working distance of 18 inches or with a different mode of operation, and show the equipment label did not warn the party of potential increased danger, concluding pure and simple negligence. This is not to say that you cannot rack a breaker out using the calculated incident energy at a longer distance, say 36 inches. The important point to note is that each work permit and planning procedure documents a specific work task and its associated requirements. If that task or working distance changes, a new work permit is required along with the possible need for new safety procedures. The employee will be properly briefed and protected if this procedure is followed.

Label with Only One Working Distance and One PPE Requirement

When equipment has multiple AFH labels with different working distances, and different PPE categories, it is a recipe for disaster in the making. With multiple options, workers now have the opportunity to select the label/PPE of their choice without management oversight. It is human nature for all of us to assume there will not be an incident. It usually goes something like this.

> *The worker looks at the front side label and reads an incident energy of 12.4 cal/cm^2 and a PPE category 3. The backside label (breaker terminals) is labeled 4.6 cal/cm^2, PPE category 1, due to the feeder breaker instantaneous trip units. The employee thinks: 1) "Man it's really hot today. I bet the humidity is 95%." 2) "I've done this same task for the past 26 years without an incident." 3) "It's almost time to go home. I really don't want to go back and get in that stupid tank suit."*

When given the choice, most people are going to take what they perceive as the easy way out. If this worker initiates an arc flash incident wearing PPE category 1 and ends up with third degree burns over half his body, who will be blamed and found liable? The objective reader may easily point the blame at the worker for being lazy or lacking intelligence. However, his attorney is going to claim: 1) The labeling process was confusing. My client could not tell which label applied to which area of the equipment. 2) The labels did not denote specific work tasks for the equipment, and they did not segregate boundaries on the equipment for their application. 3) My client was not properly trained by the company to distinguish how different labels apply to Manufacturer XYZ's equipment. In any arc flash hazard lawsuit, if there is any doubt regarding whether or not the corporation followed the industry mandates, the court jury or judge will rarely side with the corporation. In spite of the fact that the worker was lazy or broke company policy, the jury will see a traumatized man with multiple skin grafts, scarred for life and unable to ever work again.

It is critical to label the equipment using only one (worst case) energy PPE category or incident energy and one working distance per equipment. Following this procedure will minimize training requirements, confusion, and liability. Additionally, we strongly recommend standardizing on an 18 inch working distance for all equipment. Considering every enclosed equipment type from 120V through 34.5 kV, there will always be some work task that will put a worker in the 18 inch range. Labeling some equipment for 24 or 36 inches, and others for 18 inches adds confusion to your safety program. If workers want to manage down the PPE category for a "specific task" by working from an increased distance, this is properly done by a detailed Article 130.2 work permit combined with proper work procedures and training.

The only exception to this rule might be for isolated and barrier protected main breakers in a switchgear lineup. Many facilities prefer to label the incoming switchgear breaker separately from the bus and feeder breakers. This allows work on the feeder breakers to be conducted under the lower PPE category provided by the main breaker. The problems with this approach are threefold. 1) Workers could follow the ratings on the lower rated bus label beginning their work in the appropriate area and either accidentally, or intentionally, transition to the main breaker compartment where the AFH energy will typically be "extreme danger". 2) This method promotes work on the bus and feeder breakers using only a label, potentially bypassing the necessary Article 130.1 work permit requirements. 3) This method can only be done on isolated and barrier protected main devices. In most facilities this applies only to a minor portion of equipment; therefore, additional training will be

required to ensure all workers understand the specific restrictions for this particular labeling method.

Label per ANSI Z535.4

ANSI Z535.4 provides the consensus standard used in North America for safety labels. Deviation from this standard is allowed, but courts will rule that Z535 is the minimum acceptable standard. This means that deviation from this standard requires that you prove increased effectiveness is provided by your equipment labeling program.

Examples of the Z535 standard are shown below.
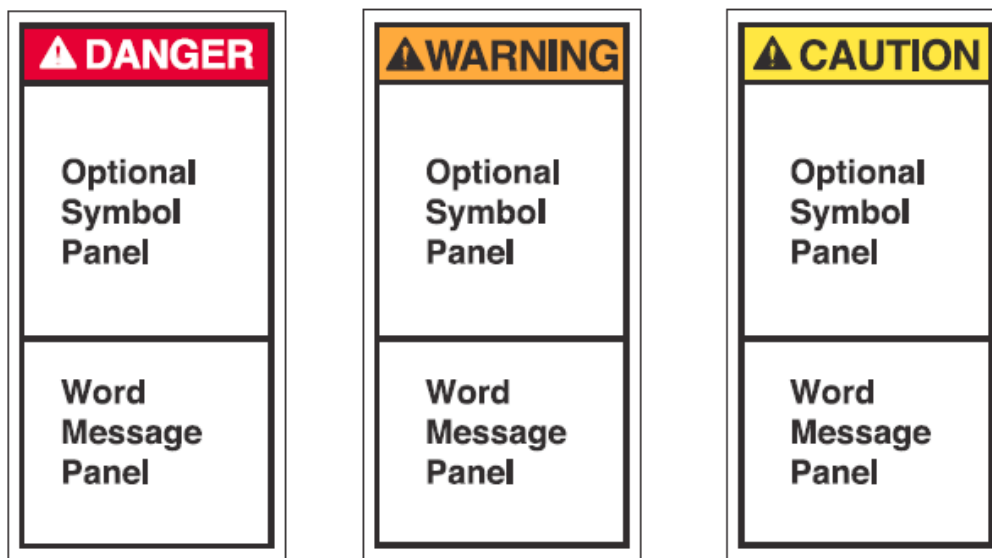
The Z535 format includes a triangle with an exclamation mark which is the safety alert symbol. This symbol appears to the left of the signal word DANGER, WARNING or CAUTION and signifies that there is a personal injury hazard potential. The ANSI Z535.4-2011 revision makes this symbol a universal element on all U.S. personal injury-related safety signs and labels.

The Z535 standard requires that a product safety label communicate the following:

- the type of hazard

- the seriousness of the hazard

- the consequence of interaction with the hazard, and

- how to avoid the hazard

We recommend labels that use the orange "Warning" label rather than the red "Danger" label. The reason for this is that "Danger" often denotes an immediate problem such as open or exposed wiring or moving equipment and indicates the need to stay away. "Warning" alerts the individual to a potential problem dependent on user interaction. This reasoning is subjective and the user should select a color based on their safety program objectives.

We have seen more than one facility color code labels based on PPE levels. Red=Extreme danger (> 40 calories), Orange =PPE Category 4 (> 25 calories), Yellow = PPE Category 2 (> 8 calories), and Green= PPE Category 1 (<1.2 calories). **Because ANSI has selected three colors to denote specific levels of hazard, we do not recommend color coding AFH labels based on PPE level.** Company defined color coding confuses the basic ANSI color coding and subjectively encourages levels of danger in the facility. In reality, an arc flash of 8 calories can have the same life changing impact as that of a 15 calorie event. Additionally, color coding any AFH label with green, conveys the message that there are no potential hazards in this equipment, since green is the universal color for "go" or "safety."

The following label is an example of a thorough ANSI Z535 AFH label.
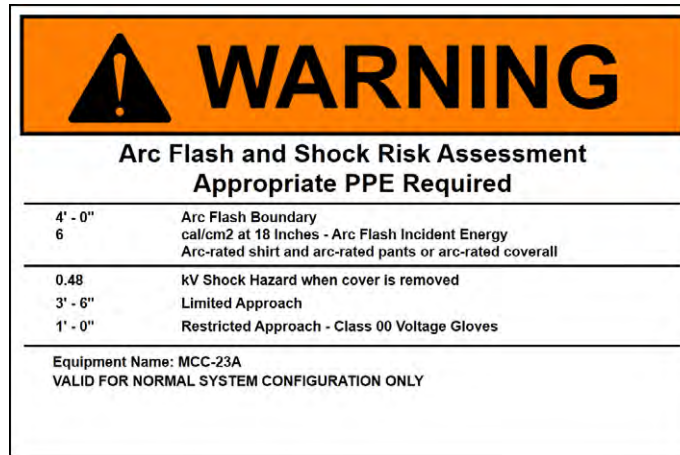
ANSI Z535 labels are the most recognized safety label in North America. Using standardized labels minimizes safety training requirements for both employees and contractors, thereby reducing liability on the part of the facility. Custom labels will require specialized training not only for your company employees, but also for every contractor coming on site. Note: Labels that display company logos, flashy colors, or vendor advertising should be avoided, as they distract from the warning!

How Many Labels per Equipment?

A frequently asked question is how many labels are enough? Obviously if one is good, more is better – right? This philosophy has both positive and negative aspects that must be considered. The more labels used the higher the visibility factor. However, too many labels clutter the objective and cause workers to ignore the warning.

For the MCC above, a simple one-word "warning" label was used without providing specific PPE, boundary information, or hazard levels. This minimizes clutter, however, if you take a step back and see 50-75 of these labels the clutter becomes obvious. The clutter is even more prevalent and confusing if the standard AFH information is included on the labels. The worker looking at the MCC must then determine 1) Which label is important?   2) If the labels are different, what information applies to this task? 3) How do I react to these circumstances?

When deciding quantity, another factor to consider is the cost of replacing the labels when system changes take place or when the IEEE 1584 calculation changes are released in 2010-2011? Re-labeling an entire facility is time consuming and expensive.

A common sense approach to labeling seems to make the most sense for general applications. Labeling with one high profile 4x6 inch or 6x8 inch label front-side and back-side should be sufficient for most switchgear, switchboard, and panelboard applications. For larger equipment such as long switchboards, two labels should be sufficient. Labels should be placed where clearly visible; the top is preferable when equipment type allows. See examples below.

For feeder bus duct, labeling every 15-25 feet with the bus duct "worst case" label, provides sufficient warning of the potential hazard. It is not necessary or recommended to label each plug-in for the reasons already stated.

For some equipment, additional labels should be considered at potential entry or work points. Examples might include open bus vaults or large junction boxes where access can be obtained from several sides.

Examples

This section provides multiple labeling examples for different types of electrical equipment, which can be modified or extrapolated to fit your system. For some equipment types, multiple options will be provided.

Panels

Panels are typically of box construction with a fixed backing plate attached to a beam, or wall mounted. The front of the panel, which provides opening access, is bolted in place. The front cover typically has a hinged opening, which allows viewing and operation of the breakers. For standard 42 circuit lighting panels, the typical labeling procedure is one label on the main cover, top center. See Figure 1.

Figure 1

Figure 2

Panelboards

Panelboards, sometimes called distribution panel boards (DPB), or distribution boards are larger than a standard panel and may range from 400-1200A. They are typically standalone, but smaller units may be wall or beam mounted. Larger units may be accessible front and back side via bolted covers. For standard DPB's, typical labeling procedures is one label on the main cover, top center. For the example shown in Figure 2, the label was moved to the bottom to prevent covering the cooling vents. Panelboards do not have isolated and barrier protected main breakers unless specially ordered and should always have only one label.

Dry Type Transformers

Dry type transformers typically have a bolted-on face plate section with exposed terminals behind the face plate. Since this is the main access point, it is usually not necessary to label the other sides.

Figure 3

Figure 4

Larger units may have two or more cubicles and can be labeled with one or multiple labels.

Variable Frequency Drives, and Control Cabinets

Variable frequency drives and control cabinets are typically hinged front opening units with an open, exposed incoming main breaker. The incoming breaker or fuse is typically not isolated or barrier protected from the other sections and therefore cannot be used for AFH protection. Like other cabinets, one "worst case" label is typically sufficient. See Figure 5.

In the example of Figure 6, the incoming line section (upper left section) is not isolated from the main SCR/reactor compartments. Therefore, any arc initiation will propagate instantly to the incoming protection and prevent its operation.

Figure 5

Figure 6

In the drive example shown in Figure 7 below, the incoming main breakers shown in the right side cubicle appear to be properly isolated by a section divider. Once this has been verified by the facility, the lower value incident energy/PPE category can be labeled on the other sections. Facilities employing this approach assume the three liabilities listed in the previous section entitled, "Label with only one working distance and one PPE requirement." We recommend that only the "worst case" label for the complete equipment be used. If they are not working in the main incoming section, we recommend that users manage down the required PPE category via work permit and strict safety procedures.
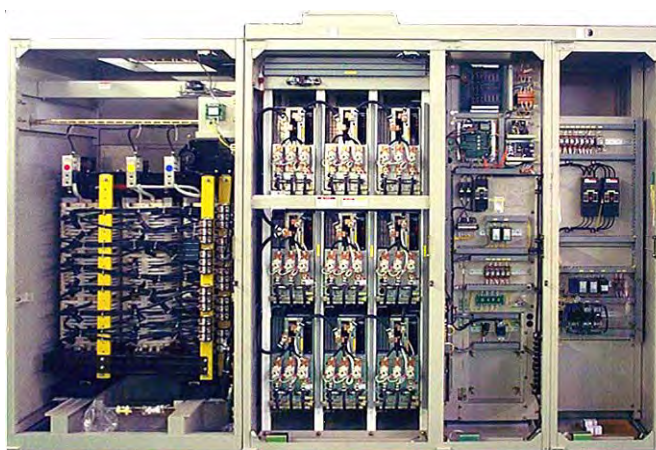

Figure 7

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Switchboards and Switchgear

Switchboards and Switchgear are the standard for low voltage distribution equipment. Switchgear by definition has isolated and barrier protected cubicles, rack-in air frame breakers/switches, and isolated bus. Switchboards may have similar attributes but will most likely be equipped with molded case or insulated case breakers, or fuses in non-isolated cubicles with non-isolated bus work. By special order, the main breaker/switch can be isolated, enhancing arc flash protection.

For a typical 4 section or less switchgear lineup, only one label (worst case) on the front side is necessary. See Figure 8. For longer sections, additional labels can be applied every 5-10 feet. Since both front and back-side switchgear covers are hinged, the back-side covers should also be labeled.

For switchboards, the back-sides are typically open exposed bus with bolted covers, which should prevent access. Labeling should be optional since access is not easily obtained.

Figure 8

If the user prefers to label the main breaker section separately, thereby providing a lower PPE category label for the bus and feeder breakers, the main incoming section should be sectioned off to clearly demark the switchgear. The main section will most likely be labeled "Extreme Danger" unless specialized relaying has been implemented, and the feeder breaker/bus section will typically have a lower incident energy. See Figure 9 below. One label on each side of the demarcation is typically sufficient, although the back-side should also be labeled if it is hinged and easily opened.

Note: EasyPower recommends "worst case" labeling for all switchgear and does not advocate demarcation lines to sectionalize equipment with different labels. The procedure shown here is presented only to show the proper method for demarcation. EasyPower recommends NFPA 70E Article 130.1 Work Permits, safety procedures, and proper planning for reduced PPE level work on different sections.

Main Breaker Section

Figure 9

Some switchgear line-ups come in combination units with a connected transformer and high voltage primary switch. These should be sectionalized with a clear demarcation line for section labeling. The preferred method is shown in Figure 10, where the "worst case" low voltage arc flash results extend from the transformer section through the low voltage switchgear. This method can be applied to all switchgear, switchboard, and panelboard combination units, with or without main breakers. Note that the transformer HV terminals would actually be labeled with the higher incident energy value LV label, since the HV terminals are in the same cabinet as the LV terminals. The HV fused switch terminals should be labeled separately.
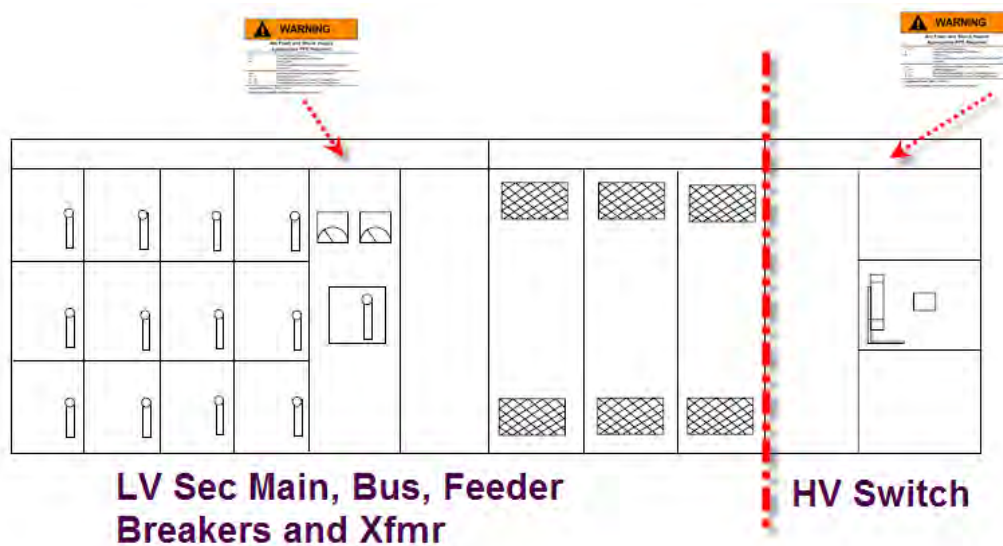

LV Sec Main, Bus, Feeder Breakers and Xfmr

HV Switch

Figure 10

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For switchgear with an isolated and barrier protected main breaker, the bus and feeder breaker section can typically be sectionalized with a lower incident energy label. Once again, clear demarcation and additional training is required. See Figure 11. This same labeling method can be applied to enclosed high voltage switchgear and fused disconnects also.
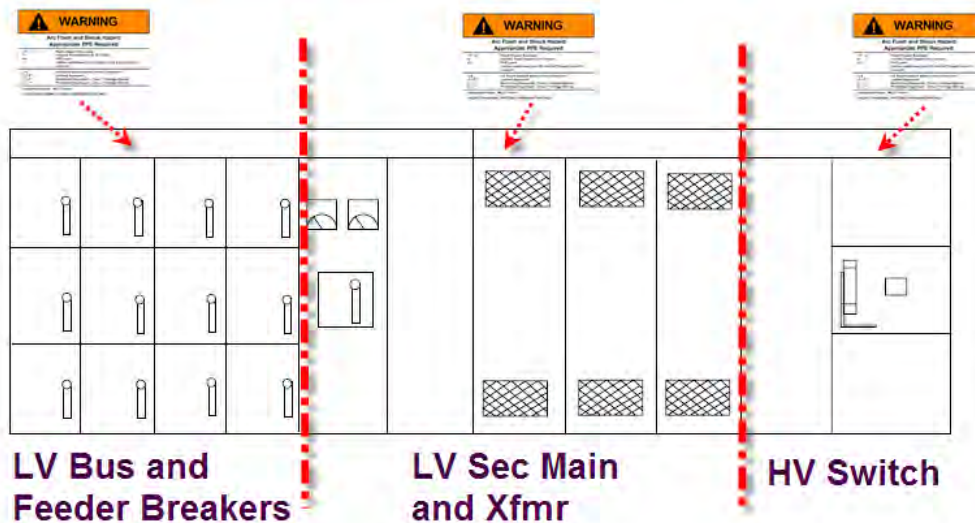

Figure 11

Feeder Bus Duct

Low voltage feeder bus duct has become the standard for many manufacturing facilities where production requirements require frequent machine tool change out, updating assembly lines, etc. The ease of simply plugging in a new feed for a different machine tool has many advantages. The disadvantages of feeder bus duct are that the phase conductors are typically not insulated, the bus structure can flex and become misaligned creating a hazard when plugging in or removing plug-ins, and the long lengths of some runs create short circuit disparities between the beginning and end sections, which create protection difficulties. All three of these issues relate directly to the best method for labeling a feeder bus duct. It is beyond the scope of this paper to explain the proper procedure for calculating the worst case PPE category or incident energy for a feeder bus duct. However, it should be sufficient to recognize that there can typically be several different PPE categories along a feeder bus duct length, due to the changing impedance and varying short circuit levels.
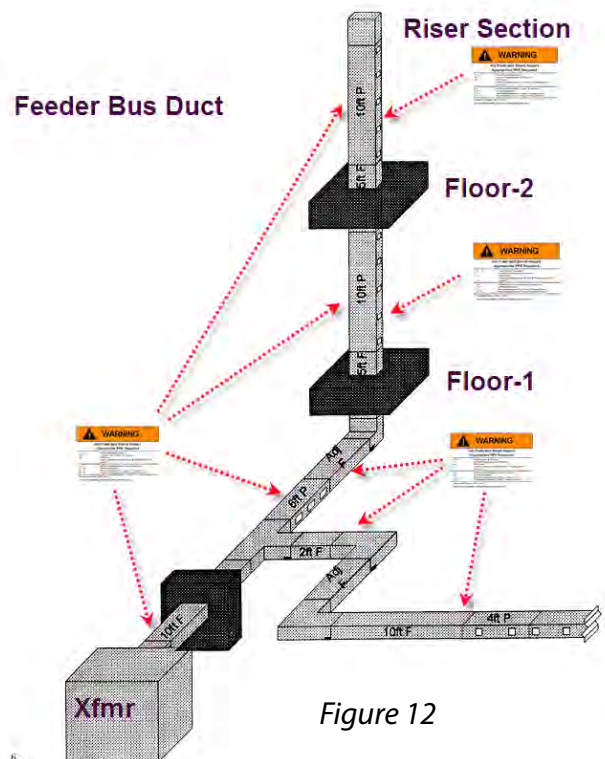

Figure 12

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We recommend that the worst case PPE category or incident energy of the entire bus duct length be used to label the entire bus duct. We do not recommend different labels for different plug-ins, or the need to label each plug-in. A 4"x6" or 6"x8" label every 10-20 feet should be sufficient. See Figure 12.

Often, bus duct can have multiple bends which can hide a label from view. Consideration should be given to labeling these sections if there is potential for plug-ins. For vertical riser sections, it is probably only necessary to label at each floor level where plug-ins occur. Labeling should include both front and back sides of all runs.

Motor Control Centers

Motor control centers raise more labeling questions than almost any other type of equipment. The reason for this is the number of individual buckets or units in the equipment. Does each bucket require a label, or can the equipment be labeled using the same procedures as described for other equipment?

Figure 13

The key factor in labeling MCCs is understanding that the breaker/fuse in the individual motor starter bucket will not protect the worker if they initiate an arc flash in that bucket. The initial arc caused by the worker will instantly ionize the air in the bucket. This will propagate the arc to the breaker/fuse primary terminals, which will sustain the arc and prevent device operation. Therefore, the arc energy for each individual bucket is controlled by the remote tripping of the breaker/fuse that feeds the MCC. This is the same issue found in panelboards, switchboards, etc. Since there is only one arc energy for the entire MCC, we recommend labeling in the same manner as the other equipment – one "worst case" label as shown in Figure 13.

If the MCC extends more than 3-4 sections, additional labeling can be applied as necessary. MCCs are manufactured with bolted-on side and back sections, preventing inadvertent exposure of the main and vertical buses. Additionally, most MCCs are located either back-to-back in the center of the room or against the wall preventing opening of the MCC back panels. Therefore, labeling the side and back sections of an MCC is typically not required.

Junction Boxes and Miscellaneous Equipment

Junction boxes come in many forms, from standard conduit interconnections, to motor terminal connections. In a typical facility, there could be hundreds-of-thousands of boxes with accessible electrical wires. NFPA 70E 130.2 indicates it is imperative to train all workers that every electrical equipment is a potential AFH that requires a work permit before any equipment is opened, including junction boxes.

The key factor in deciding labeling protocol for junction boxes may come down to how frequently are they opened? If they are never opened, the need for labeling would follow the guidelines as provided for the back of an MCC or switchboard lineup. However, if they are opened on a routine basis, labeling is appropriate and necessary. According to Article 130.2, either option still requires a work permit.

Summary – Do's and Don'ts of AFH Labeling

This paper provides guidelines and examples for proper AFH labeling to increase worker safety and minimize corporate liability. A series of equipment examples have been provided to guide users in labeling decisions. As in any type of safety procedure, common sense is the key.

Do's

- Do label "WORST" case energy or PPE category. Consider all possible modes of operation.
- Do label per ANSI Z535.4.
- Do label using only one color, Orange for Warning or Red for Danger.
- Do standardize on only one working distance – preferably 18 inches for all labels in a facility.
- Manage down PPE categories or incident energy analysis using work permits stating increased distances based on work task and proper safety procedures.
- Label to warn of potential danger, not for the purpose of working on the equipment.
- Do use common sense in your hazard labeling.
- Do implement NFPA 70E Article 130.2 work permit requirements for all energized work even if a label is present.

Don'ts

- Don't label each MCC bucket, breaker/fuse cubicle, or plug-in (busway).
- Don't label using colors for PPE category or incident energy.
- Don't label with multiple distances or PPE categories on the same equipment.
- Don't make it complicated.
- Don't substitute labeling for NFPA 70E Article 130.2 work permit requirements.

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SECOND EDITION

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