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Arc Flash Calculation Methods

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ARC FLASH CALCULATION METHODS

This course gives an overview of arc flash hazard computations suggested by IEEE and NFPA. All formulas and calculation procedures presented in this course are the property of the IEEE and NFPA. Students are encouraged to consult the standards for additional details.

IEEE STD 1584-2002

The listed methods are suggested by IEEE Standard 1584-2002 in the assessment of arc flash hazard. The empirically derived formulas were developed by IEEE working group on arc flash. These formulas were derived from test results and are applicable for the below listed conditions.

Table 1. Conditions for which the IEEE 1584 formulas are valid

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

STEP 1: DETERMINE THE ARCING CURRENT

For low voltage electrical systems (<1 kV), the arc current is determined using formula (1).

$$I_a = 10^{\{K+0.662\ \log(I_{bf})+0.0966V+0.000526G+0.5588V*\log(I_{bf})-0.00304G*\log(I_{bf})\}} \qquad (1)$$

Where

log is the $\log_{10}$

I_a = arcing current (kA)

K = -0.153 open configuration
-0.097 box configuration

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

V= system voltage (kV)

G= gap between conductors, (mm)

For medimum voltage electrical systems (>1 kV), the arc current is determined using formula (2)

$$I_a = 10^{\{0.00402+0.983\log(I_{bf})\}} \qquad (2)$$

STEP 2: DETERMINE THE NORMALIZED INCIDENT ENERGY

The normalized incident energy, which is derived from 0.2 second arc duration and 610 mm arc distance, is determined using formula (3)

$$E_n = 10^{\{K_1+K_2+1.081*\log(I_a)+0.0011\ \ \}} \qquad (3)$$

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: EVALUATION OF INCIDENT ENERGY

The normalized incident energy is used to calculate the incident energy at a normal surface at a specific distance and arcing time using the formula (4).

$$E = 4.184 C_f E_n \left(\frac{t}{0.2}\right)\left(\frac{610}{D}\right)^x \qquad (4)$$

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 2. Distance factor (x) for different voltages and enclosure models

Enclosure Model	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 staff without personal protective equipment (PPE) may suffer second-degree injuries that can be cured. It is given with formula (5).

$$D_B = 610 * \left[4.184 C_f E_n \left(\frac{t}{0.2}\right)\left(\frac{1}{E_B}\right)\right]^{\frac{1}{x}} \quad (5)$$

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= normalized incident energy

E_B= incident energy at the boundary distance (J/cm^2); 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 factor from Table 2

I_{bf}= bolted fault current (kA)

PROTECTION BOUNDARIES SET BY NFPA 70E - FLASH PROTECTION BOUNDARY

Serious burns caused by arc flash can happen within this boundary unless adequate PPE is used.

- Staff within this boundary must wear adequate PPE regardless of their task.
- The distance from the arc source at which the on-set of a second degree burn happens. 1.2 Cal/cm² > 0.1 sec. is conceived as a second degree burn threshold.
- Medical treatment may still be needed if bare skin is brought out to this level of flash. Complete recovery is anticipated.

LIMITED APPROACH BOUNDARY

Limited approach boundary sets a boundary around brought out live parts that may not be violated by “unqualified” staff unless followed by “qualified” staff.

- May be nearer than flash boundary.
- Determined exclusively on the nominal voltage.

RESTRICTED APPROACH BOUNDARY

Restricted approach boundary is boundary near brought out live parts that may be violated only by “qualified” staff using adequate shock prevention methods and tools.

- Concern is a shock hazard.
- Determined exclusively on the nominal voltage.

PROHIBITED APPROACH BOUNDARY

A shock protection boundary to be violated by only “qualified” staff using same protection as if direct contact with live part is projected. Determined exclusively on the system nominal voltage.

NFPA 70E - ARC FLASH BOUNDARY

The theoretical maximum arc power in MW is half the bolted 3-phase fault MVA. This happens when the arc current is 70.7% of the bolted fault current. Starting from this, the flash protection boundary is computed as (6):

$$D_B = \sqrt{2.65 * 1.732 * V * I_{bf} * t} \qquad (6)$$

Where

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

NFPA 70E - INCIDENT ENERGY

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

$$E = 5271D^{-1.9593}t\left[0.0016 * I_{bf}^2 - 0.0076 * I_{bf} + 0.8938\right]$$

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

$$E = 1038.7D^{-1.4738}t\left[0.0093 * I_{bf}^2 - 0.3453 * I_{bf} + 5.9675\right]$$

Arc in open air – Higher than 0.6 kV

$$E = 793D^{-2}VI_{bf}t$$

Where

E= incident energy (cal/cm^2)

I_{bf}= bolted fault current (kA)

t= arcing time (seconds)

D= working distance from arc (inches)

NFPA 70E - ANNEX C METHOD

Table 3. Formulas for arc in box for computing arc current, incident energy and flash protection limits

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

The formulas in Table 3 are only applicable to arc in box for short circuit currents in 0.6 kA and 106 kA range.

where

E = incident energy (cal/cm^2)

Ibf = bolted fault current (kA)

Ia = arc current (kA)

t = arcing time (seconds)

D = working distance from arc (inches)

D_B = separation of the flash protection boundary from the arcing point (inches)

NFPA 70E TABLES - FLASH PROTECTION BOUNDARY

NFPA 70E presents a simple method of assessing flash protection boundary. This is presented in Table 4. Information shown in this table is estimate – the actual arc flash limits may depend upon different factors such as available fault level and trip settings of the upstream protective equipment. Hence, information shown in this table is not suggested for use.

Table 4. Assessment method for determining flash protection boundary as per NFPA 70E-2003 ROP

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

CATEGORY CLASSIFICATIONS OF THE HAZARD/RISK

The NFPA 70E proposes the option of using Table 220.6(B)(9)(A) Hazard Risk Category Classifications. Information in this table does not give the flash protection limit, but only sets the hazard/risk category number. The Table 220.6(B)(9)(A) also defines the need of V-rated gloves and V-rated devices and tools. The categorization of risk class is based on several elements such as voltage, type of devices, type of task to be executed, available short circuit current, circuit breaker tripping time or fuse clearing time and the location of the enclosure doors. The different types of task presented in the table are: controlling circuit breakers or fuses, working on live elements, voltage testing, taking out and putting in bolted covers, using safety grounds, working on control circuits, etc.

An example of what NFPA 70E Table 220.6(B)(9)(A) may look like is presented for two items in Table 5: operating on live elements and voltage testing. The accurate short circuit currents for three phase bolted faults can be determined using commercial software packages. A basic estimate presented in NFPA 70E – 2003 is utilizing the upstream transformer information in the following equation (7). The accurate short circuit current will be less than this determined value due to the system impedance of the upstream to transformer.

$$I_{SC} = \left(\frac{MVA\ Base}{1.732\ V}\right)\left(\frac{100}{\%Z}\right) \qquad (7)$$

Where

I_{SC} = 3-phase bolted fault level

MVA Base = rated MVA of the upstream transformer

V = line to line voltage at the transformer secondary side

%Z = impedance of the transformer (percentage)

Table 5 (a). Hazard / Risk Category Classification for Working on Live Parts - NFPA 70E

Equipment type	**Equipment side**	**Short Circuit Current (kA)**	**Fault Clearing Time (s)**	**0.24 kV**	**0.277 to 0.6 kV**	**2.3 to 7.2 kV**	**1 to 38 kV**
Panel Board		42	0.03	1			
		<10	0.03	0	1		
		<36	0.1		2		
MCC 0.6 kV Class	Load Side of Breaker/ Fuse	65	0.03		2		
		<10	0.03		1		
	Bus	42	0.03		1		
	Bus	52	0.2		4		
	Bus	65	0.1		4		
	Bus	62	0.33		5		
	Bus	76	0.2		5		
	Bus	102	0.1		5		
	Bus	<10	0.1		3		
	Bus	<10	0.33		4		
Switchgear 0.6 kV Class		35	0.5		4		
		42	0.33		4		
		52	0.2		4		
		65	0.1		4		
		<25	0.33		3		
		62	0.33		5		
		76	0.2		5		
		102	0.1		5		
Other Equipment 0.6 kV Class		35	0.5		4		
		42	0.33		4		

Equipment type	Equipment side	Short Circuit Current (kA)	Fault Clearing Time (s)	0.24 kV	0.277 to 0.6 kV	2.3 to 7.2 kV	1 to 38 kV
		52	0.2		4		
		65	0.1		4		
NEMA E2 Motor Starters MV, Metal Clad Switchgear, MV Other Equipment		55	0.35			5	
							5
							5

Table 5 (b). Hazard / Risk Category Classification for Voltage Testing - NFPA 70E

Equipment type	Equipment side	Short Circuit Current (kA)	Fault Clearing Time (s)	0.24 kV	0.277 to 0.6 kV	2.3 to 7.2 kV	1 to 38 kV
Panel Board		42	0.03	1			
		<10	0.03		1		
		<36	0.1		2		
MCC 0.6 kV Class	Load Side of Breaker/ Fuse	65	0.03		2		
		<10	0.03		1		
	Bus	42	0.03		2		
	Bus	52	0.2		2		
	Bus	65	0.1		2		
	Bus	62	0.33		2		
	Bus	76	0.2		2		
	Bus	102	0.1		2		
	Bus	<10	0.1		1		
	Bus	<10	0.33		1		
Switchgear 0.6 kV Class		35	0.5		2		
		42	0.33		2		
		52	0.2		2		
		65	0.1		2		
		<25	0.33		1		
		62	0.33		2		
		76	0.2		2		
		102	0.1		2		
Other Equipment 0.6 kV Class		35	0.5		2		
		42	0.33		2		

Equipment type	**Equipment side**	**Short Circuit Current (kA)**	**Fault Clearing Time (s)**	**0.24 kV**	**0.277 to 0.6 kV**	**2.3 to 7.2 kV**	**1 to 38 kV**
		52	0.2		2		
		65	0.1		2		
NEMA E2 Motor Starters MV, Metal Clad Switchgear, MV Other Equipment		55	0.35			2	
							5
							5

ARC BLAST PRESSURE

Another point linked with an electric arc is the blast energy or pressure. This hazard is not addressed in NFPA 70E or IEEE Standard 1584. This power can be substantial and can blow staff away from the arc inducing falls and hurts that may be more serious than burns. Being pushed away from the arc cuts down the staff exposure to the heat radiation and molten copper, but can expose the staff to falls or impact traumas. The rough initial impulse force at 24 inches was determined to be roughly 260 lb/ft^2 as found from the formula (8) below.

$$Pressure = \frac{11.58 * I_{arc}}{D^{0.9}} \qquad (8)$$

Where

Pressure is in pounds per square foot

D = Distance from arc in feet

I_{arc} = Arc current in kA

PRACTICAL PROCEDURE TO ARC FLASH COMPUTATIONS

Few methodologies for arc flash computations are proposed NFPA 70E. Calculations are usually performed by electrical engineers, since an apprehension of the short circuit phenomena of power systems is required. If the available short circuit figures at different devices and the related fault clearing times are known, then a qualified person can also complete arc flash hazard assessment (AFH) by using the adequate NFPA 70E tables. Nevertheless, this method has major disadvantages due to large oversimplification inherent in this method. For larger electrical systems with more generation sources and various operating patterns, it is preferred to complete a comprehensive engineering assessment that can find the worst-case arc flash hazard situation that can happen. As yet remain to be seen, this will not inevitably be the conditions with the greatest fault level.

The next procedure is used in comprehensive arc flash calculation. Prior to beginning the data gathering, it should be decided upon which computation methodology will be used.

1. Distinguish all locations/devices for AFH computation.

2. Data Gathering:

a. Device information for short circuit calculations: voltage, size (MVA/kVA), impedance, X/R ratio, etc.

b. Device information for protective device features: device type, existing settings for relays, breakers and trip elements, rating amps, time-current curves, total clearing time.

c. Device information for arc flash calculations: device type, enclosure type (open air, box, etc.), gap between conductors, grounding arrangement, number of phases and estimate of working distance for the devices.

d. All electrical power system devices, their existing arrangements and potential alternative arrangements.

3. Develop a single-line diagram of the electrical system.

4. Complete short circuit calculations:

a. Determine bolted (available) three-phase fault current for each device.

b. Determine every contributing branch/load currents.

5. Determine estimated arc current:

a. Determine arc current using empirical method (NFPA, IEEE, etc.).

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

6. Determine arcing time from the protective device features and the contributing arc current going through this equipment for every branch that importantly adds to the arc fault.

7. Determine the incident energy for the device at the given working distances.

8. Find out the hazard/risk category (HRC) for the approximated incident energy level.

9. Determine the flash protection limit for the device.

10. Write down the findings in reports, single-line diagrams and with adequate labels on the devices.

STEP 1 – RECOGNITION OF LOCATIONS/DEVICES FOR AFH

Arc flash hazard study is required only for those locations where staff is exhibited to the risk. Hence, it may not be required to complete the study for each and every device in the electrical system. Panels and switchboards rated 208 volts or less can usually be neglected if the service transformer is less than 125 kVA.

The potential arc will not probably be sustainable at lower voltages and smaller fault currents. All panels with breakers and fuses should be considered in the study if there is possibility for major arc flash injury. Incidents may happen when handling the breakers or fused disconnects, even with the panel door closed. Existing single-line diagrams can be consulted for deciding the device that call for study. If single-line diagram does not exist, it should be made.

STEP 2 –EQUIPMENT DATA GATHERING FOR SHORT CIRCUIT ASSESSMENT

Even though some devices may not call for arc flash hazard study, information about this device may be needed in a short circuit assessment. Distinctive information needed for the study is shown in Table 6. Short circuit assessment needs information on utility, generators, transformers, cables, transmission lines, motors, etc. Device name-plate can give most of the necessary information. In the absence of specific information, it may be possible to get the data from the manufacturers. Also, distinctive information can be assumed by citing books. Power system software tools usually have broad library of manufacturer’s information including most electrical devices

Table 6. Typical data needed for equipment for short circuit analysis

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

DEVICE INFORMATION FOR PROTECTIVE DEVICE CHARACTERISTICS

Collect information on the different protective devices that will decide the arcing time. Table 7 presents what kind of data is needed. This information may be collected from existing drawings, relay calibration information, protective device coordination studies and from field inspection. Collect the time-current characteristics (TCC) for these devices from the manufacturers.

Decide if the protective device is reliable enough. This can be completed by asking the operators, or by testing. Some companies have occasional relay testing procedures. If the protective element is deteriorating, the information given by the manufacturer may not be useful. If the fault interruption does not happen as anticipated then the arc flash study cannot be precise. It will be essential to repair or replace such device.

Table 7. Necessary protective device information

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

DEVICE INFORMATION FOR ARC FLASH ASSESSMENT

Depending on the selected computation methodology, the following device data is needed for an arc flash hazard assessment.

Table 8. Device data for AFH assessment

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

The working distance is an estimate measure that should be based on the type of work being completed and the device type. It may vary depending on manufacturer’s design and work principles. Working distances should be attested for different work patterns and device as part of an overall safety program.

FIND OUT ALL POSSIBLE OPERATING PATTERNS

Document all possible arrangements using single line diagrams. The circuit breaker/switch/fuse position may change during contingency service. Parallel feeds can largely increase the fault current levels and resulting arc flash hazard. The contribution of associated motors to the fault level will also increase the hazard. Study should take into account both the normal operating condition as well as the worst possible arc flash condition. In principle, the higher the available fault short circuit current, the higher the arc flash energy. Nevertheless, since arc flash energy is a function of the arc duration as well as the arc current, it cannot be mechanically accepted that the greatest fault current will always be the worst-case AFH.

STEP 3 – COMPLETE SINGLE-LINE DIAGRAM

Single-line (one-line) diagrams are useful tools for recording and communicating power systems data. They are easy to read, present the connections and condition of devices and contain information needed for assessment. The assessment findings such as short circuit studies and arc flash hazard assessment can be presented on the single line diagrams. Majority of the plants should already have single-line diagrams. The accuracy of these has to be checked before starting the study. If a new single line diagram is needed, it can be made using the collected information. Study using commercial integrated software asks for information entry to build a power system model. Major software tools provide an advanced graphical drag and-drop single-line diagram totally incorporated with short circuit, protective device coordination, and arc flash study. These tools give an easy way to make, update and maintain your power system single-line in accordance with NFPA-70E rules.

STEP 4 – SHORT CIRCUIT CALCULATIONS

Complete instructions on completing short circuit assessment are not part of this course. But more considerations linked to AFH when completing short circuit calculations are briefly presented in the following sections. Only 3-phase short circuit currents are looked at when completing AFH. This may seem strange, but it is uniform with the recommendations in IEEE-1584 and NFPA-70E. There are few reasons for this. One is that 3 phase short circuit currents typically give the greatest possible short circuit energy and can be considered as the worst-case.

Another crucial argument is that experience has shown that arcing faults in devices or air that begin as line-to-ground faults, can very rapidly step up into 3-phase faults as the air ionizes across phases. This advancement from single-phase to 3-phase typically happens within a few cycles. Because of this, majority of the tests completed on arc flash energy has been based on 3-phase short circuit currents. For singe-phase systems, IEEE-1584 suggests that computations are done for the same 3-phase system and says that this will yield conservative findings. Based on the collected information for different system operating conditions, arc flash assessments should be completed for each possible condition. When completing short circuit computations to decide on maximum short circuit current level, conservative guesses and assumptions are implemented. This makes sense if the objective is to decide on the maximum breaker or device duties. Nevertheless, for AFH, using too conservative short circuit information can yield non-conservative findings since a very high fault current may develop very short arc duration due to the operation of instantaneous trip devices. The highest fault current does not inevitably mean the highest possible arc flash hazard since the incident energy is a function of arcing time that may be an inversely proportional function of the arcing current. For AFH calculations, short circuit computations should be conservative, but not too conservative.

COMPUTING BOLTED FAULT CURRENT

Compute the 3-phase bolted fault current in symmetrical rms amperes for all buses or devices, and for each potential operating condition. Verify for the following while conceiving different interconnections at the concerned bus or device:

- Numerous utility sources that may be switched in or out of operation.
- Multiple local generator sources that are run in parallel or isolated depending on the system arrangement.
- Emergency operating conditions. This may be with only small backup generation.
- Maintenance conditions where short circuit currents are low but arc duration may be long.
- Parallel lines to Switchgear or MCC’s.

- Tie breakers which can be serviced open or closed.

- Large motors or process sections not in service.

A short circuit/arc flash scenario should be determined for each operating condition. This can be a complex task for most software or spreadsheet calculators. Hand calculations and spread sheet calculators usually neglect the transient short circuit information that last for a few cycles. These are greater than the sustained short circuit values. The generator and motor transients during the fault add to the arc fault. To take these into account:

Consider sub-transient and transient impedances of the generators in order to find the bolted short circuit current if the arcing time is small. For long arcing times, use the sustained short circuit figures. This implies an iterative technique, since the arcing time depends upon the fault current going through the upstream protective device. Take into account contribution of connected motors.

COMPUTE CONTRIBUTING BRANCH SHORT CIRCUIT CURRENTS

Contributing branch currents to total faults are computed to determine the contributing arc currents by different branches that are used to determine the trip times of the protective devices on the branches. The protective device upstream to the fault can register only the current going through it. The short circuit current may be higher than the current going through the upstream protective device. Hence, the total short circuit current cannot be used to determine the trip time unless other branch currents are importantly smaller than the upstream current. Likewise, for parallel lines, the contributing currents from each line must be computed to decide the trip time. Special attention is required when calculating branch currents through transformers. This could be one of the common sources of errors since the branch current needs to be adapted by the transformation ratio. When a fault happens on the low voltage side of a power transformer, the protective device on the high voltage side of the transformer registers a smaller current due to the transformer turns ratio.

STEP 5 – CALCULATE EXPECTED ARC CURRENT VALUE

COMPUTE ARC CURRENT

Compute arc current for each device or bus using one of the empirical equations accepted by the NFPA-70E (NFPA, IEEE, or other standards). 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.

RANGE OF ARC CURRENT / TOLERANCE DUE TO VARIATION BASED ON IEEE-1584

To account for the variation that can happen in arcs, IEEE methodology proposes the following.

1. Compute the maximum anticipated bolted fault condition.

2. Compute the minimum anticipated bolted fault condition. The minimum bolted fault current could be a light load condition with many motor loads or generators out of service.

3. Compute the arcing current at 100% of IEEE 1584 approximation for the above two scenarios.

4. Compute the arcing current at 85% of IEEE 1584 approximation for the two above scenarios.

5. At these four arcing currents compute the arc flash incident energy and utilize the greatest of the incident energies to determine PPE. The minimum fault current may need longer to clear and could end in a greater arc flash incident energy level than the maximum-fault current condition. The short circuit current in the main fault current source should be found since the current in this equipment may influence the fault

clearing time for the great part of the arc flash incident energy.

Even though IEEE suggests considering a range of 85% to 100% of the approximated arc current, IEEE test data suggests that the evaluated values of arc current differ from 67% of the approximation to 157% of the approximation. Careful use of tolerances is needed for the following reasons:

1. The operating time of inverse-time protective elements is determined by the arc current.

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

3. A more realistic and fairly conservative judgement of arcing time can be found by accurate selection of tolerances of arc current.

The following section gives guidelines based on statistical assessment of test information for different voltage levels and enclosure models.

TOLERANCE DUE TO VARIATION BASED ON REAL INFORMATION

Due to the random nature of arc currents, the real arc current may take any value within a range of values. The computed arc current is only a single approximation within the range. The computed arc current or the greatest potential arc current may not inevitably cause the largest incident energy to which staff may be exposed. The arcing time may depend upon the arc current due to the tripping features of the protective element. Hence, the incident energy may be higher for smaller arc currents if the contributing branch fault current of the arc current lies in the inverse-time section of trip characteristics.

Table 9. Minimum and maximum tolerances for arc current obtained from IEEE 1584 test data for confidence level of 95%

Voltage	Enclosure Type	Minimum Arc Current	Maximum Arc Current

LV	Open	-26.5%	26.0%
LV	Box	-26.9%	33.0%
MV	Open	-6.7%	10.2%
MV	Box	-20.8%	12.3%

When taking into account the range of the computed arc current, the easiest way is to take a tolerance. This tolerance is a percentage of the computed arc current. The tolerance is found from statistical assessment of the test information. The tolerances dissent for IEEE 1584 method and NFPA 70E methods. Table 9 gives tolerances for IEEE 1584 arc current estimate for a confidence level of 95%. A confidence level of 95% entails that there is a probability of 95% that the arc current will be in the tolerance range. To be more conservative, confidence level of 99% can be taken. This would extend the tolerance range.

EXAMPLE

For a 0.48 kV devices in open air, the calculated arc current (I_{arc}) using IEEE 1584 estimate was 50 kA. What is the potential range of the arc current? From Table 9 the minimum and maximum margins of arc current are –26.5% and +26% respectively.

Minimum arc current = I_{arc}*(100+Min.Tolerance %)/100
=50*(100-26.5)/100=36.75 kA

Maximum arc current =I_{arc}*(100+Max Tolerance %)/100
=50*(100+26.0)/100=63 kA

VARIATION OF ARCING CURRENT WITH ARC GAP

If the precise arc gap (or gap between conductors) was utilized in determining the arc current approximations, then additional modifications need not be used. Nevertheless, if the gap is mean value or an assumed figure, then the potential range of arc current may need to be corrected. The gap is utilized in computations in the IEEE 1584 formulas. NFPA 70E does not take the gap into consideration. Table 10 gives the sensitivity of arc current to gap. For every mm of difference in gap the arc current figure is changed by the sensitivity amount. The voltage across an arc gap is approximately relative to the length of the gap. Greater voltage means greater arc power for the same arc current. Since the arc resistance is non-linear, the resistance is not directly relative to the gap length. Hence, statistical approach is favoured in the assessment of the effect of fluctuation of arc gap length on arc current. The method presented below should be utilized only for small differences in arc gap, as with most other sensitivity assessments.

Table 10. Sensitivity of arc current to gap for IEEE 1584 methodology

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

EXAMPLE

The accurate gap between conductors for different elements is not known. For low voltage box, it was discovered that the gap varied from 25 mm to 40 mm with an average of 32 mm. There are two possible ways to cope with this. The first way is to get two approximations for arc current, one for the least gap and the other for the greatest gap. The second way is to adapt the IEEE approximation for the mean gap using the sensitivity presented in Table 10. Let us assume that the arc current for 32 mm gap was found to be 50 kA.

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

=50*(1-1.0*(25-32)/100)

=53.5 kA

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

=50*(1-1.0*(40-32)/100)

=46 kA

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

LIMITATIONS FOR ARC CURRENTS

After computing the range of potential arc current, it is required to verify if the computed figures are within the practical range. Verify for the following:

- Upper limitation: It is not feasible for the arc current to be higher than the bolted fault current due to the additional impedance of the arc. Hence, after employing corrections for random variations and for gap variations, if the upper limit of the range of arc current is higher than the bolted fault current, then cast away that figure and take the bolted fault current as the upper limitation.

EXAMPLE

For a bolted fault current of 50 kA at medium voltage equipment in box, the arc current was determined to be 49 kA using IEEE 1584 formulas. To consider random variations tolerance data from Table 9 was used. This takes the upper limit of arc current to 12.3% higher than the approximated figure. Hence, the upper limit of the arc current was determined to be 49*(100+12.3)/100 = 55 kA. This is higher than the bolted fault current (50 kA), and hence, is not possible. Take the upper limit of arc current as 50 kA.

- Lower Limit: Arcs do not hold when the current is very low. For 480-volt electrical systems, the industry assumed minimum level for a sustaining arcing fault current is 38% of the available three-phase fault current. Test information coming with IEEE Standard 1584 presents arc sustaining for 0.2 seconds at 0.208 kV at a current of 21% of bolted fault current. Table 11 presents the minimum arc current as a percentage of bolted fault current found during experiments. The lower limit of arc current is not yet final. Until additional details are collected, it may be fair to use Table 11 as the cut-off minimum arc current as a percentage of the bolted fault current.

Table 11. Adapted minimum arc current as a percentage of bolted fault currents

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

COMPUTE BRANCH CURRENTS CONTRIBUTING TO THE ARC CURRENT

This is completed using the branch current additions to the bolted fault current. To compute the contributing currents to the arc fault, use formula (9).

$$I_{x,arc} = I_{x,BF} * I_{arc}/I_{BF} \tag{9}$$

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 discovered to be non-sinusoidal due to the non-linear nature of the arc resistance. The harmonic share of different branches may change nevertheless the fundamental part can be estimated using the method presented above. It has been discovered that even though the voltage waveform is highly distorted, the arc current has low harmonic share. Hence, the linear relation (9) is a reasonable approximation.

The branch contribution must be computed for each scenario. These are further used to check the trip time of protective elements.

STEP 6 – CHECKING ARCING TIME

Determine arcing time from the protective element features and the contributing arc current going through this element for every branch that importantly adds to the arc fault. Since we are conceiving a range of arc currents instead of a single figure, we need to define the trip time for each arc current figure – the upper limit, the lower limit and the value computed from NFPA 70E or IEEE 1584 formulas.

The trip time of a protective element is determined from its time-current characteristics (TCC). Data may be got from manufacturers in the form of TCC plots or formulas. Relays and circuit breaker trip elements frequently have changeable time delay for tripping service. The delay time may depend upon the magnitude of the current registered by the element. Time delays are left to coordinate the tripping of the relays so that maximum reliability of supply may be kept. Check literature on protective element coordination for further information. Since arc flash hazard can be minimized by cutting down the duration of faults, it is useful to have a solid apprehension of protective device coordination. Usually, 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 higher than the instantaneous pickup of the protective element, and hence the element may trip at the minimum response time. For fault currents near the transition from the inverse-time curve to the instantaneous trip, a small modification in arcing current figure can cause a very large difference in determined arc energy.

Deciding the trip time manually asks for visual check of each time-current curve to find out the operating time for a particular fault current. This also calls for adjustment of the fault currents to reflect the transformation ratio of any connected transformers. This must be completed before getting the trip times of the protective elements across the transformer.

Usually, for any given current, protective elements have a tolerance about the specified trip time. Many low voltage breakers and fuses define the upper and lower limits of the trip time for different current figures. For such situations, the time-current curve looks like a thick band instead of a single line. Relays usually show a single line for the TCC curve, and set the tolerance as +/-x% (typically 10% to 15%). Some fuse curves give only the mean melting time or the minimum melting time. Use the directions provided below for getting 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 element.

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

- Fuse TCC with total clearing time: No adjustment is needed since total clearing time is what we require.

- Fuse TCC with mean melting time: Get the tolerance from the product literature, TCC information or the manufacturer. Add the tolerance to the mean melting time found for the TCC. If tolerance information is not available, make an assumption using information with similar elements. For most applications, a tolerance of +/-15% should be sufficient. IEEE 1584 advises taking a tolerance of 15% when mean trip time is below 0.03 seconds and 10% otherwise. Some frequently used fuse curves have been found to have a tolerance as high as 40%. If the tolerance is known to be small, then additional calculations can be neglected.

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

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

ASSESS PROTECTIVE DEVICE FUNCTIONING

Special care is needed when the computed branch currents seen by any protective element is close to pickup current of the element. If the branch current is lower than the pickup then the element will not trip. Usually, protective elements are coordinated such that the downstream element operates before upstream element for the same current (or the same current changed to the same voltage base). Nevertheless, in the absence of correct coordination, if the downstream element does not trip at a given fault current, then the upstream element may trip. Hence, it is essential to distinguish which element will interrupt the arc fault. Selective coordination of elements should be maximized by adjustment of trip element settings. This will not only improve the continuity of supply but will also give the chance to lower arc flash hazard by cutting down the arcing time (although selectivity and arc flash reduction are often contradictory objectives).

The arcing fault currents close to pickup current of instantaneous trip function should be closely checked. If the computed fault current figure is within the tolerance band of the pickup, then there is a likelihood of the element not tripping at the anticipated instantaneous figure. In such situations, if the time-overcurrent function exists in the element then the trip time for the time-overcurrent function should be taken for arc flash computations.

It is also crucial to understand that any modifications to the protective element settings can have a major impact on the arc energy. If element or setting variations are made, the arc flash computations must be re-checked and adequate variations made.

TRIP TIME FOR MULTIPLE LINES

When a bus is supplied from more sources a fault at the bus may induce a series of breaker operations. The real fault current will vary as the breakers open, since the power sources will be sequentially moved out from the faulted bus. Since the current seen by the relays will change over time, additional computations are needed to find out the real trip time for each breaker. We cannot simply get the trip time matching to a single branch current by observing the TCC information. Protective elements with time-overcurrent functions usually function like an integrating element. That means, the overcurrent or its function is incorporated or "added" over time until the sum arrives at a predetermined trip figure. This is when the relay operates. For further information on how a relay or fuse integrates the function of current, refer to documentation on operation of protective elements.

STEP 7 – FIND OUT THE INCIDENT ENERGY

Approximate the incident energy for the device at the given working distances. The incident energy is a function of the arc current, arcing time, the enclosure type and the distance from the arc. IEEE 1584 standard also considers the gap between electrodes as a parameter. NFPA 70E methodology uses the bolted fault current rather than the arc currents.

In steps 5 and 6, different scenarios were conceived. Using the predefined methodology, compute the incident energy for each case. Ensure the following scenarios are checked:

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

2. Lower bound of arc current due to random changes, and its related trip time.

3. Upper bound of arc current due to random changes and its related trip time.

4. Multiple feed cases:

a. Determine incident energy for each type of possible arrangements as mentioned in Step 4.

b. Determine incident energy for arc current varying through series of breaker sequences, as presented in step 6. An example is shown below.

CALCULATED INCIDENT ENERGY TOLERANCES

The picked out methodology may have tolerance about the computed figure of incident energy due to the random nature of arcs. Different computation methodologies will typically yield different findings. For IEEE 1584 formulas use Table 12 to find a more conservative estimate that takes into account for the randomness of arcs. This table is based on further assessment of test information coming with IEEE Standard 1584. The maximum tolerance should be added to the computed incident energy.

This methodology is advised to minimize risk to staff since test information has been found to have higher incident energy than that yielded by IEEE 1584 equation.

Table 12. Tolerances for IEEE 1584 incident energy approximations

	Maximum Tolerance (% of Calculated Incident Energy)	
	For adjusted arc current	**For IEEE 1584 arc current**
Low voltage arc in open air	66%	85%
Low voltage arc in box	63%	64%
Medium voltage arc in open air	93%	54%
Medium voltage arc in box	50%	52%

Table 12 presents incident energy tolerances for two different scenarios of arc currents. It can be noted that there no major difference in incident energy for arc in box whether the exact IEEE 1584 arc current or the arc currents modified for random changes is used. The selection of arcing current importantly affects only the arcing time, which in turn involves the incident energy. From the table it can be noted that the computed incident energy is greater than maximum measured figures for low voltage open air.

Nevertheless, for other cases, the approximation may be much lower than the maximum measured figures.

EXAMPLE

The incident energy for low voltage in box was computed to be 10 cal/cm^2 utilizing the IEEE 1584 formulas. The modified arc current was used in this approximation. What is the maximum possible incident energy presuming random behavior of arcs? From Table 12, the maximum tolerance is 63% of computed figure.

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

=10 * (100 + 63)/100 = 16.3 cal/cm^2.

STEP 8 – DETERMINE HAZARD/RISK CATEGORY

Hazard/risk category (HRC) is defined as a number showing the level of danger that depends upon the incident energy. Category 0 presents little or no risk, whereas category 4 is the most dangerous. Table 13 gives the categorization guide for the risk category number.

Table 13. Hazard/risk classification as per NFPA 70E

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

Staff should get ready according to the risk category before starting work or inspection near exposed, live conductors. Certification and warning labels are also needed. Even though the incident energy itself may give a more precise picture of the risk, the scale of 0 to 4 for the risk category may convey more meaningful data to most staff. Companies are obliged to complete hazard study before starting any work near live conductors.

STEP 9 – FIND OUT FLASH PROTECTION BOUNDARY

The flash protection boundary is the distance at which staff exposed to arc flash, without adequate PPE, will get second degree burns that can be cured. The flash protection limit is a function of the arc flash incident energy. The greater the arc flash energy, the farther away the limit will be. Compute the flash protection boundary using the formulas presented by the standard being followed. Use the greatest incident energy computed in step 7, after accounting for all the system arrangements and changes due to randomness of arcs. Use the equation (10) to find out the flash protection boundary. This is relevant for both IEEE Std 1584 and NFPA 70E.

$$D_B = D\left(\frac{E}{E_B}\right)^{\frac{1}{x}} \qquad (10)$$

where,

D_B = distance of the boundary from the arcing point

D = working distance

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

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

x = distance exponent factor (see Table 14)

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

Table 14. Distance exponent “x”

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

EXAMPLE

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

Flash protection boundary can be computed as follows:

D_B = 18* (25 / 1.2)1/1.6 = 120 inches.

STEP 10 – PRESENT THE ARC FLASH HAZARD ASSESSMENT

The arc flash hazard assessment should be attested in comprehensive reports, single-line diagrams and on the devices. Give as much information as possible. Documentation has the following advantages:

1. Easy for staff to find the necessary information and drawings. This is required for safety planning.

2. Compliance with OSHA and NFPA.

3. Easy to enforce modifications in study when power system modifications are made or

when the standards are revised.

4. In case of arc flash related incidents, investigation is helped by reports. Lack of study reports may result in penalty to the company.

INFORMATION IN REPORTS

The study report should include the following information:

1. Name of person performing the study.

2. Date of the study.

3. All information gathered and used in the study, including protective device settings.

4. Assumptions utilized in the absence of actual information.

5. Methodology of hazard assessment utilized – the standard and the revision year.

6. If software was utilized, the name of the software and the version.

7. The findings – incident energy, hazard/risk category and flash protection boundary for every device.

8. If different operation sequence is possible, document study for each operation mode.

The study report should be available to all concerned staff. Some of these may be:

1. Safety coordinator.

2. Safety department.

3. Foremen and electricians.

4. Electrical engineer.

5. Affiliated contractors.

INFORMATION IN ONE-LINE DIAGRAMS

A person working on the switchgear should check the drawing for the arc flash incident energy levels and the hazard category on all the exposed conductor parts. This would provide the staff the knowledge of risk at each part of the panel. The following steps are suggested for a real documentation of arc flash information on single-line diagrams:

1. Put the arc flash hazard study findings on every device that poses a risk.

2. Determine the flash protection boundary, also known as arc flash boundary (AFB).

3. Determine the incident energy at the approximated working distance in the standard unit, for example in calories per cm^2. Also, determine the estimated working distance.

Staff should check if the working distance will be kept while working on live devices. If closer working distances are needed, then it may be required to revise the study to reflect real working situation. The closer the distance the more the incident energy, and greater the risk.

4. Determine the hazard risk level at the approximated working distance.

5. For breakers and fuses, define the figures for both the line side and the load side. Keep in mind that a fault on the load side of the protective element would be cleared by that element itself. Nevertheless, should a fault happen at the line side of the protective element, than the fault would be cleared by the upstream protective element. This would usually have greater incident energy due to longer tripping time. Hence, it is important to determine and document arc flash energies for the line side of protective element, and communicate this with staff.

6. Use arrows to give a clear indication of the load side and line side on the device if the arc flash figures are different.

7. In any device, if different elements have different incident energy values, the worst scenario should be highlighted or mentioned first in the list.

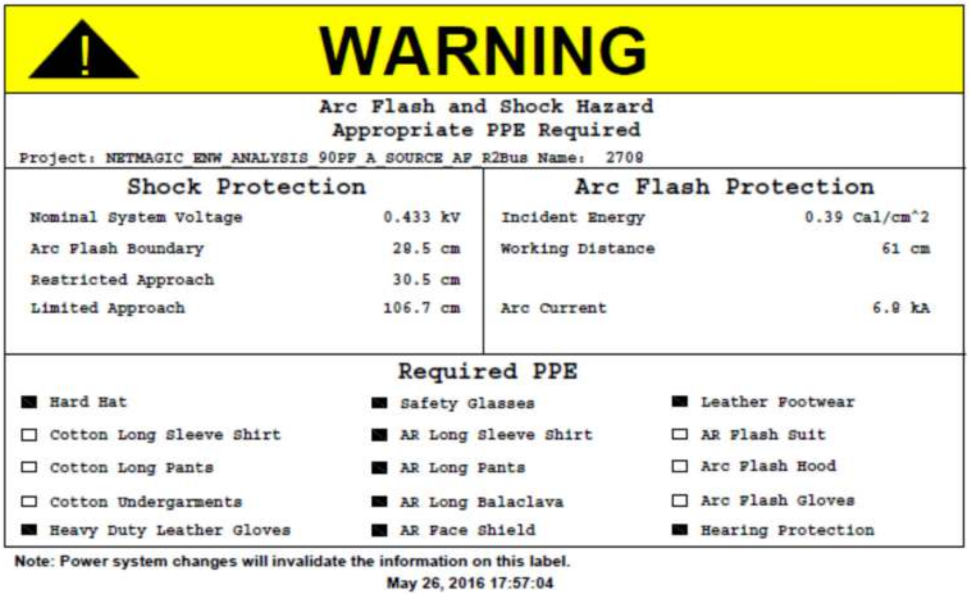
8. Include the protective element that limits the incident energy. If that element is at some distance, give details on its location. It is also recommended that the settings be documented.

9. If there are different possible sources or arrangements, clearly mention in the single line diagram, which source is connected and/or which breaker is open or closed. Staff should first check if the assumed condition in the diagram reflects the situation of the power system at the time of work. If the system arrangement is different from those for which the study was completed, it is essential to modify the assessment.

DOCUMENTATION ON DEVICES

Three types of documentation are suggested for arc flash hazard study results put on the devices:

1. Warning labels with arc flash figures: Permanent stickers with a warning sign of right size. The label should be put in a location that is easily visible and readable from some distance. The flash protection boundary and its units, the incident energy at the estimated working distance and its risk category number must be clearly shown on the label. Additional details that are useful for next revisions are the date of study, the calculation methodology, and the software name and version. Warning labels should also be put just outside the flash protection boundary, so that staff may notice it and prepare adequately before they enter the hazardous area.



WARNING

Arc Flash and Shock Hazard
Appropriate PPE Required

Project: NETMAGIC_ENW_ANALYSIS_90PF_A_SOURCE_AF_R2Bus Name: 2708

Shock Protection

Nominal System Voltage	0.433 kV
Arc Flash Boundary	28.5 cm
Restricted Approach	30.5 cm
Limited Approach	106.7 cm

Arc Flash Protection

Incident Energy	0.39 Cal/cm^2
Working Distance	61 cm
Arc Current	6.8 kA

Required PPE

■ Hard Hat
☐ Cotton Long Sleeve Shirt
☐ Cotton Long Pants
☐ Cotton Undergarments
■ Heavy Duty Leather Gloves
■ Safety Glasses
■ AR Long Sleeve Shirt
■ AR Long Pants
■ AR Long Balaclava
■ AR Face Shield
■ Leather Footwear
☐ AR Flash Suit
☐ Arc Flash Hood
☐ Arc Flash Gloves
■ Hearing Protection

Note: Power system changes will invalidate the information on this label.
May 26, 2016 17:57:04

Figure 1. Example of arc flash warning label

2. Arc flash study findings, in the form of a table and a small single-line diagram as shown in the previous section, need to be put on the device at a spot which staff can easily access.

3. Large multi-section devices may be labeled at different sections. This eases hazard communications. Various parts may have various potential arc flash energies. If the same label is to be utilized on all parts, the highest possible incident energy must be defined. For example, a large transformer can have higher incident energy on the low voltage terminals than on the high voltage terminals. If the incident energy variations are high, different labels can be put. This averts staff having to wear additional PPE while operating terminals with less incident energy.

NEC, NFPA and IEEE do not define information to be put on arc flash warning labels. The labels may be more or less comprehensive than the one shown in Figure 1. It is up to the management to decide on necessary detail. Arc flash computations give the maximum expected incident energies. There are a number of operations that can be completed around electrical devices that does not need the maximum PPE to be used.

Referring to NFPA 70E Table 3.3.9-1 the operation of reading meters with the door closed is defined as risk category 0 (zero), while NFPA lists racking in a breaker as risk category 3, if computations give the maximum PPE as category 4, then risk category 4 should override NFPA risk class 3. Table 15 below is an overview of the NFPA operation table.

Table 15. Overview of NFPA 70E Operation and Risk Categories

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