

ARC FLASH HAZARDS AND THEIR ANALYSES

In the past, industrial electrical systems in the United States have been designed considering prevalent standards, that is, ANSI/IEEE, NEC, OSHA, UL, NESC, and the like, and arc flash hazard was not a direct consideration for the electrical system designs. This environment is changing fast, and the industry is heading toward innovations in the electrical systems designs, equipment, and protection to limit the arc flash hazard, as it is detrimental to the worker safety. This opens another chapter of the power system design, analysis, and calculations hitherto not required. There is a spate of technical literature and papers on arc flash hazard, its calculation and mitigation. References [1–8] describe arcing phenomena and arc flash calculations, sometimes commenting on the methodology of arc flash hazard calculations in IEEE Guide 1584 [9] (see Chapter 3).

These issues have become of great importance in the power system planning, designs and protective relay applications. “Safety by Design” is the new frontier (see Chapter 2).

Awareness of the various hazards caused by arc flash has increased significantly over the past decade. Arc flash is a dangerous condition associated with the unexpected release of tremendous amount of energy caused by an electric arc within electrical equipment [10]. This release is in the form of intense light, heat, sound, and blast of

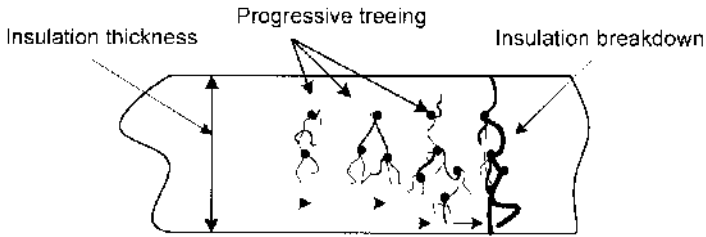


Figure 1.1. Treeing phenomena in nonslf-restoring insulation, leading to ultimate breakdown of insulation.

arc products that may consist of vaporized components of enclosure material—copper, steel, or aluminum. Intense sound and pressure waves also emanate from the arc flash, which resembles a confined explosion. Arcing occurs when the insulation between the live conductors breaks down, due to aging, surface tracking, treeing phenomena, and due to human error when maintaining electrical equipment in the energized state. The insulation systems are not perfectly homogeneous and voids form due to thermal cycling. In nonslf restoring insulations, treeing phenomena starts with a discharge in a cavity, which enlarges over a period of time, and the discharge patterns resemble tree branches, hence the name “treeing” (Figure 1.1). As the treeing progresses, discharge activity increases, and, ultimately the insulation resistance may be sufficiently weakened and breakdown occurs under electrical stress. Treeing phenomena is of particular importance in XLPE (cross-linked polyethylene) and nonslf restoring insulations. Surface tracking occurs due to abrasion, irregularities, contamination, and moisture, which may lead to an arc formation between the line and ground. An example will be a contaminated insulator under humid conditions. Though online monitoring and partial discharge measurements are being applied as diagnostic tools, the randomness associated with a fault and insulation breakdown are well recognized, and a breakdown can occur at any time, jeopardizing the safety of a worker, who may be in close proximity of the energized equipment. Arc temperatures are of the order of 35,000°F, about four times the temperature on the surface of the sun. An arc flash can therefore cause serious fatal burns.

1.1 ELECTRICAL ARCS

Electrical arcing signifies the passage of current through what has previously been air. It is initiated by flashover or introduction of some conductive material. The current passage is through ionized air and the vapor of the arc terminal material, which has substantially higher resistance than the solid material. This creates a voltage drop in the arc depending upon the arc length and system voltage. The current path is resistive in nature, yielding unity power factor. Voltage drop in a large solid or stranded conductor is of the order of 0.016–0.033 V/cm, very much lower than the voltage drop in an arc, which can be of the order of the order of 5–10 V/cm of arc length for virtually all arcs in open air (Chapter 3). For low voltage circuits, the arc length consumes a substantial portion of the available voltage. For high voltages, the arc lengths can be

considerably greater, before the system impedance tries to regulate or limit the fault current. The arc voltage drop and the source voltage drop are in quadrature. The length of arc in high voltage systems can be greater and readily bridge the gap from energized parts to ground.

Under some circumstances, it is possible to generate a higher energy arc from a low voltage system, as compared with a high voltage system.

In a bolted three-phase short circuit, the arcing resistance is zero, and there is no arcing, and no arc flash hazard. Sometimes, when short circuit occurs, it can be converted into a three-phase bolted short circuit by closing a making switch or circuit breaker, which solidly connects the three-phases. The fault current is then interrupted by appropriate relaying. This method, however, will subject the system to much greater short-circuit stresses and equipment damage, and, is, therefore, not recommended.

1.1.1 Arc as a Heat Source

The electrical arc is recognized as high-level heat source. The temperatures at the metal terminals are high, reliably reported to be 20,000 K (35,000°F). The special types of arcs can reach 50,000 K (about 90,000°F). The only higher temperature source known on earth is the laser, which can produce 100,000 K. The intermediate (plasma) part of the arc, that is, the portion away from the terminals, is reported as having a temperature of 13,000 K.

In a bolted three-phase fault, there is no arc, so little heat will be generated. If there is some resistance at the fault point, temperature could rise to the melting and boiling point of the metal, and an arc could be started. The longer the arc becomes, the more of the system voltage it consumes. Consequently, less voltage is available to overcome supply impedance and the total current decreases.

Human body can exist only in a narrow temperature range that is close to normal blood temperature, around 97.7°F. Studies show that at skin temperature as low as 44°C (110°F), the body temperature equilibrium starts breaking down in about 6 hours. Cell damage can occur beyond 6 hours. At 158°F, only a 1-second duration is required to cause total cell destruction.

1.1.2 Arcing Phenomena in a Cubicle

The arc formation in a *cubicle* may be described in four phases:

Phase 1: Compression. The volume of air is overheated due to release of energy, and the remaining volume of air inside the cubicle heats up due to convection and radiation.

Phase 2: Expansion. A piece of equipment may blow apart to create an opening through which superheated air begins to escape. The pressure reaches its maximum value and then decreases with the release of hot air and arc products.

Phase 3: Emission. The arcing continues and the superheated air is forced out with almost constant overpressure.

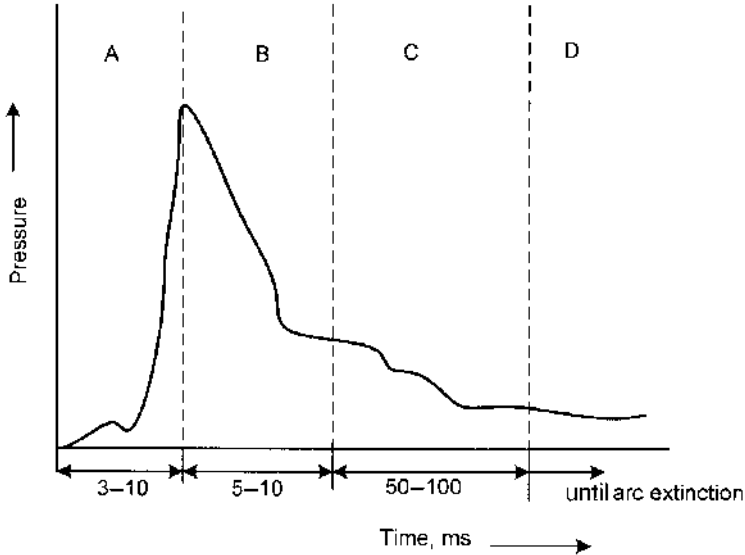


Figure 1.2. The various stages of pressure buildup and its release for an arc in a cubicle. A: Compression, pressure rises; B: Expansion, relief of pressure; C: Emission, gases exhausted; D: Thermal, pressure equalizes (not to scale).

Phase 4: Thermal. After the release of air, the temperature inside the switchgear nears that of an electrical arc. This lasts till the arc is quenched. All metals and insulating materials undergo erosion, may melt and expand many times, produce toxic fumes, and spray of molten metal.

Figure 1.2 shows these four phases.

1.2 ARC FLASH HAZARD AND PERSONAL SAFETY

The phenomenal progress made by the electrical and electronic industry since Thomas Edison propounded the principle of incandescent lighting in 1897 has sometimes been achieved at the cost of loss of human lives and disabilities. Although reference to electrical safety can be found as early as about 1888, it was only in 1982 that Ralph Lee [11] correlated arc flash and body burns with short-circuit currents. This article is considered by many as pioneering work on arcing phenomena in the open air. It quantified the potential burn hazards. Lee established the curable burn threshold for the human body as 1.2 cal/cm^2 , which is currently used to define the arc flash boundary. Lee published a second article in 1987, "Pressure Developed from Arcs" [12].

Doughty et al., published two articles [13, 14], and Jones et al. published an article in 2000 [15]. The IEEE 1584 Guide can be considered a breakthrough for arc flash analyses. The previous methods in NFPA 70E were based upon theoretical concepts or drawn from limited testing. The new testing concentrated on arcing faults in a variety

of electrical equipment enclosures, arcs in boxes, which is more typical of actual work locations. Yet some researchers are critical of the methodology of the IEEE 1584 Guide; for example, Stokes and Sweeting in “Electrical Arc Burn Hazards” [5], critique Lee’s models and IEEE 1584 Guide equations and testing setup for arc flash burns. Yet the statistics collected on the prevention of arc flash hazard injuries shows that such injuries were prevented when the workers used the required personal protective equipment (PPE) calculated according to the IEEE Guide; see Chapter 3. Wilkins et al. published an article, “Effect of Insulating Barriers in Arc Flash Testing,” in 2008 [16]. The authors used vertical conductors terminated in insulating barriers for their testing methodology. See Chapter 3 for further discussions and observations on these issues.

The OSHA definition of a recordable injury, TRIR, for 1 year of exposure, is as follows:

$$\text{TRIR} = \frac{\text{Total number of recordable injuries and accidents}}{200,000 \text{ hours}}. \quad (1.1)$$

Most insurance companies accept this parameter of definition because there is a cost associated with these incidents.

1.3 TIME MOTION STUDIES

Of necessity and for the continuity of processes, maintenance of electrical equipment in energized state has to be allowed for. If all maintenance work could be carried out in deenergized state, short circuits cannot occur and therefore there is no risk of arc flash hazard. For the continuous process plants, where the shutdown of a process can result in colossal amount of loss, downtime and restarting; it becomes necessary to maintain the equipment in the energized state. Prior to the institution of arc flash standards, this has been carried out for many years, jeopardizing worker safety, and there are documented cases of injuries including fatal burns.

The time/motion studies show that human reaction time to sense, judge, and run away from a hazardous situation varies from person-to-person. A typical time is of the order of 0.4 second. This means that 24 cycles is the shortest time in which a person can view a condition and *begin* to move or act. In all other conditions, it is not possible to see a hazardous situation and move away from it. As will be further demonstrated, this reaction time is too large for a worker to move away and shelter himself from an arc flash hazard situation.

1.4 ARC FLASH HAZARDS

Apart from thermal burns, an arcing phenomenon is associated with other hazards too, namely:

- electrical shock
- molten metal

- projectiles
- blast and pressure waves
- intense light
- intense sound
- fire
- effect of strong magnetic fields and plasma, of which not much is known
- toxic gases and vapors.

Thus, thermal burns due to arc flash *are only a part the picture* for overall worker safety. Figure F.1a,b in NFPA 70E [17], not reproduced here, provides hazard risk analysis procedure flowchart. It implies that each establishment must perform a number of tasks and establish training and safety procedures that should be implemented for workers' safety. The numbers of injuries from arc flash accidents are high (see Chapter 2). IEEE 1584 Guide documents many such cases.

This book is confined to the analysis of arc flash thermal damage and calculation of arc flash boundary, subsequently defined, according to IEEE 1584 Guide equations. The book concentrates on the various design, planning, and protection strategies by which the arc flash hazard can be reduced.

1.5 ARC BLAST

As opposed to arc flash, which is associated with thermal hazard and burns, arc blast is associated with extreme pressure and rapid pressure buildup. Consider a person positioned directly in front of an event and high pressure impinging upon his chest and close to the heart and the hazard associated with it.

The reports of the consequences of arc in air include descriptions of the rearward propulsion of personnel who were close to the arc. In many cases, the affected people do not remember being propelled away from the arc. The heat and molten metal droplet emanation from the arc can cause serious burns to the nearby personnel.

A substance requires a different amount of physical space when it changes state, say from solid to vaporized particles. When the liquid copper evaporates, it expands 67,000 times. This accounts for the expulsion of vaporized droplets of molten metal from an arc, which is propelled up to distance of 10 ft. It also generates plasma (ionized vapor) outward from the arc for distances proportional to the arc power. One cubic inch of copper vaporizes into 38.8 cubic feet of vapor.

The air in the arc stream expands in warming up from the ambient temperature to that of an arc, about 20,000 K. This heating is related to the generation of thunder by passage of lightning current through it. In documented instances a motor terminal box exploded as a result of force created by the pressure build-up, parts flying across the room [18]. Pressure measurement of 2160 lbs/ft² around the chest area and sound level of 165 dB at 2 ft have been made.

The pressure varies with the distance from the arc center and the short-circuit current. Figure 1.3 shows this relation based upon Lee's classical work [12].

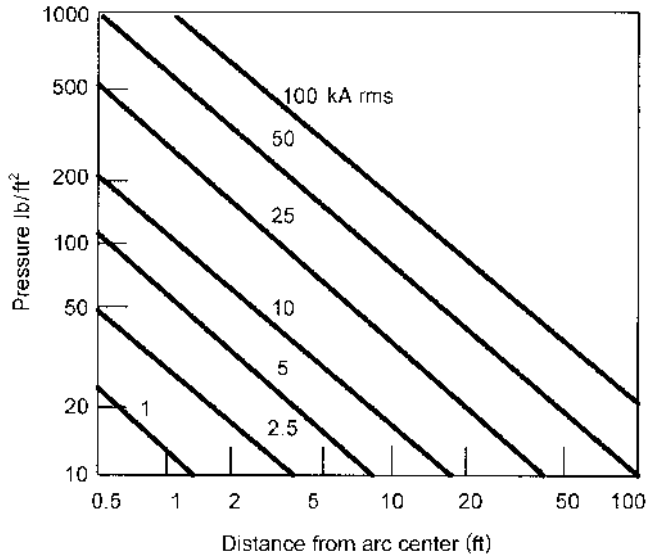


Figure 1.3. Pressure versus distance from the center of the arc, based on Lee's work.
Source: Reference [12].

The hot air vapor from the arc starts to cool immediately; however, it combines with the oxygen of the air, thus becoming the oxide of the metal of the arc. These continue to cool and solidify, and become minute particles in the air, appearing as black smoke for copper and iron and gray smoke for aluminum. These are still hot and cling to any surface these touch, actually melting into many insulating surfaces that these may contact. The oxide particles are very difficult to remove because surface rubbing is not effective. Abrasive cleaning is necessary on plastic insulation. A new surface varnish should be applied, or surface current leakage could occur and cause failure within days.

Persons exposed to severe pressure from proximity of an arc are likely to suffer short-time loss of memory and may not remember the intense explosion of the arc itself. This phenomenon has been found true even for high-level electrical shocks.

The PPE is currently designed and tested to address the heat energy hazard. The arc-rated FR (fire resistant), including face hood shields window materials, have been observed to provide protection for the molten metal splatter hazard. There have been considerations of pressure-wave hazard [12, 19] and noise hazard [20]. This has resulted in NFPA 70E specifying hearing protection.

Noise has been monitored with microphones to understand its relationship with arc parameters. The noise results from initial explosive expansion of air and formation of a plasma region between conductors. The noise in single-phase arc events is assumed to behave similarly.

Figure 1.4 shows variations in noise level measurements, at a distance of 1.8 m from a variety of arc configurations—a scatter plot. These variations will narrow down

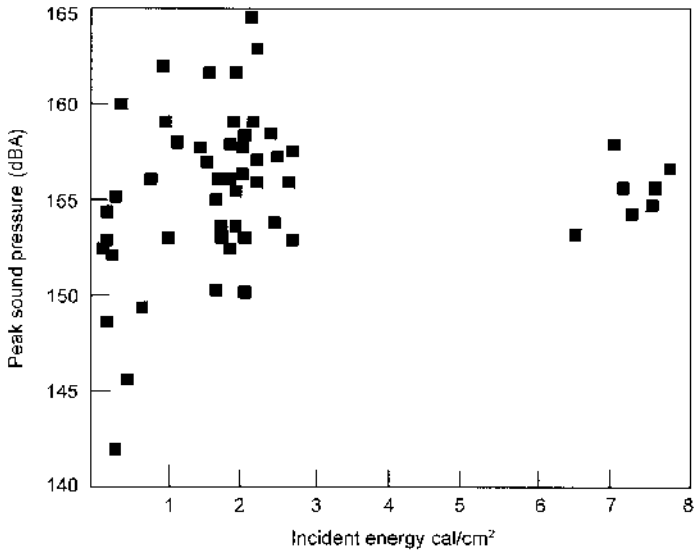


Figure 1.4. Peak sound pressure in dBA, at a distance of 1.8 m from a variety of arcing configurations. *Source:* Based on Reference [20].

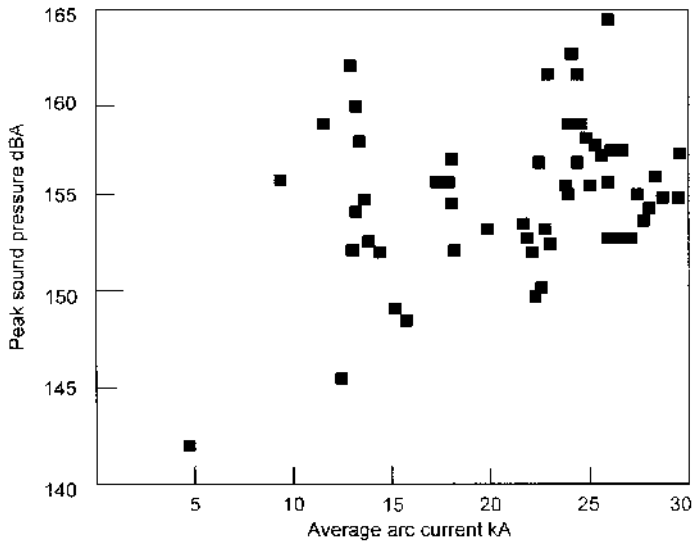


Figure 1.5. Average arcing current versus the peak sound pressure dBA. *Source:* Based on Reference [20].

if the test conditions were done in a fixed configuration. The arc ratings using PPE cannot be applied to hearing or pressure-wave protection. Figure 1.5 shows that for lower levels of arcing current, the noise levels can even be higher. This figure shows measurements at 0.61 m (2 ft) from a variety of three-phase arc configurations. NFPA 70E, table 130.7(C)(16), in 2009 was revised and recommends hearing protection (ear

TABLE 1.1. Ballistics V_{50} Results for Arc-Rated Fabric Systems

Multilayer Fabric Systems	Arc Rating, cal/cm ²	Ballistic Layer	Fabric System Weight, g/m ²	V_{50} , m/s	Fragment Diameter, mm
Cotton with flame retardant	100	No	1424	186	5.6
Aramid fabric system	100	No	932	210	5.6
Aramid fabric system	80	Yes	780	280	5.6
Aramid fabric system	100	No	881	191	7.8
Aramid fabric system	100	Yes	922	240	7.8

Adapted from Reference [20].

canal inserts) even for category 0. In the 2002 edition, hearing protection was not specified for category 0 and 1 hazards. See also table 130.7(C)(15)a,b.

If current limiting fuses are used, which operate in about 1/2 cycle or less, the arcing time is reduced and so also the noise levels—this relation is not so well defined, and additional testing is recommended [20].

Figure 1.5 shows that noise sound pressure levels can exceed OSHA impulsive or impact noise level of 140 dB peak. Even at 1.8 m level the measured sound levels are well above small arms firing and without hearing protection, some individuals may suffer traumatic damage, including eardrum rupture [13]. A worker will be positioned closer than 1.8 m when working on energized equipment.

The shrapnel hazard has not been quantified or related to arc-flash parameters, but it is possible to measure shrapnel resistance of arc flash fabric systems and hood shield windows to standardized threats.

Arc flash hood windows and face shields must meet projectile impact requirements of ANSI Z87.1, which specifies that a 6.4-mm (0.25 in) steel ball projectile must not penetrate the shield window or face shield at a velocity of 91.4 m/s (300 ft/s). It does not consider irregular-shaped projectiles or velocities that may be from 150 to 180 m/s (500–600 ft/s) and accompany an arc fault event. Thus, testing of arc-flash PPE was conducted using fragments instead of bullets [20]. Table 1.1 provides the test results. V_{50} signifies the velocity at which 50% of the projectiles penetrate the target specimen. This shows benefits of additional tightly woven para-armid ballistic fiber layer without weight increase.

1.6 ELECTRICAL SHOCK HAZARD

One of the most complete analyses of occupational electrical injuries in the United States are two papers by Jim Cawley [37, 38]. On an average, one person is electrocuted in work places *every day in United States*. There are a number of ways the exposure

to shock hazard occurs. The resistance of the contact point, the insulation of the ground under the feet, flow of current path through the body, the body weight, the system voltage, and frequency are all important. A dangerous consequence is a heart condition, known as ventricular fibrillation, resulting in immediate arrest of blood circulation. Currents as small as a few milliamperes through the heart can cause disruption of electrical signals that the heart uses to perform its functions. Voltages as low as 50 V can cause fibrillation and can result in death.

The following synopsis of tolerable currents is from IEEE Standard 80, Guide for Safety in AC Substation Grounding [21]:

At 50 or 60 Hz, a current of 0.1 A can be lethal. The human body can tolerate slightly higher 25 HZ current and five times the DC current. At frequencies of 3000–10,000, even higher currents are tolerated. The most common physiological effect, stated in terms of increasing current, are: threshold of perception, muscular contraction, unconsciousness, fibrillation of heart, respiratory nerve blockage and burning [22], and IEC 604791 [23].

The perception level is 1 mA. Currents in the range of 9–25 A may be painful and may make it difficult or impossible to release energized objects. In the range 60–100 mA, ventricular fibrillation, stoppage of heart, or inhibition of respiration might occur, causing injury or death. As shown by Dalziel and others [24], the nonfibrillating current of magnitude I_B at durations ranging from 0.03 to 3.0 seconds is related to energy absorbed by the body, given by:

$$S_B = (I_B)^2 \times t_s, \quad (1.2)$$

where t_s is the time duration of the current in seconds, and S_B is an empirical constant related to the energy through the body. Thus, reducing the arc flash incident energy through fast fault clearance times also reduces S_B .

Based upon the Dalziel and Lees' studies [25], it is assumed that 99.5% of all persons can safely withstand, without ventricular fibrillation, the passage of current I_B , given by:

$$I_B = \frac{k}{\sqrt{t_s}}, \quad k = \sqrt{S_B}. \quad (1.3)$$

Dalziel found that $S_B = 0.0135$ for a body weight of 110 lbs (50 kg). Then:

$$I_B = \frac{0.116}{\sqrt{t_s}}. \quad (1.4)$$

This gives 116 mA for 1 second and 367 mA for 0.1 second. For 70 kg weight, $S_B = 0.0246$ and $k = 0.157$. These values are adopted in IEEE Guide 80 [21]. Fibrillation current is assumed to be the function of body weight (Figure 1.6).

Other researchers have suggested different values of I_B . In 1936, Fwerris et al. [26] suggested 100 mA as fibrillation threshold; this value was derived by extensive experimentation at Columbia University. Some more recent experiments suggest

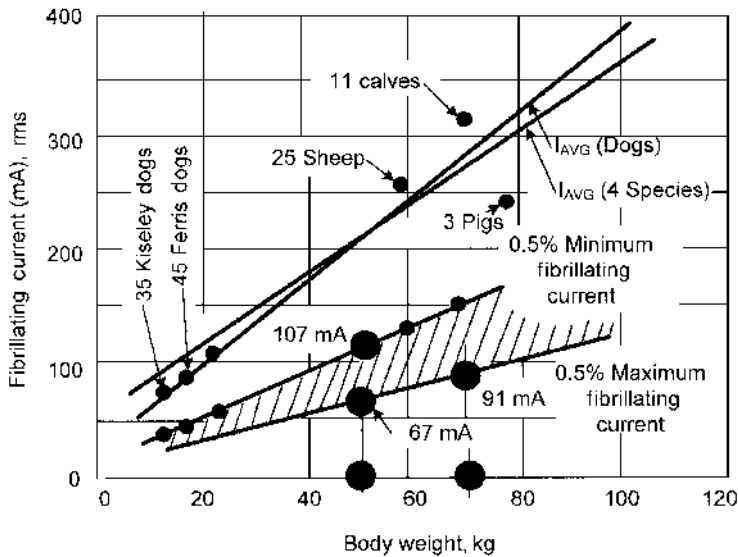


Figure 1.6. Fibrillating current (ma) rms, versus body weight. Source: Reference [21].

the existence of two thresholds: one for shock duration less than one heartbeat period, and the other for the current duration longer than one heartbeat period. For a /50 kg body weight, Biegelmeier [27] proposed threshold levels of 500 and 50 mA, respectively. Other studies were carried out by Lee and Kouwenhoven [28]. Figure 1.7 shows a comparison of Equation (1.4) and Z-shaped body current time developed by Biegelmeier.

1.6.1 Resistance of Human Body

For DC and AC 50 or 60 HZ currents, the human body can be approximated by a resistance. For the calculation of this resistance, the current path is considered from:

- one hand to both feet
- from one foot to another foot.

The internal resistance of the body is approximately 300 Ω , while the body resistance, including skin range from 500 to 3000 Ω . Based on Dalziel tests, using saltwater to wet hands and feet to determine let-go currents, hand-to-hand contact resistance is 2330 Ω , and hand-to-feet resistance equals 1130 Ω . Thus, the IEEE Guide for Safety in AC Substation Grounding considers that hand and foot contact resistances are zero, that glove and shoe resistances are zero, and a value of 1000 Ω is taken that represents the body from hand-to-feet and also from hand-to-hand resistance.

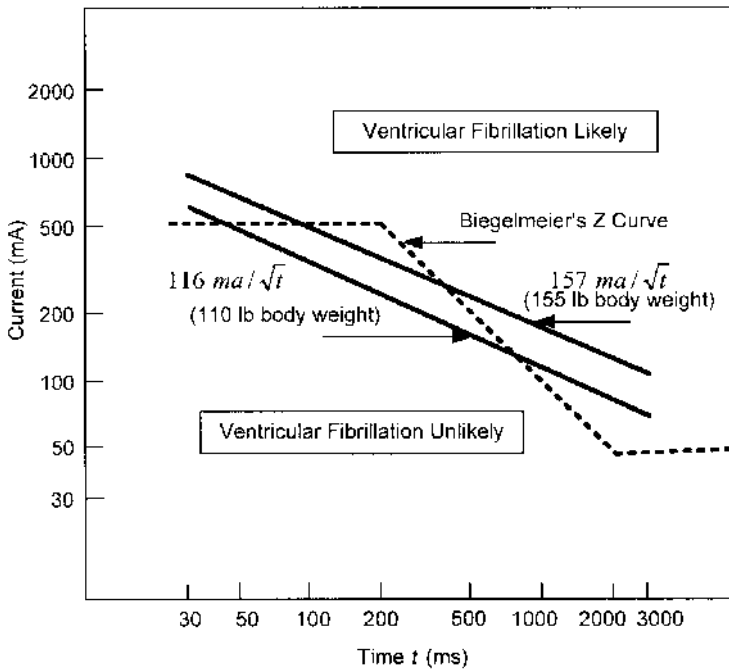


Figure 1.7. Ventricular fibrillation curves, current versus time. *Source:* Reference [21].

NFPA 70E states that energized parts operating at less than 50 volts are not required to be de-energized to satisfy an “electrical safe working condition.” It further lays down that considerations should be given to the capacity of the source, any overcurrent protection between the source and the worker, and whether the work task related to the source operating at less than 50 volts increases exposure to electrical burns or to explosion from an electric arc.

Reference [29] contends that 50 V is inadequate and calculates the maximum and minimum body resistance for path from arm-to-arm and arm-to-leg of the order of 300–500 Ω . IEC standard 604791 [23] recommends shock voltages of less than 50 V in some situations. Some jurisdictions, for example, in France, the safe voltage limit is accepted as 35–50 V. However, NFPA 70E qualifies the 50 V limits by additional cautionary statements as indicated above.

Table 1.2 provides resistance values for 130 cm^2 areas of various materials. It is customary to overlay the natural soil with high resistivity materials to increase the step and touch potentials in utility substations [21]. For the grounding systems in industrial electrical distributions, generally, the concept of higher soil resistivity layers to increase step and touch potentials can be applied for the grounding installations around buildings, tanks, substations, fences, and motor and transformer pedestals.

Figure 1.8 from IEC standard [23] illustrates the time–current zones for AC currents of 15–100 Hz, and Table 1.3 provides the physiological effects. IEC considers that hand-to-hand body impedance for 125 V is between 850 and 2675 Ω , and grasping

TABLE 1.2. Resistance of 130-cm² Areas of Various Materials

Material	Resistance in MΩ
Rubber gloves or soles	>20 0
Dry concrete above grade	1 0–5.0
Dry concrete on grade	0.2–1 0
Leather sole, dry, including foot	0.1–0.5
Leather sole, damp, including foot	0.05–0.2
Wet concrete	0.01–0.05

Source: Reference [23].

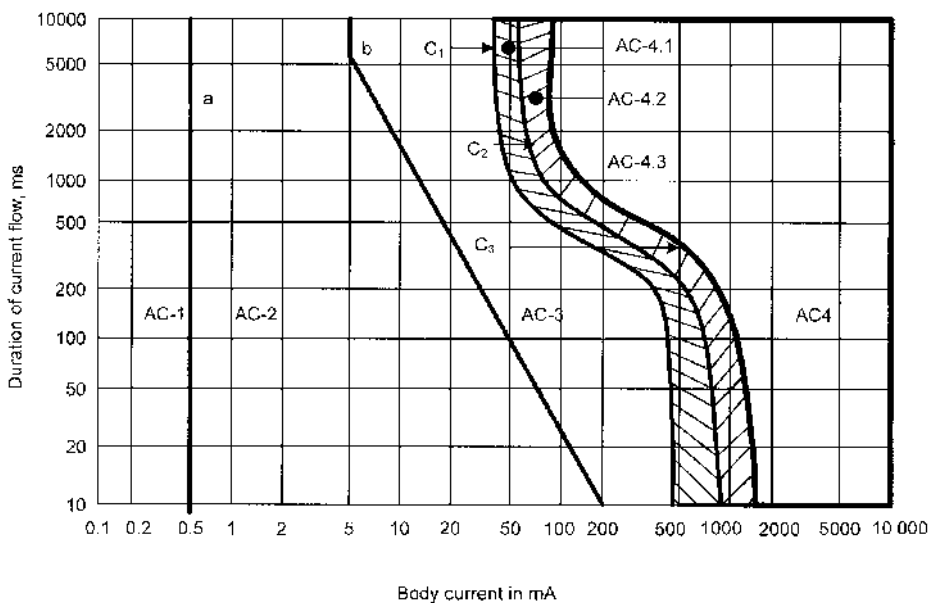


Figure 1.8. Shock hazard categories according to IEC. Source: Reference [23].

a conductor or faulty electric device rated 120 V can result in a current flow between 45 and 140 mA.

See also Section 2.4.

1.7 FIRE HAZARD

NFPA and National Fire Incident Reporting Systems (NFIRS) statistics of fire hazard can be viewed on websites. These statistics are based upon:

- heat source, that is, arcing
- contributing factors like electrical failure or malfunction
- equipment involved in electrical distribution, lighting, and power transfer.

TABLE 1.3. Time–Current Zones for 15–100 Hz AC Currents for Hand-to-Feet Pathway

Zone	Boundaries	Physiological Effects
AC-1	Up to 0.5 mA, curve a	Perception possible but usually no “startled” reaction
AC-2	0.5 mA up to curve b	Perception and involuntary muscular contractions likely but usually no harmful physiological effects
AC-3	Curve b and above	Strong involuntary muscular contractions, difficulty in breathing. Reversible disturbances of heart function. Immobilization may occur. Effects increasing with current magnitude. Usually no organic damage to be expected.
AC-4 ^a	Above curve c ₁	Pathophysiological effects may occur, such as cardiac arrest, burns, or other cellular damage. Probability of ventricular fibrillation increasing with current magnitude and time
	c ₁ –c ₂	AC-4.1: Probability of ventricular fibrillation increasing up to about 5%
	c ₂ –c ₃	AC-4.2: Probability of ventricular fibrillation increasing up to about 50%
	Beyond curve c ₃	AC-4.3: Probability of ventricular fibrillation increasing above 50%

^a For duration of current flow below 200 ms, ventricular fibrillation is only initiated within the vulnerable period if the relevant thresholds are passed. As regards to ventricular fibrillation, this figure relates to the effects of current which flow in the path from left hand to feet. For other current paths, the heart current factor has to be considered.

Source: Reference [23].

In 1999–2003, arcing was the heat source that resulted in 37,700 home fires, 240 deaths, 890 home fire injuries, and \$703 million in direct property damage [30, 31].

Fires can develop in electrical equipment due to overloads and loose connections that are not cleared by overcurrent devices. The equipment should be listed by a nationally recognized test laboratory (NRTL), which helps to reduce the fire risk. Some precautionary and design measures are:

- Fire detection and suppression equipment should be permanently installed or readily accessible around the electrical equipment. Such equipment could possibly include smoke detectors, sprinkler systems, and portable fire extinguishers.
- The workplace should be designed so that escape routes are sufficiently wide, clear of obstructions, well marked and lighted. Normal and emergency lighting and exit signs are important.
- Special considerations should be applied to the electrical equipment located in hazardous areas, according to NEC.
- All conductors and wiring should be properly sized for protection against overheating (see Article 310 of NEC).
- Overcurrent protection should be provided to meet the requirements of NEC.

- Motors and generators should be properly protected so that these do not cause a fire hazard.
- The transformers should be protected and installed according to NEC, UL, and FM (factory mutual) guidelines. In general, all electrical equipment must be installed, operated, and maintained according to codes and standards (see Chapter 2).

The fire hazards are not further discussed in this book.

1.8 ARC FLASH HAZARD ANALYSIS

As early as December 1970, the Occupational Safety and Health Act required that each employer shall furnish to his employees, employment and place of employment that are free from recognized hazards that are causing or likely to cause death or serious physical harm to his employees. It was not till late 1991 that OSHA added words acknowledging arc flash as an electrical hazard. NFPA published the first edition of NFPA 70E in 1979.

Effective from January 1, 2009, the National Electric Safety Code (NESC) [32] requires that all power generating utilities perform arc flash assessments. The employer shall ensure that 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 1.2 cal/cm^2 exists, 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.

Currently, there are four major guides for arc flash calculations:

1. NFPA 70E, revised in 2018 [17]
2. IEEE 1584 Guide, 2018, which will undergo revisions [9]
3. IEEE 1584a, 2004, amendment 1 [33]
4. IEEE P1584b/D2 Draft 2, unapproved [34].

NFPA 70E 2012, in annex D, table D.1, provides limitations of various calculation methods. This is reproduced in Table 1.4. *The standard does not express any preference for which method should be used.* Reference [33] recognizes use of knowledge and experience of those who have performed studies as a guide in applying the standard. IEEE 1584 Guide also contains a theoretically derived model applicable for any voltage.

It is recognized that to construct an *accurate* mathematical model of the arcing phenomena is rather impractical. This is because of the spasmodic nature of the fault caused by arc elongation blowout effects, physical flexing of cables and bus bars under short circuits, possible arc reignition, turbulent flow of plasma, and high temperature gradients (the temperature at the core being of the order of 25,000 K, while at the arc boundary, of the order of 300–2000 K).

IEEE 1584 Guide equations are empirical equations based upon laboratory test results, though the standard includes some of Lee's equations also.

TABLE 1.4. Limitations of ARC Flash Hazard Calculation Methods

Source	Limitations/Parameters
Ralph Lee [11]	Calculates arc flash boundary for arc in open air; conservative over 600 V and becomes more conservative as voltage rises
Doughty and Neal [14]	Calculated incident energy for three-phase arc on systems rated 600 V and below, applies to short-circuit currents between 16 and 50 kA
Ralph Lee [11]	Calculated incident energy for three-phase arc in open air on systems rated above 600 V, becomes more conservative as voltage rises
IEEE Standard 1584 [9]	Calculates incident energy and arc flash boundary for 208 V to 15 kV, three-phase 50–60 Hz; 700–106,000 A short-circuit currents and 13–152 mm conductor gaps. ^a
ANSI/IEEE C2, tables 410-1, 410-2 [32]	Calculates incident energy for open-air phase-to-ground arcs 1 kV to 500 kV for live line work.
Doan	Arc flash calculations for exposure to DC systems. Calculates incident energy for DC systems up to 1000 V DC.

^a Equations for higher voltages are included.

Source: NFPA 70E-2018.

If the equipment is maintained under deenergized condition, there is no arc flash hazard. NFPA 70E [17] states that energized electrical conductors and circuit parts that operate at less than 50 V to ground should not be required to be de-energized. Again, it is qualified that the capacity of the source and any overcurrent protection between the source and the worker should be determined and there should be no increased exposure to electrical burns or explosion due to electrical arcs. The IEEE 1584 Guide states that equipment below 240 V need not be analyzed for arc flash unless it involves at least one 125 kVA or larger low impedance transformer in its immediate power supply. The “low impedance” is not defined. Sometimes, the arc flash hazard can be high even in systems of 240 V. When incident energy exceeds 40 cal/cm², the equipment should only be maintained in the de-energized condition. There is no PPE (personal protective equipment) outfits specified for incident energy release >40 cal/cm²; see Section 1.9 for definitions and discussions of PPE.

That an arc flash analysis shall not be required where all the following conditions exist has been deleted in NFPA 70E 2012:

- The circuit is rated 240 V or less.
- The circuit is supplied by one transformer.
- The transformer supplying the circuit is rated less than 125 kVA.

This qualification has now been removed in 1584, 2018 edition.

The user is referred to IEEE Guide 1584 for three-phase systems rated less than 240 V.

1.8.1 Ralph Lee's and NFPA Equations

Ralph Lee equations from Reference [11] are as follows:

Maximum power in a three-phase arc is:

$$P = MVA_{bf} \times 0.707^2 \text{ MW}, \quad (1.5)$$

where MVA_{bf} is bolted fault mega-volt-ampere (MVA).

The distance in feet of a person from an arc source for a just curable burn, that is, skin temperature remains less than 80°C, is:

$$D_c = (2.65 MVA_{bf} t)^{1/2}, \quad (1.6)$$

where t is the time of exposure in seconds.

The equation for the incident energy produced by a three-phase arc in *open air* on systems rated above 600 V is given by:

$$E = \frac{793 F V t_A}{D^2} \text{ cal/cm}^2, \quad (1.7)$$

where:

D = distance from the arc source in inches

F = bolted fault short-circuit current, kA

V = system phase-to-phase voltage, kV

t_A = arc duration in seconds.

For the low voltage systems of 600 V or below and for an arc in the *open air*, the estimated incident energy is:

$$E_{MA} = 5271 D_A^{-1.9593} t_A \left[0.0016 F^2 - 0.0076 F + 0.8938 \right], \quad (1.8)$$

where E_{MA} is the maximum open air incident energy in cal/cm², F is short-circuit current in kA, range 16–50 kA, and D_A is distance from arc electrodes, in inches (for distances 18 in and greater).

The estimated energy for an arc in a *cubic box of 20 in*, open on one side is given by:

$$E_{MB} = 1038.7 D_B^{-1.4738} t_A \left[0.0016 F^2 - 0.0076 F + 0.8938 \right], \quad (1.9)$$

where E_{MB} is the incident energy and D_B is the distance from arc electrodes, inches (for distances 18 in and greater).

1.8.2 IEEE 1584 Guide Equations

This is based on IEEE 2002 Guide. Included here for reference and completeness.

The IEEE equations are applicable for the electrical systems operating at 0.208 to 15 kV, three-phase, 50 or 60 Hz, available short-circuit current range 700–106,000 A, and conductor gap = 13–152 mm. For three-phase systems in open air substations,

TABLE 1.5. Classes of Equipment and Typical Bus Gaps

Classes of Equipment	Enclosure Size (in)	Typical Bus Gaps (mm)
15-kV switchgear	45×30×30	152
15-kV MCC	36×36×36	152
5-kV switchgear	36×36×36	104
5-kV switchgear	45×30×30	104
5-kV MCC	26×26×26	104
Low voltage switchgear	20×20×20	32
Shallow low voltage MCCs and panel boards	14×12×≤8	25
Deep voltage MCCs and panel boards	14×12×>8	25
Cable junction box	14×12×≤8 or 14×12×>8	13

Source: IEEE 1584-2018 Guide [9]. Also see Chapter 3.

open-air transmission systems, a theoretically derived model is available. For system voltage *below* 1 kV, the following equation is solved:

$$\log I_a = K + 0.662 \log_{10} I_{bf} + 0.0966V + 0.000526G + 0.5588V(\log_{10} I_{bf}) - 0.00304G(\log_{10} I_{bf}), \quad (1.10)$$

where:

I_a = arcing current in kA

G = conductor gap in mm, typical conductor gaps are specified in [9] (see Table 1.5)

K = -0.153 for open air arcs, -0.097 for arc in a box

V = system voltage in kV

I_{bf} = bolted three-phase fault current kA, rms symmetrical.

For systems of 1 kV and higher, the following equation is solved:

$$\log_{10} I_a = 0.00402 + 0.983 \log_{10} I_{bf}. \quad (1.11)$$

This expression is valid for arcs both in open air and in a box. Use $0.85 I_a$ to find a second arc duration. This second arc duration accounts for variations in the arcing current and the time for the overcurrent device to open. Calculate incident energy using both $0.85 I_a$ and I_a and use the higher value.

Equation (1.11) is a statistical fit to the test data and is derived using a least square method; see Appendix A for a brief explanation of least square method.

Incident energy at working distance, an empirically derived equation, is given by:

$$\log_{10} E_n = K_1 + K_2 + 1.081 \log_{10} I_a + 0.0011G. \quad (1.12)$$

The equation is based upon data normalized for an arc time of 0.2 seconds, Where:

- E_n = Incident energy (J/cm^2) normalized for time and distance
- K_1 = -0.792 for open air and -0.555 for arcs in a box
- K_2 = 0 for ungrounded and high resistance grounded systems and -0.113 for grounded systems. Low resistance grounded, high resistance grounded, and ungrounded systems are all considered ungrounded for the purpose of calculation of incident energy.
- G = conductor gap in mm (Table 1.5).

Conversion from normalized values gives the equation:

$$E = 4.184C_fE_n\left(\frac{t}{0.2}\right)\left(\frac{610^x}{D^x}\right),$$

(1.13)

where:

- E = incident energy in J/cm^2
- C_f = calculation factor = 1.0 for voltages above 1 kV and 1.5 for voltages at or below 1 kV
- t = arcing time in seconds
- D = distance from the arc to the person, working distance (Table 1.6)
- x = distance exponent as given in Reference [9] and reproduced in Table 1.7.

A theoretically derived equation can be applied for voltages above 15 kV or when the gap is outside the range in Table 1.5 (from Reference [9]).

$$E = 2.142 \times 10^6 VI_{bf} \left(\frac{t}{D^2} \right).$$

(1.14)

TABLE 1.6. Classes of Equipment and Typical Working Distances

Classes of Equipment	Working Distance
15-kV switchgear	36
15-kV MCC	36
5-kV switchgear	36
5-kV switchgear	36
5-kV MCC	36
Low voltage switchgear	24
Shallow low voltage MCCs and panel boards	18
Deep voltage MCCs and panel boards	18
Cable junction box	18

Source: IEEE 1584-2018 Guide [9]. Also see Chapter 3.

TABLE 1.7. Factors for Equipment and Voltage Classes

System Voltage, kV	Equipment Type	Typical Gap between Conductors	Distance × Factor
0.208–1	Open air	10–40	2.000
	Switchgear	32	1.473
	MCC and panels	25	1.641
	Cable	13	2.000
>1–5	Open air	102	2.000
	Switchgear	13–102	0.973
	Cable	13	2.000
>5–15	Open air	13–153	2.000
	Switchgear	153	0.973
	Cable	13	2.000

Source: IEEE 1584 Guide [9].

For the arc flash protection boundary, defined further, the empirically derived equation is:

$$D_B = \left[4.184 C_f E_n \left(\frac{t}{0.2} \right) \left(\frac{610^x}{E_B} \right) \right]^{1/x}, \quad (1.15)$$

where E_B is the incident energy in J/cm² at the distance of arc flash protection boundary.

For Lee's method:

$$D_B = \left[2.142 \times 10^6 V_{I_{bf}} \left(\frac{t}{E_B} \right) \right]^{1/2}. \quad (1.16)$$

Due to complexity of IEEE equations, the arc flash analysis is conducted on digital computers. It is obvious that the incident energy release and the consequent hazard depend upon:

- The available three-phase rms symmetrical short-circuit currents in the system. The actual bolted three-phase symmetrical fault current should be available at the point where the arc flash hazard is to be calculated. In low voltage systems, the arc flash current will be 50–60% of the bolted three-phase current, due to arc voltage drop. In medium and high voltage systems, it will be only slightly lower than the bolted three-phase current. The short-circuit currents are accompanied by a DC component, whether it is the short circuit of a generator, a motor, or a utility source. However, for arc flash hazard calculations, the *DC component is ignored*. Also, any unsymmetrical fault currents, such as line-to-ground fault currents, need not be calculated. As evident from the cited equations, only three-phase symmetrical bolted fault current need be calculated.

- The time duration for which the event lasts. This is obviously the sum of protective-relay (or any other protection device) operating time plus the opening time of the switching device. For example, if the relay operating time is 20 cycles, and the interrupting time of the circuit breaker is 5 cycles, then the arc flash time or arcing time is 25 cycles.
- The type of equipment, that is, switchgear or MCC, or panel and the operating voltage
- The system grounding. This is deleted in 2018 edition, see Chapter 3

We can add to this list:

1. Electrical electrodes and potential arc lengths; spacing between phases, spacing between phases and ground, orientation-vertical or horizontal, insulated versus non-insulated buses.
2. Atmospheric conditions like ambient temperature, barometric pressure, and humidity.
3. Dissipation of energy in the form of heat, light, sound, and pressure waves.
4. Arc conditions like, randomness of arc, its interruption, arc plasma characteristics, size, and shape of enclosure.

For using the IEEE equations, the factors listed above need not be considered. As an example, there are many discussions about the gap distances specified in IEEE 1584 Guide and their effects on the incident energy release. While critique of IEEE equations and methodology does add to the technical aspects and paves the way for further revisions, this book limits the calculations according to current IEEE methodology. See also Chapter 3.

IEEE Standard 1584 Guide also provided equations for class L and RK1 fuses, not reproduced here.

1.9 PERSONAL PROTECTIVE EQUIPMENT

NFPA table 130.7(C)(16) describes the PPE characteristics for hazard risk category of 0, and 1 through 4. These are shown in Table 1.8.

The standard ASTM F1506 [35] calls for every flame-resistant garment to be labeled with an arc energy rating, ATPV (arc thermal performance exposure value). The rating of the garment is matched with the calculated incident energy release level. The test method of determining the ATPV specifies the incident energy on a multilayer system of materials that results in a 50% probability that sufficient heat transfer through the test specimen is predicted to cause onset of second-degree skin burn injury (see Reference [9]). Arc rating is reported as the minimum of ATPV or E_{BT} (breakopen threshold). E_{BT} is defined in ASTM F1959-06.

The maximum incident energy for which PPE is specified is 40 cal/cm^2 (167.36 J/cm^2). *It is not unusual to encounter energy levels much higher than 40 cal/cm^2 in*

TABLE 1.8. Protective Clothing Characteristics

Hazard Category	Clothing Description	Range of Calculated Incident Energy	Arc Rating of PPE, cal/cm ²
0	Nonmelting, flammable materials, that is, untreated cotton, wool, rayon, or silk, or blends of these materials, with a fabric weight of 4.5 oz/yd ²	$0 \leq E \leq 1.2$	N/A
1	Arc-rated clothing, minimum arc rating of 4 cal/cm ²	$1.2 < E \leq 4$	4
2	Arc-rated clothing, minimum arc rating of 8 cal/cm ²	$4 < E \leq 8$	8
3	Arc-rated clothing selected so that the system rating meets the required minimum arc rating of 25 cal/cm ²	$8 < E \leq 25$	25
4	Arc-rated clothing selected so that the system rating meets the required minimum arc rating of 40 cal/cm ²	$25 < E \leq 40$	40

Source: NFPA 70E [17]. (All details in the NFPA table have not been reproduced.)

actual electrical systems. Standards do not provide guidelines for higher incident energy levels. Incident energy reduction techniques can be applied; otherwise, it is prudent not to maintain such equipment in energized state.

A category 4 PPE outfit looks like a space suit with face hood, eye shields, cover, and gloves. It restricts the mobility of a worker to perform delicate tasks, for example, maintenance work on terminals and wiring.

Thus, not only an accurate calculation of incident energy level, but its reduction in the planning and design stage and selection of appropriate protection and relaying of electrical systems are gaining importance [36].

A very significant change in NFPA70E 2012 from 2009 is the redefinition of PPE hazard risk categories. This will be based on developing a clothing system meeting a specific tested cal/cm² level and comprised of arc-rated materials. Suppose that an 8 cal/cm² protection is required; this can be achieved by:

- 8-cal/cm² arc-rated pants and shirts
- 4-cal/cm² treated pants and shirts and 4 cal/cm² arc-rated overall
- 8-cal/cm² arc-rated overall cotton shirts and pants.

It is the total level of arc-rated protection that matters. To achieve 8 cal/cm² of the example being discussed, any 8 cal/cm² system of one layer or more is acceptable. Natural fiber clothing like cotton, wool, and silk are still allowed but cannot add to the protection level because of risk of ignition. A note of caution is required in interpretation: a 4 cal/cm² arc-rated shirt and another 4 cal/cm² arc-rated shirt put together *do not add* to 8 cal/cm². *When layers are used, the total system must be tested to get the total arc rating, though most often the testing may prove that even greater protection*

may be provided than the arithmetic sum of the two layers. Also, layering of clothing that is not arc-rated cannot be used to increase arc rating of the clothing. See appendix H of NFPA 70E.

In NFPA 70E 2012, the hazard risk category (HRC) 2* is eliminated. All HRC 2 tasks will require the use of a balaclava under an arc-rated face shield or the use of an arc-rated hood. Commercially, arc-rated outfits even up to 100 cal/cm² are available, still for category 4 applications.

1.10 HAZARD BOUNDARIES

The boundaries are defined in NFPA, and the following synopsis is relevant here (Figure 1.9).

The flash protection boundary is the distance at which the threshold of second-degree burns can occur and the incident energy release is 1.2 cal/cm² (5.0 J/cm²). This is the boundary that is calculated by computer-based programs and IEEE Guide equations. Inside the boundary, the energy level will be higher. This boundary should not be crossed by any one, including a qualified person, without wearing the required PPE, (Table 1.8). The PPE outfits are designed to minimize the risk of sustaining energy greater than 1.2/cal cm². *That is, the threshold of second-degree burns can still occur even with appropriate PPE, and these burns are considered curable.*

Unqualified persons, that is, those not specifically trained to carry out the required tasks, are safe when they stay away from the energized part of a certain distance, which is the limited approach boundary. They should not cross the limited approach boundary and arc flash boundary unless escorted by a qualified person.

Crossing the restricted approach boundary means that special shock prevention techniques and equipment are required, and an unqualified person is not allowed to cross this boundary. Finally, the prohibited approach boundary establishes the space that can be crossed only, as if a live contact with exposed energized conductors or circuits was planned.

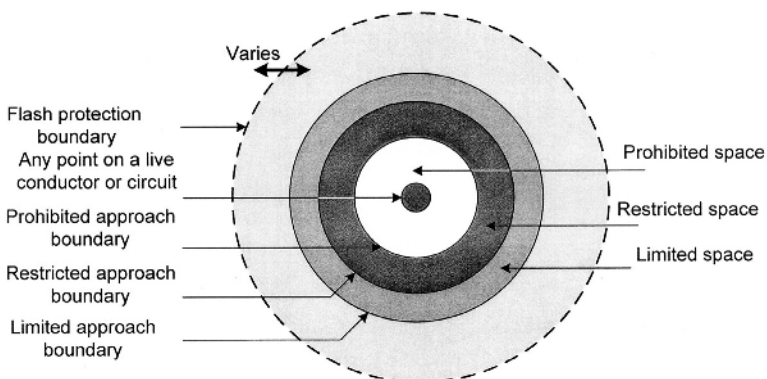


Figure 1.9. Hazard boundaries around an arcing source, adapted from NFPA 70E. *Source:* Reference [17].

TABLE 1.9. Limited Approach and Restricted Approach Boundaries

System Voltage Range	Limited Approach Boundary		Restricted Approach Boundary, Included Inadvertent Movement Adder
	Exposed Movable Conductor (i.e., Overhead Line Conductors Supported on Poles)	Exposed Fixed Circuit Part	
Phase-to-Phase			
Less than 50 V	Not specified	Not specified	Not specified
50–300 V	3.0 m	1.0 m	Avoid contact
301–750 V	3.0 m	1.0 m	0.3 m
751 V–15 kV	3.0 m	1.5 m	0.7 m
15.1–36 kV	3.0 m	1.8 m	0.8 m
36.1–46 kV	3.0 m	2.5 m	0.8 m
46.1–72.5 kV	3.0 m	2.5 m	1.0 m
72.6–121 kV	3.3 m	2.5 m	1.02 m
138–145 kV	3.4 m	3.0 m	1.15 m

Source: NFPA 70E [17]. (All details in the NFPA table have not been reproduced.)

The limited approach, restricted approach, and prohibited approach boundaries are all defined based upon the system voltage. *No calculations are required for establishing these boundaries.* Table 1.9 illustrates the limited approach and restricted approach boundaries based upon NFPA 70E.

1.10.1 Working Distance

Working distance is defined as the closest distance to a worker’s body excluding hands and arms. IEEE 1584 Guide [9] specifies required working distances (Table 1.6). For the 15-kV switchgear, it is 36 in, while for a 480-V MCC, it is 18 in. A larger working distance reduces the incident energy and therefore the HRC. Recommendations of IEEE for the working distances are followed in the calculations in this book. The working distance does exclude hands and arms, which will be much closer to the seat of arc. It is the vital organs like eyes, chest, and heart that are at the working distance from the seat of the arc. *This assumes that a worker does not stick his head inside the switchgear door!*

1.10.2 Arc Flash Labels

The labeling on the equipment contains the following data:

- system voltage
- arc flash boundary
- PPE category
- incident energy release in cal/cm²
- working distance
- restricted approach boundary
- prohibited approach boundary

TABLE 1.10. Arc Flash Boundary and Incident Energy Release for 30 kA of Bolted Fault Current (Arc Flash Current = 28.58 kA rms) in 13.8-kV Switchgear, 13.8-kV System Resistance Grounded, Working Distance = 36", Gap = 153 mm

Arc Duration in Seconds	Arc Flash Boundary in Inches	Incident Energy, cal/cm ²
0.058	74	3.0
0.5	851	26
1.0	1736	52
1.5	2633	78
2	3539	104

Source: Reference [17].

- equipment identification
- the protective device identification that clears the fault.

The labels can be generated on a variety of media, including plastic weatherproof laminates, and most commercial arc flash analysis program will allow custom designing the labels. A user can choose what goes on the label, including the description of PPE. Even the type fonts can be user selectable.

In NFPA 70E 2012, equipment labeling has been reworded to reflect Article 110.16 of the NEC. Each label must contain the incident energy at working distance or the arc rating of the required PPE, or the maximum HRC for that type of equipment. Also, arc flash boundary needs to be specified.

1.11 MAXIMUM DURATION OF AN ARC FLASH EVENT AND ARC FLASH BOUNDARY

A maximum duration of 2 seconds for the total fault clearance time of an arc flash event is considered, though, in some cases, the fault clearance time can be higher. In IEEE 1584 Guide Annexure B, it is stated that: “if the time is longer than 2 seconds, consider how long a person is likely to remain in the location of the arc-flash. It is likely that a person exposed to arc flash will move away quickly, if it is physically possible and 2 seconds is a reasonable maximum time for calculations. A person in a bucket truck or a person who has crawled into equipment may need more time to move away.”

Tables 1.10 and 1.11 show the arc flash boundary calculations according to IEEE 1584 Guide equations for a bolted three-phase fault current of 30 kA, in 13.8-kV switchgear, 13.8-kV system resistance grounded, and also in a 480-V MCC, and 480-V system high resistance grounded.

For a 30-kA, 2-second fault in 13.8-kV switchgear, the incident energy boundary is 3539 in equal to 295 ft. For 1-second fault duration, it is 144.6 ft. The arc flash boundary at which a worker can be exposed to 1.2 cal/cm² of incident energy and sustain threshold of second degree burns seems to be very large.

The working space, in an electrical room switchgear installation in front of electrical equipment, is limited and may be as low as 5–6 ft, and must meet NEC requirements. Many companies, as a policy, keep the electrical rooms locked, and a worker must have the required PPE outfit before entering the electrical rooms.

TABLE 1.11. Arc Flash Boundary and Incident Energy Release for 30 kA of Bolted Fault Current (Arc Flash Current = 16.76 kA rms) in 480-V MCC, 480-V System High Resistance Grounded, Working Distance = 18", Gap = 25 mm

Arc Duration in Seconds	Arc Flash Boundary in Inches	Incident Energy, cal/cm ²
0.050	36	3.8
0.5	147	38
1.0	225	75
1.5	288	113
2	343	151

TABLE 1.12. Statistics of Arc Flash Incidents

Accident Occurrence	Percentage
When the operator or worker is working with equipment doors open	65
When the operator happens to be in front of a closed door and the equipment is not arc resistant	10
When the operator is not present at all, and the equipment is not arc resistant	25

1.11.1 Arc Flash Hazard with Equipment Doors Closed

There is some controversy in interpreting the intent of NFPA 70E, whether the arc flash hazard exists at all times, with the equipment door closed, or it exists only when the doors of an energized equipment are opened for maintenance? Let us first consider most common reasons for arc flash accidents:

- human error
- mechanical faults
- failed connections, loose connections, and terminals
- Adverse ambient conditions and pollution. This should consider pollution specific to plant operation, that is, corrosive gases and vapors may be present.
- rodents.

Table 1.12 shows statistical data of arc flash incidents, when these can occur. This shows that some arc flash hazard exists, even when someone is walking around the closed-door electrical energized equipment, though this probability is relatively small. *The IEEE Guide equations are based upon the hazard calculations with the door open.* With the door closed, the hazard level will be less. It is not so easy to calculate it. The manufacturers are reinforcing the latching mechanisms and strengthening the doors, yet the withstand capability of the doors in closed position under an arc flash event is a question mark. Only when the equipment is arc resistant is the incident energy level outside the equipment zero, so long as no doors and panels that are not intended to be opened are not opened (see Chapter 13).

To resolve this conflict, NFPA 70E 2012 adds:

It is the collective experience of the Technical Committee on Electrical Safety in the Workplaces that normal operation of the enclosed electrical equipment, operating at 600V or less, *that has been properly installed and maintained by qualified persons* is not likely to expose the employee to an electrical hazard.

It is also the opinion of the committee that there is little risk in performing normal operations of electrical equipment and devices, such as opening and closing circuit breakers, motor control centers (MCCs), or starters. When the committee states “interacting with equipment in a manner that could cause an arc flash hazard,” it refers to operations, such as racking circuit breakers or installing and removing MCC buckets.

1.12 REASONS FOR INTERNAL ARCING FAULTS

The internal arcing fault can be caused by various factors, such as:

1. Insulation defects due to quality deterioration of components
2. Overvoltages of atmospheric origin or generated within the equipment due to switching transients
3. Incorrect operation due to not adhering to the procedures
4. Inadequate training of the persons involved with installation, maintenance, and operation
5. Breakage or tempering of safety interlocks
6. Highly polluted atmospheric conditions, high humidity, temperatures, corrosive gases, and salt-laden winds
7. Overheating of the contact area due to presence of corrosive agents, loose connections.
8. Faulty assemblies
9. Lack of proper protection and inadequate relaying. Though protective relaying by itself will not prevent an arcing fault, it will limit the arc fault energy and consequently equipment damage.
10. Insufficient maintenance and testing procedures, like insulation resistance records, infrared testing, and partial discharge measurements which can indicate a deteriorating insulation situation.
11. Incorrect operation of disconnects, switches, and grounding switches because of lack of interlocks
12. Problems with cable terminations, like inadequate design, faulty installation, and insulation failures
13. Ferroresonance voltages of instrument transformers
14. Inadequate protection for ground faults and improper selection of system grounding
15. Aging under electrical stress

16. Entrance of dust and rodents, corrosion at contact surfaces producing heat, loose contacts creating sparks. Snapping of the connections and wiring due to inadvertent force, human errors, and incorrect operation.
17. Closing on to an existing fault, without prior rectification and analyses of the faulty condition.
18. Sparking produced due to racking of circuit breakers, operation of fuses, and excessive current flows through loose contacts.
19. Human errors, that is, some parts or tools left or dropped inside the equipment during maintenance

This list may not be exhaustive and is indicative only. In the first place, if the electrical installations are inadequately designed and do not meet the requirements of national standards and safety codes, these will be more prone to higher incidents of arcing faults. Design and operational measures can be adopted for enhancing safety (see Chapter 2). The list also implies that improvements in arc flash hazard reduction can be achieved by avoiding the listed items and taking remedial measures. As an example, the incipient breakdowns can be predetermined by proper testing with infra red scans or partial discharge measurements (see Chapter 14).

1.13 ARC FLASH HAZARD CALCULATION STEPS

We can summarize the calculation procedures as follows:

1. Calculate bolted three-phase symmetrical short-circuit currents throughout the system where arc flash calculations are to be carried out. The data collection, single line diagrams, and switching conditions to be studied are all akin to the short-circuit calculations; see Chapters 5 and 6.

It will be necessary to consider the various operating conditions, for example:

- Normal operation
- A tie circuit breaker is closed
- Alternate operating situations that is transformers run in parallel, a generator is brought in or taken out of service
- Dual feeds.

It will be erroneous to conclude that if the arc flash calculations are based upon the maximum short-circuit currents in any operating conditions, the results will give maximum hazard levels, and other scenarios need not be considered. This is so because at reduced short-circuit currents, the protective relaying times may increase, giving rise to even greater arc flash hazard.

2. The arcing currents can be calculated based upon the system voltage and the bolted three-phase currents and gap length. Calculate second arcing current at 85% I_a .

3. The working distance and gap lengths in all the examples and discussions in this book are according to IEEE standard. Their impact on arc flash calculation results is, however, documented in Chapter 3.
4. Input the correct equipment type, switchgear, MCC or panels, or arc in the open air.
5. Conduct a rigorous relay coordination study throughout the distribution system. This is an important step, where alternate protective relay types, relay characteristics, and settings, protection strategies, current limiting devices, equipment selection, and alternate settings during maintenance modes become important. The protection and relaying is important, and for arc flash hazard reduction, it becomes an iterative calculation. With all other parameters well-defined, relaying can be manipulated to reduce HRC.
6. Calculate the incident energy, arc flash boundary, and the PPE level.

1.13.1 NFPA Table 130.7(C)(15)(a)

NFPA table 130.7(C)(9)(a) [17] relates the hazard risk category and PPE with respect to maintenance tasks to be carried out on energized equipment within arc flash boundary. For example, if a worker is inserting or removing a starter “bucket” from MCC, the risk category is 3, but if he is just reading a panel meter while operating a meter switch, the risk category is zero. This table is applicable for specific three-phase short-circuit currents for specific durations as specified in the many foot-notes to the table. The IEEE equations are based upon an arc in an enclosure, with one side open, and it seems logical to relate the hazard level with respect to task activity; the following observations apply:

- All commercially available computer programs calculate the arc flash hazard for a bus fault. It is opined that for safety and conservatism, HRC for a bus fault should be considered. For example, the HRC for a fault downstream of a low voltage or medium voltage MCC (a fault on the load side of the motor starter) can be zero, while for a fault on the bus, cleared by an upstream device, it can be 3 or 4. MCC as a whole is labeled for the bus fault—a fault on the bus can shatter the isolation partition in the MCC on arc blast pressure, unless the equipment is arc resistant.
- It will be practically difficult to provide multiple arc flash hazard labels on the same equipment, and lay down procedures for various personal protective outfits based upon the maintenance task to be performed.
- A rigorous calculation procedure for task-based HRC is not available, though guidelines in this table can be applied.
- Multiple tasks are normally performed in one single instance.
- The recommendations of the table can be misapplied (see Section 3.13).
- *The table is judgmental; there are no mathematical calculations.*

The calculations, examples, and study cases in the book consider a bus fault, which gives maximum HRC on an equipment and ignore the nature of the task activity.

1.14 EXAMPLES OF CALCULATIONS

Example 1.1

This example is for calculations as per 2002 Guide. It is included here for reference. The results are compared with 2018 methodology in Chapter 3.

Calculate the incident energy using IEEE equations for a 30-kA three-phase bolted fault current in a 13.8-kV metal-clad switchgear, resistance grounded. The arcing time is 30 cycles for the arc fault current through the protective device.

Using IEEE Equation (1.11), calculate arcing current:

$$\log I_a = 0.00402 + 0.983 \log I_{bf}.$$

This gives $I_a = 28.578$ kA. Note that the arc flash time is calculated based upon the arcing fault current through the protective device and not the bolted fault current. A further calculation for arc flash time is required at $0.85I_a$. Let us assume for this example that 30 cycles is applicable even for reduced $0.85I_a$. Then, calculate normalized incident energy from Equation (1.12):

$$\log E_n = (-0.555) + (-0.113) + 1.081 \log(28.578) + 0.0011(153).$$

Here, $K_1 = -0.555$ (arc in a box), $K_2 = -0.113$, resistance grounded system, and $G = 153$ mm (Table 1.5). This gives $\log E_n = 1.074$. Calculate incident energy in J/cm^2 using Equation (1.13):

$$E = 4.184(1)(11.858) \left(\frac{0.5}{0.2} \right) \left(\frac{610^{0.973}}{910^{0.973}} \right).$$

Here, t is the arcing time = 0.5 second, the distance x is given in Table 1.7, and for 15 kV, it is 0.973, and D , the working distance from Table 1.6, is 910 mm.

This gives $E = 84.4 \text{ J}/\text{cm}^2 = 20.08 \text{ cal}/\text{cm}^2$.

Calculate the arc flash boundary (see Equation 1.15):

$$D_B = \left[4.184(1)(11.858) \left(\frac{0.5}{0.2} \right) \left(\frac{610^{0.973}}{5} \right) \right]^{1/0.973}.$$

Here, $C_f = 1$, E_n as calculated before is $11.858 \text{ J}/\text{cm}^2$, $E_B = 5 \text{ J}/\text{cm}^2$ by definition. This gives $D_B = 16,541 \text{ mm} = 54.267 \text{ ft}$. This is rather a large distance at which a worker can get threshold of second-degree burns.

Example 1.2

Repeat Example 1.1, but for arc in the open air. For high voltage applications, no distinction is made between open and box construction for calculation of arcing current. Therefore, arcing current = 28.578 kA, same as before.

In Equation (1.12), the factor K_1 is -0.792. This gives:

$$\log E_n = (-0.792) + (-0.113) + 1.081 \log(28.578) + 0.0011(153) = 0.837.$$

$E = 4.184(1)(6.871)(0.5/0.2)(610^{0.973}/910^{0.973}) = 48.70 \text{ J}/\text{cm}^2$. This is equal to $11.60 \text{ cal}/\text{cm}^2$.

Also, arc flash boundary reduces to:

$$9437 \text{ mm} = 30.96 \text{ ft.}$$

This shows a considerable difference between arc in open air and a box.

Example 1.3

Repeat Example 1.2 using Lee's equations.

The incident energy is given by Equation (1.7). Substituting the values:

$$E = \frac{793 \times 30 \times 13.8 \times 0.5}{36^2} \text{ cal/cm}^2.$$

This gives 126.6 cal/cm^2 , and from Equation (1.6), distance in feet for a curable burn is 30.82 ft. There is a vast difference in these calculations: 11.6 cal/cm^2 with IEEE method and 126.6 cal/cm^2 with Lee's method; his equations do not consider system grounding, and do not calculate arc flash currents.

Example 1.4

Calculate the incident energy and arc flash boundary based upon the IEEE simplified equations for a 480-V power circuit breaker (low voltage power circuit breaker [LVPCB]) of 800 A rating provided with electronic trip programmer, LS (long time and short time). Also, calculate similarly for a 400-A molded case circuit breaker (MCCB) with thermal magnetic trip. The bolted fault current is 36.8 kA.

800-A LVPCB

The incident energy is given by the equation:

$$4.560I_{bf} + 27.230 \text{ J/cm}^2.$$

Substituting, incident energy is $= 195.04 \text{ J/cm}^2 = 46.80 \text{ cal/cm}^2$

The arc flash boundary is given by the equation:

$$47.2I_{bf} + 2660 \text{ mm.}$$

Substituting

Arc flash boundary = 173 in.

400-A MCCB

The incident energy equation is:

$$0.189I_{bf} + 0.548 \text{ J/cm}^2.$$

Which gives 1.80 cal/cm^2

The arc flash boundary is:

$$9.16I_{bf} + 194 \text{ mm.}$$

Substituting, this gives: 20.9 in.

Example 1.5

Repeat Example 1.4 with rigorous calculations.

Table 1.8 equations do not specify the gap length and also the system grounding. As the equations are for the maximum incident energy, it can be assumed that the system is ungrounded. Also for Table 1.8 equations, a working distance of 610 mm (2 ft) is specified in 1584 Guide. Thus, there are qualifications and compromises in using these equations.

To start the rigorous calculations, a time–current plot of settings on 800-A LVPCB and 400-A MCCB is shown in Figure 1.10. The maximum time on the trip band is used, shown by dots in this figure. This figure is based on circuit breakers of a certain manufacturer. This shows that the LVPCB *maximum* ST delay band is used, as the approximate equations are based upon this assumption. *The opening time of the low voltage circuit breakers is built in the time–current plots supplied by the manufacturer.* Thus, we consider the maximum operating times as shown by bold dots in Figure 1.10. These arcing times are 0.5 second for 800-A LVPCB and 0.017 second for the 400-A MCCB.

The results of the calculations are in Table 1.13. The calculations have been made for grounded and ungrounded systems, and with gaps and working distances as shown. A LVPCB will be provided in a lineup of LV switchgear, and a working distance of 610 mm and gap of 32 mm are applicable as per IEEE 1584 Guide. A 400-A MCCB may be installed in a MCC, where the working distance is reduced to 455 mm and the gap is 25 mm. The variations in the results are apparent and significant for an application.

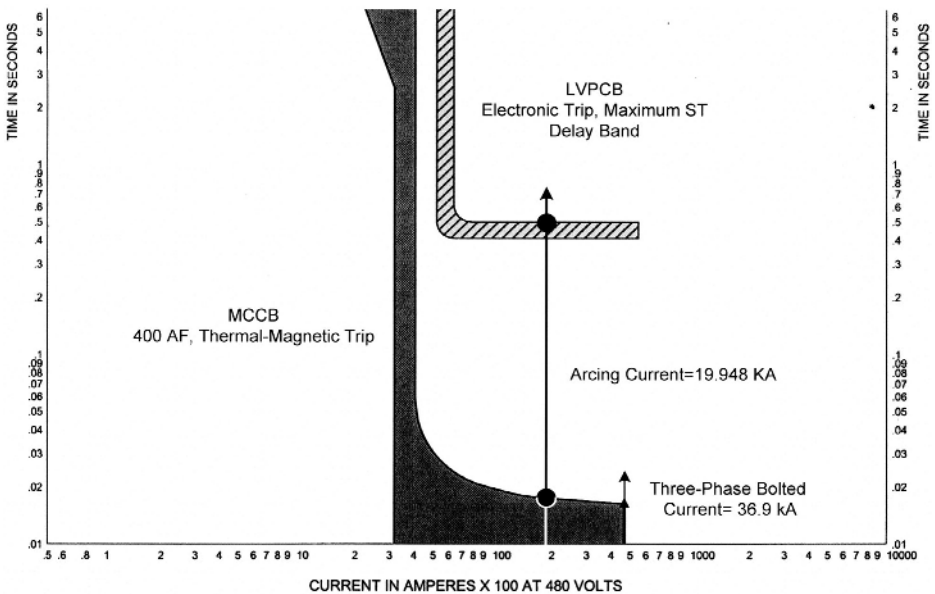


Figure 1.10. To illustrate the arcing time for low voltage circuit breakers, at the calculated arcing current.

TABLE 1.13. Arc Flash Calculations, Example 1.5

Breaker	Bolted Fault (kA)	Arcing Fault (kA)	Trip Time (sec)	Opening Time (sec)	Arc Time (sec)	Ground	Gap (mm)	Working Distance (in)	Arc Flash Boundary (in)	Incident Energy Cal/cm ²	PPE
800-A	36.8	19.95	0.5	0	0.5	No	32	610	198	27	4
LVPGB						Yes	32	610	166	21	3
400-A	36.8	19.95	0.017	0	0.017	No	25	455	21	1.5	1
MCCB (MCC)						Yes	25	455	18	1.2	0

1.15 REDUCING ARC FLASH HAZARD

Electrical arc flash hazard cannot be reduced to HRC zero even in small distribution systems. Electrical power systems vary in complexity—an industrial power system may have a number of in-plant generators in cogeneration mode with utility tie and consume 200 MW of power with hundreds of unit substations and extensive power distribution at medium voltages and low voltage levels, containing motors of thousands of horsepower, a single motor exceeding ratings of 25,000 hp or more and multiple utility interconnections. Conversely, a system with a one or two 480 V transformers of 1000 KVA will also be classified as industrial systems. Thus, it is difficult to lay down all the general rules for reducing arc flash hazard in power systems.

This book contains many study cases and examples, and it is recommended that a reader may do a first reading of the book to grasp an overall picture, followed by a subsequent study. The following common parameters can be stated for arc flash hazard reduction:

1. Reduce the short-circuit currents by proper system designs and load distribution. The arcing current is a function of the bolted three-phase current, and its reduction in the first place will reduce the arc flash hazard (see Chapters 5 and 6).
2. Manipulate the protection and protective device coordination without sacrificing selectivity. Generally, it can be said that reducing the short-circuit currents in an existing system will be practically impossible, but the protective relaying can be manipulated to reduce the arcing time. See Chapters 7 through 14, which discuss differential protections, arc flash detection protection, zone selective interlocking, use of maintenance mode switches to alter the protective relay settings, application of modern multifunction microprocessor-based protective relays, and coordination on instantaneous basis with current limiting devices.
3. Consider high resistance grounding systems—though the IEEE equations give a *lower* incident energy for solidly grounded systems, as compared with resistance grounded or high resistance grounded systems; because it takes

a safe stance that single line-to-ground faults will quickly escalate to three-phase faults; yet approximately 70% of the faults start as single line-to-ground faults. The single line-to-ground faults in solidly grounded systems can be even higher than the three-phase faults. See Chapter 4.

The IEEE Guide equations reveal that the incident energy and the resulting arc flash hazard for a certain equipment type depends only upon these three parameters as stated above. Yet there are many aspects to be considered for a workers safety, discussed above and in the chapters to follow:

- Remote operation, avoiding human machine interface to avoid human errors during routine operation
- Remote racking of circuit breakers
- Proper system designs and maintenance. See 10 bulleted items describing design features and maintenance in Chapter 2.
- Proper worker training and documentation of safety procedures, and safety awareness
- Proper testing, online monitoring, and diagnostics of the systems
- Proper record keeping
- Applications of new equipments and technologies for arc flash reduction
- Proper rigorous arc flash hazard studies, labeling, and use of appropriate PPE
- Adherence to safety codes, standards, and recommended practices
- Remote operation, avoiding human machine interface to avoid human errors during routine operation
- Remote racking of circuit breakers

1.15.1 Reduction

The protection system, coordination and suitable selection of additional protective devices can reduce the arcing times. Examples are differential protection, light sensing supervised by current signature, zone interlocking, arc flash maintenance switches which bring alternative relay settings into operation.

In some cases the arc fault current can be low resulting in increased fault clearing time. For example, the fault on the secondary side of a transformer, which is used by the transformer primary protection device. Due to ratio of transformation this current will be reduced resulting in prolonged clearing time. A secondary protective relay can be applied which will transfer trip primary proactive device.

Well-planned procedures, work practices and training can avoid arc flash hazards. Remote racking, remote control panels for switching, supervisory controls can help worker for safe operation from a distance outside the arc flash boundary. Infra-red windows, partial discharge sensors can be very helpful diagnostic tools.

Arc-resistant equipment can be used.

TABLE 1.1.4. Measures to Protect Against Arc Flash

Mitigation	Type	Advantages	Disadvantages	Recommendations
Compartmentalization (IEC type-4b or ANSI equivalent barriers and boots)	Prevention	Reduces the likelihood of arc flash by compartmentalization and insulating energized parts	Equivalent to a guard on a saw. Hazard is still present. Maintenance and testing may require exposure to energized parts	It does not reduce the energy available, it does reduce the probability of a fault. Compartmentalization or change incident energy calculation.
Arc-resistant equipment	Containment (passive)	Protects the worker by directing energy away from the worker when required covers are on. Tested per IEEE Std. C37.20.7	Maintenance and testing may require removal of covers. Equipment is exposed to damage and has a larger footprint. May require second migration means to stay within rated arcing duration especially at LV	This measure offers protection for specific tasks, but does not reduce available energy. This measure is recommended where active mitigation methods are not acceptable.
High-speed shorting switch	Active (reduction)	Fights fire with fire. Re-directs arc flash energy into the bus by creating an intentional bolted fault; may use optical, differential and current waveform recognition.	Unconventional method and requires additional equipment.	May qualify as arc resistant per IEEE Std. 37.20.7. Needs robust controls to minimize chances of nuisance operation.
ZSI (blocking schemes)	Active (reduction)	Communication-aided transfer trip scheme that reduces breaker trip time and amount of energy released	Requires communication wiring between breakers. Trip units or relays must be installed with ZSI capability	Recommended for LV applications. Also available with some MV relays.

TABLE 1.15. Matrix of Sample Arc Flash Mitigation Measures

Technology	Arc-Flash Mitigation	Incremental Commissioning Complexity	Protection for			Protection			Arc Flash Incident			Typical Application
			Intentional Exposure	Incidental Exposure	Foot-print	Capital Expense	Operational Expenditure	Equipment Survivability	Energy Reduction			
Prevention	Barriers	Low	Limited	Limited	No change	Low	Low	Moderate impact	None	None	LV switchgear switchboard	
	ANSI compartmentalization IEC-4b	Low	Limited	Limited	No change	Low	Low	Moderate impact	None	None	LV switchgear switchboard	
	compartmentalization HRG	High	Limited	Limited	Increased	Medium	Low	Moderate impact	None	None	LV switchgear switchboard	
	Shielding barriers	Low	Limited	Limited	No change	Low	Low	No impact	None	SLG fault only	480V to 5 kV	
Containment	Adm. controls	N/A	Limited	Limited	No change	Low	Low	No impact	None	None	LV arc-resistant switchgear	
	Arc-resistant equipment	Low	No	Yes	Increased	High	Low	No impact	None	None	All, training requirement	
	Solid dielectric bus	Medium	Yes	Yes	No change	Low	Low	Moderate impact	None	None	MV switchgear	
	Differential protection	High	Yes	Yes	No change	High	Medium	Moderate impact	Significant	Significant	LV/MV switchgear	
Reduction	ZSI	Medium	Yes	Yes	No change	Low	Medium	Moderate impact	Significant	Significant	LV switchgear/switchboard	
	Transfer trip	High	Yes	Yes	Increased	High	Medium	impact	Significant	Significant	LV switchgear fed from transformers of >750 kVA	

TABLE 1.16. Measures for Mitigating Arc Flashes at Key Locations in Data Centers

System Location	Issue	Recommendations
LV service entrance equipment	Protection on HV side of transformer does not respond quickly for LV faults	Transfer trip, differential protection along with ZSI
UPS input/output switchboards	Selectivity requirements lead to extended clearing times	ZSI or optical detection
PDU secondary (480 V to 208/120 V)	Low fault levels and P combined with transformer inrush currents extend arc-clearing times	Maintenance switch, compartmentalization of PDU with administrative controls
Generator paralleling equipment	Low fault levels combined with multiple sources extend arc-clearing times	Bus differential or optical detection, adaptive relay settings
MV distribution equipment	Multiple utility sources and/or generator sources result in high fault currents	High-speed shorting switch, bus differential, and optical relaying



Figure 1.11. An outfit for PPE HRC4.

Figure 1.11 shows a PPE outfit for HRC=4. It looks like a space suit and hampers the mobility of a worker to render fine tasks. The arc flash energy must be reduced to no more than 8 cal/cm² with appropriate measures.

1.15.2 Arc Flash Labels

Computer-based software can generate a variety of arc flash labels. The format, size of the label, and even colors can be modified according to user’s choice. NFPA specifies minimum data that should be included in an arc flash label. Generally, the labels are laminated to withstand weathering effects. Figure 1.12 shows a specimen arc flash label.

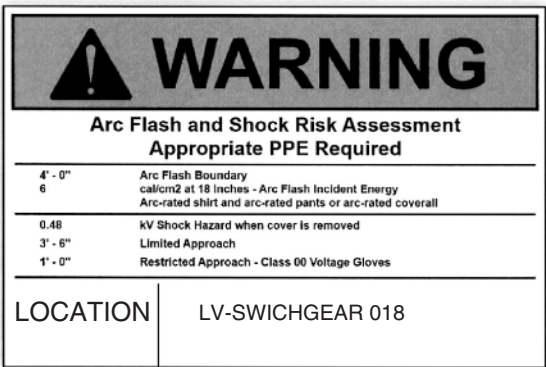


Figure 1.12. A specimen arc flash label.

REVIEW QUESTIONS

1. The calculated symmetrical three-phase bolted fault in a 480-V switchgear assembly is 40 kA. Using IEEE equations, calculate the arc fault current. Assuming that the fault is cleared in 0.1 seconds, both for I_a and 85% I_a , calculate the incident energy release and arc flash boundary. Use the gap length and working distance as per IEEE tables. The 480 V three-phase system is high resistance grounded.
2. Repeat with Lee’s equations.
3. Repeat using Equation (1.9) of the text.
4. Consult NFPA 70 E and the text in this paper and specify the PPE outfits for category 3 and 4 hazard levels in detail.
5. What is the IEEE intent of calculating a second arcing fault current at 85% of I_a ?
6. List five points in order of their importance for worker’s safety.

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