Arc Flash Hazard Standards:

The Burning Question

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Abstract

During the last 5 years, arc flash safety compliance has been introduced at many industrial sites in Australia. This is primarily based on the compliance requirements originating from the United States. Hence, arc flash safety compliance in Australia is mainly based on American standards. Arc flash safety has now become an important issue in Australian industries, since arc flash incidents are regularly being reported in public forums. At present, Australia is in the process of developing its own arc flash standards.

Arc flash safety is primarily concerned with preventing arc flash burns when operating personnel are directly exposed to energized electrical conductors. In such cases arc flash protection is provided by appropriate Personal Protective Equipment (PPE) for the expected incident heat energy due to an arc flash. The primary standards for arc flash protection in industrial sites in the U.S. are NFPA – 70E and IEEE 1584. However, there are other associated standards for working on overhead lines, arc flash labeling and testing of PPE.

This paper provides an overview of the arc flash standards available in the U.S. and Australia.

Introduction

The arc flash hazard was introduced to the world by Ralph Lee, when he presented the paper “The Other Electrical Hazard: Electric Arc Blast Burns” in the United States in 1982. Traditionally, electrical safety was concerned with electric shock. However, Lee’s paper highlighted the fact that working near energized electrical conductors can result in arc flash burns – which can result in serious burn injury and in the case of severe burns can also result in death..

After the publication of Lee’s paper, the National Fire Prevention Association (NFPA) in the U.S. took note of the arc flash hazard and started collecting data regarding arc flash burn injuries in electrical installations. By about 1994, NFPA statistics showed the alarming nature of arc flash hazard. As per the statistics, there were about 1 to 2 fatalities per day in the U.S. in electrical installations. However, there were more than 5 serious burn injuries per day which required extensive burn treatment and skin grafts. These statistics motivated NFPA to initiate research with regard to calculation of incident heat energy due to an arc flash and specifying appropriate Personal Protective Equipment (PPE) to provide arc flash protection.

Due to historical reasons, NFPA also maintains the National Electric Code (NEC) in the U.S. The NEC is also referred to as NFPA 70. NFPA 70 serves as the design & installation standard for electrical installations in the U.S. The corresponding standard in Australia is AS/NZS 3000. However, NFPA also maintains an associated electrical operational safety standard, namely NFPA 70E. Year 2000 edition of NFPA 70E included equations for arc flash incident heat energy calculations based on the research carried out by Doughty, Neal and Floyd for switchboards up to 600V. NFPA 70E – 2000 edition also included a Hazard Risk Category (HRC) table with corresponding Flame Retardant (FR) clothing & PPE specifications. In addition, NFPA 70 was updated to include Arc Flash Hazard warning labels and requirement to use arc flash PPE.

Almost concurrently, the Institution of Electrical and Electronic Engineers (IEEE) in the U.S. conducted extensive experiments up to 15kV and developed new equations for arc flash incident heat energy calculations. This was published as IEEE Standard 1584 – 2002, entitled “IEEE Guide to Performing Arc-Flash Calculations”. Obviously, this created confusion in the electrical community, since IEEE - 1584 equations are different from NFPA – 70E equations. However, this was resolved when IEEE 1584 – 2002 equations were included in NFPA 70E – 2004 edition. It was recognized that the IEEE 1584 equations were based on more extensive experiments and could be used for a wide variety of installations up to 15kV. However, NFPA 70E equations are limited to systems up to 600V. The option of which equations to use was left to the discretion of the user.

In the U.S., there is now an agreement that future work on arc flash incident heat energy calculations will be carried out by IEEE in association with NFPA. In fact, IEEE/NFPA Technical Advisory Committee on arc flash calculations now includes representatives from other countries, including an invited member from Australia. Hence, in the future, the prime mover of arc flash calculation standards in the U.S. will be IEEE. The arc flash protection (arc flash PPE) standards will be updated and maintained by NFPA.

NFPA has already published the 2009 edition of NFPA 70E standard. This new edition has incorporated subtle but important changes to HRC / PPE table in NFPA 70E – 2004. The new table is based on Arc Thermal Performance Value (ATPV) of FR clothing, rather than number of layers of FR clothing. In addition, NFPA 70 E – 2009 provides more clear PPE specifications for face and hand protection. As the arc flash protection technology advances, it can be expected that better and simpler standards will be developed by NFPA.

General electrical installations in the U.S. are under the ambit of NFPA 70 and NFPA 70E. However, electric utilities are covered under the National Electrical Safety Code (NESC). From 1 January 2009, electrical utilities are required to follow the arc flash safety guide lines for working on overhead transmission and distribution lines provided in NESC 2007. A brief overview of the NESC 2007 requirements is presented in this paper.

Electrical operational safety code in Australia is enforced by State governments through Occupational Health & Safety Act and Electrical Work Code. At present, Electrical Work Code includes only a brief reference to arc flash protection and specifies cotton/wool clothing for electrical work. As per this Work Code, cotton and wool fabric are considered flame retardant.

Detailed guidelines for arc flash calculations and arc flash PPE are specified ESAA NENS 09 – 2004 standard developed by Energy Supply Association of Australia (ESAA). The name ESAA has now been changed to Energy Networks Association (ENA) and the same standard has been reissued as ENA NENS 09 – 2006. A revised NENS 09 standard is expected in the near future.

In Australia, there continues to be considerable criticism with regard to IEEE 1584 standard and methodology. This has created a lot of confusion in the electrical community in Australia with regard to use of IEEE / NFPA standards. The only available Australian Standard is NENS 09. However, this standard needs to be revised before it can be used by Australian industries. An overview of NEN 09 and and its limitations have been presented in this paper.

Considerable research work on arc flash has been carried out in Australia by Dr. David Sweeting and Prof. Tony Stokes. Their research has raised some serious questions about the validity of IEEE 1584 equations. However, their research papers do not as yet provide alternative equations for calculation of incident energy at electrical switchboards. Hence, it has become necessary for industries in Australia to continue to use IEEE / NFPA standards for protecting their personnel against arc flash hazards.

Arc Flash Protection Standard – NFPA 70E

NFPA 70E introduced the concept of ‘Limits of Approach’ and the definition of ‘Flash Protection Boundary’ in the 1995 edition. This edition also provided the equation for establishing Arc Flash Protection Boundary for a given transformer size and arc fault duration. This equation was based on the incident energy equation developed by Ralph Lee in 1982. However, NFPA also initiated further research to develop specific arc flash incident energy equations for switchboards rated at 600V and below. The results of this research were published as an IEEE paper by Doughty, Neal and Floyd in 1998. NFPA 70E – 2000 edition included these equations and more importantly this edition also included appropriate tables to assist the user in selecting Flame Resistive (FR) clothing and other Personal Protective Equipment (PPE) required for head, face and neck protection.

Almost concurrently IEEE initiated extensive research in the area of arc flash incident energy calculations and published a set of empirical equations to calculate arc flash incident energy for various switchboard configurations up to 15kV. Consequently, a separate standard IEEE 1584 – 2002, “Guide to Performing Arc Flash Hazard Calculations” was published by IEEE. These equations were included in NFPA 2004 edition and it was also recognized that IEEE will be the prime mover for further research work in the area of arc flash calculations

The main objective of the NFPA 70E is to provide a standard for electrical safety, which includes arc flash safety. Hence, the main motivation of NFPA 70E is the specification of PPE requirements for the expected value of incident heat energy (cal/cm^2) at a given electrical installation. In other words, the actual calculation of incident heat energy for a given installation is not a part of the main body of the standard. However, NFPA 70E includes a detailed overview of the arc flash calculations in the Appendix.

For the purposes of arc flash PPE specifications, NFPA 70E – 2000 introduced the concept of 'Hazard Risk Category' (HRC) and specified 5 categories, namely Category 0 to Category 4. Each category specified the PPE requirements for arc flash protection for a given range of incident heat energies. Hazard Risk Category (HRC 0 to HRC 4) is often colloquially referred to as PPE Category (PPE 0 to PPE 4). The term PPE Category is commonly associated with FR clothing specification. However, this categorization is also applicable to other PPE such as face shields and gloves. The specifications for FR clothing as per Table 130.7(C)(11) of NFPA 70E – 2004 is as given Table 1. It can be noted that, FR clothing for an arc rating greater than 40 cal/cm2 is not specified, since 'Dangerous' arc blast conditions can be present for these incident energy values.

Table 1: Protective Clothing Characteristics - NFPA 70E - 2004

Hazard/ Risk Category	Required Minimum Arc Rating of PPE (cal/cm^2)	Clothing Description (Typical Number of Layers)
0	N/A	Untreated cotton / wool (Min fabric weight of 153gsm)
1	4	FR Shirt & FR Pant or FR Coverall
2	8	Cotton Underwear [Shirt & Shorts] + FR Shirt & FR Pant
3	25	Cotton Underwear [Shirt & Shorts]+ FR Shirt & FR Pant + FR Coverall
4	40	Cotton Underwear [Shirt & Shorts] + FR Shirt & FR Pant + Multilayer Flash Suit

Traditionally, cotton fabric which has been treated with flame resistant chemical is recognized as flame resistant clothing. The popular trade names of these clothes are Kevlar, Nomex and Indura. However, recent advances in research have lead to the development of inherently flame resistant fabrics, such as carbon fibre clothing Carbtex. By definition, a flame resistant material should not catch fire or burn. However, a flame resistant material may be charred by arc flash heat, but will not continue to burn after the arcing ceases. The burning of material can often cause more injury to the skin than the initial exposure to the arc flash.

In Table 1, 'Arc Rating' of PPE is defined as the incident energy on a fabric or material that results in sufficient heat transfer through the fabric or material to cause the onset of a second degree burn. A 'second degree' is also referred to as a 'curable' burn. A curable burn is burn which can be cured without extensive medical treatment. For a curable burn, the skin temperature must remain within 80°C. Onset of a second degree burn corresponds to incident energy on the body of less than 1.2 cal/cm^2 for a duration greater than 0.1s or 1.5 cal/cm^2 for a duration of 0.1s or less.

The above definition of 'Arc Rating' assumed that a given FR clothing provides a 'certain degree' of protection against arc flash burns. Hence, it was considered necessary to provide additional layers of FR clothing to provide adequate protection against higher values of incident energy. For example, HRC Category 2 in Table 1 specifies 2 layers of clothing. It was considered that the air gap between layers is also an important aspect of arc flash protection. Hence, the specification of HRC Category numbers (1, 2, 3 and 4) essentially refers to the number of layers of FR clothing. Such a specification did not provide for advances in FR clothing research and development. For example, if a given FR clothing is rated for 8 cal/cm^2 and meets the requirement of onset of second degree burn under specified test conditions, then the specification of 2 layers for HRC Category 2 is confusing and unnecessary.

The term 'cotton underwear' in Table 1 created considerable confusion in the industrial community. The table in NFPA 70E clearly defines 'cotton underwear' as 'conventional short sleeve and brief/shorts'. This definition was open to interpretation by the reader. In fact, most articles in arc flash literature just used the term 'cotton underwear' in their tables without properly defining the term. This resulted in unnecessary confusion.

NFPA 70E – 2009 edition addressed both the above issues and made subtle but important changes to HRC / PPE category table. The revised table has done away with the term 'cotton underwear' and also the concept of layers. However, the table still retains the definition of HRC Category number. The revised specifications for FR clothing as per Table 130.7(C)(11) of NFPA 70E – 2009 is as given Table 2.

Table 2: Protective Clothing Characteristics - NFPA 70E - 2009

Hazard/ Risk Category	Required Minimum Arc Rating of PPE (cal/cm^2)	Clothing Description (Typical Number of Layers)
0	N/A	Untreated cotton / wool (Min fabric weight of 153gsm)
1	4	Arc-rated FR Shirt & FR Pant or Arc-rated FR Coverall
2	8	Arc-rated FR Shirt & FR Pant or Arc-rated FR Coverall
3	25	Arc-rated FR Shirt & FR Pant or Arc-rated FR Coverall and Arc Flash Suit selected so that the system meets required arc rating
4	40	Arc-rated FR Shirt & FR Pant or Arc-rated FR Coverall and Arc Flash Suit selected so that the system meets required arc rating

The revised Hazard Risk Category table is considerably simplified. It is now feasible to use only one layer of FR clothing for Categories 1 and 2 as long as the clothing meets the required minimum arc rating. However, an arc flash suit is required for Categories 3 and 4. Hence, it can be expected in future that the table will be simplified further. In fact, a simplified two category FR clothing system has already been suggested in the Appendix H of NFPA 70E – 2009, as shown in Table 3.

Table 3: Simplified, Two Category, FR Clothing System

Clothing	Applicable Tasks
Everyday Work Clothing FR Shirt & Pant or FR Coverall with minimum arc rating of 8 cal/cm^2	Hazard Risk Category 1 & 2
Arc Flash Suit Total FR clothing system with Minimum arc rating of 40 cal/cm^2	Hazard Risk Category 3 & 4

It can be noted that the above tables do not explicitly specify protection for head, face and hands. NFPA 70E – 2004 did specify these protection requirements in Table 130.7(C)(10). However, most of the literature on arc flash did not include this table, possibly because this table was not clearly laid out. However, this table has been revised in NFPA 70E – 2009 edition. A condensed version of the revised table is as given in Table 4.

Table 4: FR Clothing and Protective Equipment – NFPA 70E - 2009

Hazard/Risk Category	Protective Clothing & PPE
0	Non-melting Shirt (Long Sleeve) Non-melting Pants (Long) Safety glasses Hearing protection Leather gloves
1 & 2	Arc-rated long sleeve shirt & Pants or Arc-rated coverall Arc-rated face shield Hard hat & Safety glasses Hearing Protection Leather Gloves & Leather work shoes
3 & 4	Arc-rated long sleeve shirt & Pants or Arc-rated coverall Arc rated flash suit Arc-rated arc flash suit hood Hard hat and Safety glasses FR Hard hat Liner Hearing Protection Arc-rated Gloves Leather work shoes

Table 4 definitely provides a clear and complete specification of arc flash protection PPE. Apart from the above tables, NFPA 70E includes detailed information on arc flash clothing characteristics, selection, and maintenance. The reader is strongly recommended to refer to NFPA 70E – 2009 for a more detailed presentation on arc flash protection PPE.

Finally, it can be noted that NFPA 70E is a complete standard for electrical operational safety in the United States. Hence, NFPA 70E includes detailed safety procedures for electrical isolation, work permits and prevention of electric shock. Such safety procedures are already a part of the safety practices existing in Australia. Hence, the only sections which are of interest for our purposes are the sections dealing with arc flash protection.

Testing of Arc Flash Protective Equipment – ASTM F 1959

‘Arc Rating’ specified in the previous section is the value attributed to materials that describes their performance when exposed to an electrical arc discharge. The arc rating is expressed in cal/cm^2. To determine the arc rating, the test specimen is subjected an arc discharge under controlled conditions and the arc electrodes are enclosed in modified Faraday cage to minimise the effect of magnetic fields on the directionality of the arc. The fault current, the duration of arc and the test specimen distance from the arc are set at pre-defined values for each test. The heat sensor is mounted on the test setup to measure the arc incident energy. Two other heat sensors are also mounted in the test setup to measure the heat transfer through the specimen and predict the second degree burn as per the Stoll curve criteria specified in the ASTM F 1959 standard.

The ASTM F 1959 standard and the test setup are primarily designed for testing Flame Retardant (FR) clothing material. If the specimen survives the test, then the corresponding incident energy is referred to as the ‘Arc Thermal Performance Value’ (ATPV). If the specimen fails the test, then the corresponding incident energy is referred to as the ‘Incident Energy to Break Open’ (E_{BT}). After the test, arc rating of the specimen is reported either as ATPV or E_{BT}, whichever is the lower value.

In the United States, it is a requirement that all FR material and material system are tested as per ASTM F 1959 and the value of ATPV in cal/cm^2 is reported. This ensures that the FR material or system meets the specified arc rating in NFPA 70E standard.

Overview of Arc Flash Hazard Calculation Methods

As discussed in previous sections, the primary parameter required for specifying the arc flash protection is the expected ‘Incident Heat Energy’ on the body of the person exposed to an arc source. Arc flash incident energy is dependent on the distance of the body from the arc source. Such a distance is called the ‘Working Distance’. Working distance generally depends on the voltage rating of the equipment, equipment design and type of work being carried out. However, in most cases, the working distance is generally specified based on the voltage rating of the equipment.

Arc flash calculation methods provides equations for the calculation of incident heat energy at a specified working distance. Conversely, the same equations can used to determine the distance which needs to be maintained by a person so that incident energy on the body is limited to onset of a second degree burn. Such a distance is called ‘Flash Protection Boundary’. It is obvious that any person entering inside the Flash Protection Boundary must wear appropriate arc flash protection gear. Hence, arc flash hazard calculation methods are used to calculate both incident energy at a specified working distance as well as the Flash Protection Boundary.

The primary factors which influence the arc flash incident energy are the following:

- Working distance or the distance from the arc source
- Arcing current or the fault current
- Rated voltage
- Arc duration

The theoretical equation developed by Ralph Lee in 1982 was based on the above parameters. This equation assumes arc propagation in free air. It was found that the equations developed by Ralph Lee results in conservative values of incident energy, especially for voltages greater than 1kV. In addition, Lee's equation did not consider factors such as propagation of the arc in enclosed switchboards, which is more relevant in the case of LV switchboards.

With the support of NFPA, Doughty, Neal and Floyd published new empirical equations in 1998, which specifically addressed arc propagation in LV switchboards up to 600V. They developed two separate equations, namely, one for 'arc in open air' and another for 'arc in a box'. The equation for 'arc in a box' is relevant for typical LV switchboards. Equations by Doughty et al were incorporated into NFPA 70E – 2000 edition for arc flash incident energy calculations and specification of arc flash PPE.

The above equations used three phase bolted fault currents for arc flash energy calculations. However, in practice, the arc fault current could be much less than the bolted fault current due to the arc voltage drop. This is particularly significant in the case of LV systems. In fact, for LV systems the arc current can be as low as 30 to 50% of the bolted three phase fault current. In addition, factors such as arc gap between conductors, size of the switchboard and type of grounding also influence the arc flash incident energy. Almost, concurrently with the NFPA research efforts, extensive research was initiated by IEEE with due consideration of the above factors. The results of this research were published as IEEE Standard 1584 – Guide to Performing Arc Flash Hazard Calculations in 2002. IEEE Standard 1584 also included a spreadsheet to perform these calculations. This spreadsheet has almost become a de-facto standard for presenting arc flash analysis results. After publication of IEEE Standard 1584, these equations were included NFPA 70E – 2004 edition. In the United States, IEEE is the prime mover of the research and development of arc flash hazard calculations. However, IEEE 1584 committee is now supported by NFPA and also includes other invited members from overseas including Australian researchers. Hence, further revisions and improvements to arc flash calculations can be expected in the near future.

The primary motivation of IEEE 1584 & NFPA 70E is to establish arc flash hazard incident energy and provide protection while working on enclosed LV and MV switchgear commonly used in industrial electrical installations. For such systems, a single phase to ground arc quickly degenerates into a three phase arc due to the ionization of the surrounding air. Hence, IEEE 1584 explicitly ignores single phase to ground arcs and in addition it also ignores earth fault relay operation under arc fault conditions. Hence, the equations included in IEEE 1584 are not directly applicable for overhead transmission and distribution lines. In addition, the IEEE 1584 equations are valid only up to 15kV and recommends use of Ralph Lee's theoretical equation for higher voltage systems. In the case of MV and HV overhead transmission and distribution systems, single phase to ground arc may be more relevant due to large gap between phase conductors and arc flash incidents involving phase to ground is more likely while carrying out overhead line maintenance.

Quite independent of the above work by IEEE / NFPA, arc flash research was conducted by Electric Utilities in the United States and Canada to establish arc flash hazard incident energy levels for overhead lines from 1kV to 800kV. These experiments were conducted primarily for open air phase to ground arcs. Hence, these results are not applicable for phase to phase arcs nor for arc in a box. The details of the research carried out and the equations are not available in the public domain. However, the results of the experiments are included in the form of tables in 2007 edition of National Electrical Safety Code (NESC). This safety code published by NESC is applicable to all Electric Utilities in the United States. The supporting standard for NESC is maintained by ANSI / IEEE C2 standard. Effective 1 January 2009, NESC has mandated that electric utilities in the U.S. must follow the guide lines specified in NESC – 2007 when personnel are working on or near energized parts. It can be noted here that all electrical industries and building sites in the United States, except for electric utilities, are covered by National Electric Code (NEC or NFPA 70). However, it is interesting to note that NESC – 2007 arc flash tables have also been included in the Appendix D of NFPA 70E – 2009 edition. The reason being that NFPA 70E is the primary document for selection of arc flash PPE, even for NESC. Hence, NFPA 70E – 2009 not only provides a clear and detailed specification of arc flash protection PPE requirement, but it also provides a good overview various arc flash hazard calculation methods.

In the Australian context, the only standard which is provides arc flash protection specification and arc flash hazard calculation method is NENS – 09 guidelines developed by Electrical Network Association (ENA). This document is available for purchase through Standards Australia Inc (SAI).

Details of IEEE 1584 & NENS 09 arc flash hazard calculation equations and NESC arc flash hazard calculation tables are presented in the following sections.

Arc Flash Hazard Calculations – IEEE Standard1584

The equations presented in IEEE Standard 1584 are based on statistical analysis and curve fitting of the available experimental test data. Details of the experimental data have also been published as a part of this standard. An overview of the IEEE 1584 equations is as given below:

1. Calculation of Arcing Current

For applications with a system voltage under 1kV,

$\lg I_a = K+0.662 \lg I_{bf}+0.0966V+0.000526G+0.5588V(\lg I_{bf})–0.00304G(\lg I_{bf})$

For application with a system voltage greater than or equal to 1kV

$\lg I_a = 0.00402+0.983 \lg I_{bf}$

where,

$\lg = \log_{10}$

I_a = arcing current in kA

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

I_{bf} = bolted three phase short circuit current (symmetrical rms) (kA)

V = system voltage in kV

G = conductor gap (mm) [See Table 5]

2. Calculation of Incident Energy

Incident energy is first calculated at for a normalized working distance of 610mm and normalized arc duration of 0.2s.

$\lg E_n = k_1+k_2+1.081 \lg I_a+0.0011G$

where,

E_n = incident energy (J/cm2) normalised for time and distance

k_1 = -0.792 for open air arcs; -0.555 for arc in a box

k_2 = 0 for ungrounded and high resistance grounded systems

= -0.113 for grounded systems

G = conductor gap (mm) [See table 5]

Incident energy (E in J/cm^2) at a given working distance ‘D’ is given by

$E = 4.184\ C_f\ E_n\ (t /0.2)\ (610^X/D^X)$

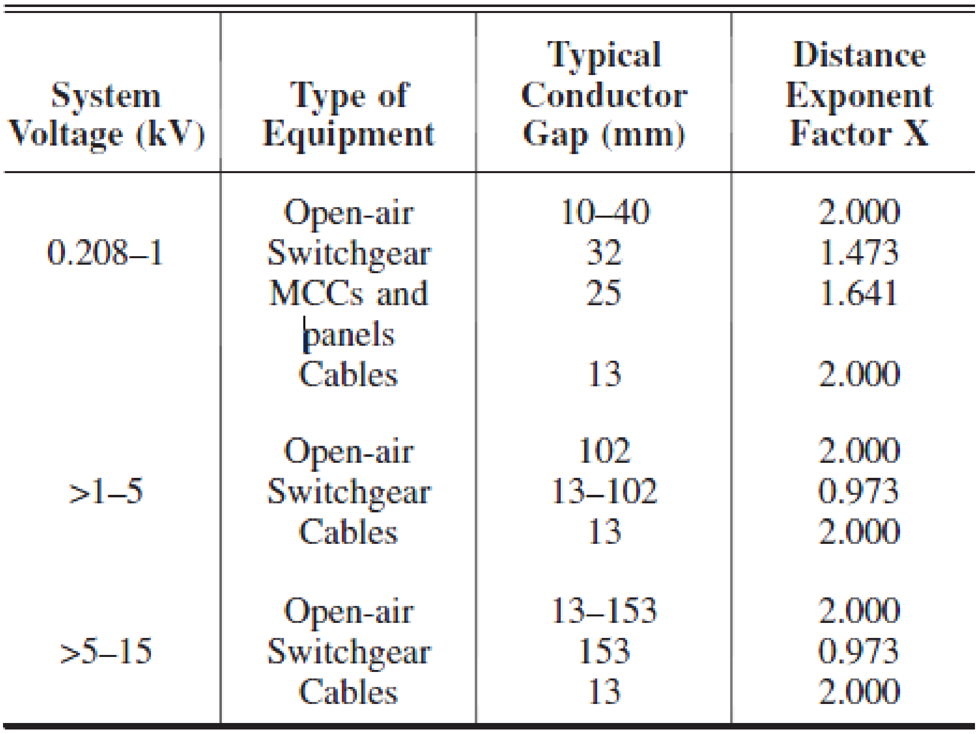
where,

C_f = 1.0 for voltages above 1 kV; 1.5 for voltage at or below 1kV

t = arcing time (seconds)

X = distance exponent [See table 5]

Table 5: Factors for Equipment and Voltage Classes



System Voltage (kV)	Type of Equipment	Typical Conductor Gap (mm)	Distance Exponent Factor X
0.208–1	Open-air	10–40	2.000
	Switchgear	32	1.473
	MCCs and panels	25	1.641
	Cables	13	2.000
>1–5	Open-air	102	2.000
	Switchgear	13–102	0.973
	Cables	13	2.000
>5–15	Open-air	13–153	2.000
	Switchgear	153	0.973
	Cables	13	2.000

IEEE 1584 recommends usage of theoretical equation developed by Ralph Lee, if the rated voltage is over 15kV and the conductor gap is outside the range specified in Table 5.

Ralph Lee's equation for calculating incident energy is as given below:

$E = 2.142 \times 10^6 \, V \, I_{bf} \, (t / D^2)$

The above incident energy equations can also be used calculate the 'Flash Protection Boundary', by setting the incident energy (E) value to 5 J/cm^2 (which is equivalent to 1.2 cal/cm^2). In such a case, the calculated value of D corresponds to the Flash Protection Boundary. It can be noted that a person not wearing the required arc flash PPE must remain outside the Flash Protection Boundary

In the case of overcurrent protection with inverse time-current characteristics, incident energy can be higher at a lower value of arc current due to relatively higher value of protection operating time. Hence, IEEE 1584 specifies calculation of incident energy at both 100% and 85% of the arcing current (I_a) calculated using the above arcing current equation. The higher value of incident energy is used for specification of Hazard Risk Category and selection of arc flash protection PPE.

IEEE Std 1584 also includes extensive set of equations for specific types of low-voltage circuit breakers and current-limiting fuses. However, care should be taken while using these equations, since they implicitly assume that these protection devices will operate in the instantaneous region.

Criticism with regard to IEEE Standard 1584

There is considerable criticism in Australia with regard to arc flash incident energy calculations using IEEE Standard 1584. The criticism is based on the arc flash research work carried out by Dr David Sweeting and Prof Tony Stokes in Australia. Technical papers based on their work have been published in various international forums including IEEE Transactions.

The main criticisms are as given below;

- The electrode arrangement used for IEEE 1584 tests does not represent the worst case situation.
- Calorimeters have too much shrouding and the thermocouples will not withstand the arc current.
- IEEE 1584 model is based on radiation of arc energy. Any hazard assessment based on radiation only will lead to the wrong conclusion and corrective measure.

These are very serious criticisms and create serious doubts with regard to correctness of using IEEE 1584 equations for arc flash incident energy calculations. However, there are no credible alternative equations available at present for arc flash calculations. Until an Australian standard is established, it has become necessary to use IEEE 1584 to conduct arc flash calculations for industries in Australia. Future work on arc flash calculations is being carried out as a joint venture of IEEE/NFPA. Dr Sweeting a member of this Technical Advisory Committee. It is hoped that future revisions to IEEE 1584 will take into account criticism listed above.

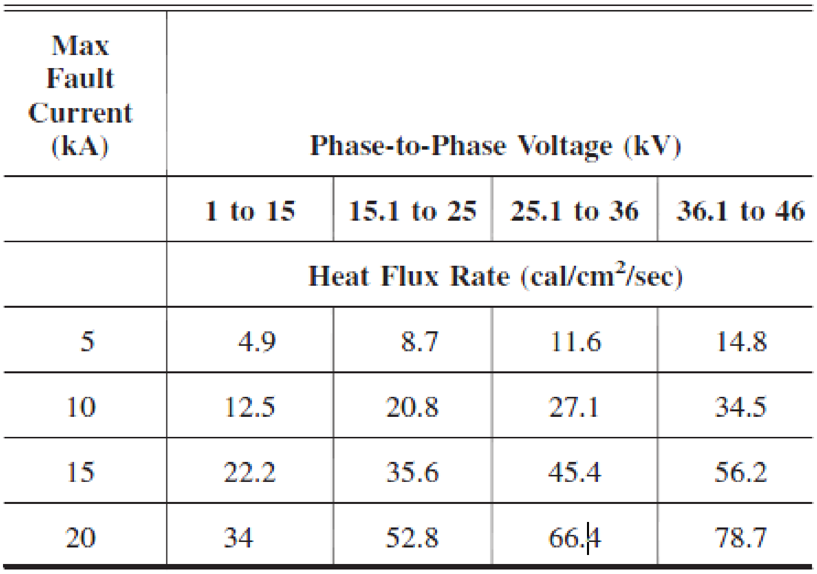
Arc Flash Hazard Calculations for Overhead lines – NESC - 2007

National Electrical Safety Code (NESC) in the United States is applicable to work carried out by electric utilities. A large part of the work carried out by electric utilities involves operation and live line maintenance of overhead transmission and distribution lines. In such cases, phase to ground faults are more relevant for arc flash hazard calculations. NESC – 2007 edition included tables for arc flash calculations for single phase to ground faults in open air. These tables are based on equations derived from experimental data, but the details of the experiments or the arc flash calculation equations are not available in the public domain.

However, it is interesting to note that commercial software called ARCPRO developed by a Canadian company Kinectrics is available for purchase by the public. Apparently, NESC tables are based on the Kinectrics ARCPRO software. As per the Kinectrics brochure, ARCPRO is a very sophisticated software, which considers both thermal energy radiated by the arc and also heat release due to convective effects. The output of the software includes heat flux gradient curves and spatial heat contours. The brochure states that ARCPRO computations have been verified by live arc testing in Kinectrics High Current Laboratory.

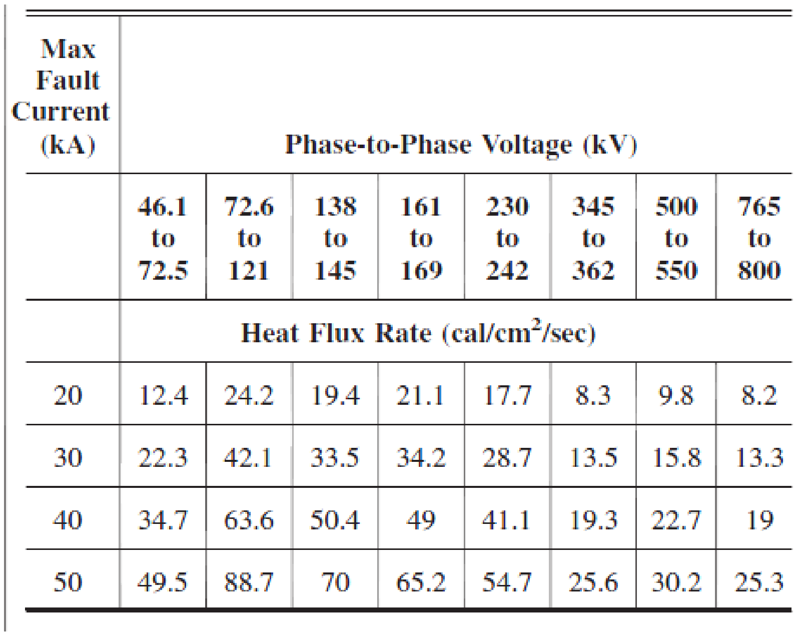
Arc flash hazard calculation results as per the NESC – 2007 are as shown in Table 6 and Table 7. It can be noted that these tables have also been included in the Appendix of NFPA 70E – 2009 edition.

Table 6: NESC – 2007 Arc Flash Table 410-1



Max Fault Current (kA)	Phase-to-Phase Voltage (kV)			
	1 to 15	**15.1 to 25**	**25.1 to 36**	**36.1 to 46**
	Heat Flux Rate (cal/cm²/sec)			
5	4.9	8.7	11.6	14.8
10	12.5	20.8	27.1	34.5
15	22.2	35.6	45.4	56.2
20	34	52.8	66.4	78.7

Table 7: NESC – 2007 Arc Flash Table 410-2



Max Fault Current (kA)	Phase-to-Phase Voltage (kV)							
	46.1 to 72.5	**72.6 to 121**	**138 to 145**	**161 to 169**	**230 to 242**	**345 to 362**	**500 to 550**	**765 to 800**
	Heat Flux Rate (cal/cm²/sec)							
20	12.4	24.2	19.4	21.1	17.7	8.3	9.8	8.2
30	22.3	42.1	33.5	34.2	28.7	13.5	15.8	13.3
40	34.7	63.6	50.4	49	41.1	19.3	22.7	19
50	49.5	88.7	70	65.2	54.7	25.6	30.2	25.3

A footnote in the NESC tables states that “These calculations were derived from a commercially available computer program. Other methods are available to estimate arc exposure values and may yield slightly different but equally acceptable results.”

The conductor (arc) gaps used for the above NESC tables are as given below;

1 to 15kV	= 2 in (51mm)
15.1 to 25kV	= 4 in (102mm)
25.1 to 36kV	= 6 in (153mm)
36.1 to 46kV	= 9 in (229mm)
Above 46.1kV	= Rated Phase to ground voltage divided by 10

A fixed working distance of 15 in (381mm) has been used for voltage up to 46kV. The working distance for voltages above 46kV is the minimum approach distance specified in ANSI/IEEE C2 standard and subtracting two times the assumed arc gap length. It can be noted National Electrical Safety Code (NESC) is supported by ANSI/IEEE C2 standard.

Finally, it can be noted that NESC – 2007 tables essentially provide expected incident energy in cal/cm^2 at a given working distance. However, NFPA 70E tables are still applicable for selection of arc flash protection gear.

Australian Arc Flash Standard – ENA NENS 09

The first Australian national standard for selection, use and maintenance of PPE for arc flash hazards was published by Energy Supply Association of Australia (ESAA) in 2004. ESAA has now been redesignated as Energy Networks Association (ENA). Consequently, ESAA NENS 09 -2004 standard has been redesignated and issued as ENA NENS 09 - 2006.

This standard specifies two equations for the calculation of incident energy, one for copper conductors and another for aluminium conductors. The equation for copper conductors for a phase to ground fault is as given below.

$$HF = 1.2667 \times 10^{-4}\, t\, I_{rms}^{\ 1.12} / r^2$$

where,

HF = Heat Flux or Incident heat energy (cal/cm^2)

t = fault duration (seconds)

I_{rms} = Single phase to ground fault current (A)

r = Distance from arc source (m)

NENS 09 specifies that, heat flux values for two phase to ground and three phase faults are 2 to 3 times the corresponding single phase heat flux value respectively.

Based on the above equation, NENS 09 provides a table of working distances (distance from the arc source) for given values of fault current, fault duration, heat flux value and the required clothing weight and layers for 100% cotton drill material. The table for LV (≤1kV) systems is as shown in Table 8.

Table 8: NENS 09 – Clothing requirements for Phase to Earth Faults

PROS-PECTIVE FAULT CURRENT (Amperes)	FAULT DURATION (seconds)	REQUIRED EQUIVALENT 100% COTTON DRILL WEIGHT [grams per square metre (gsm)]									
		185	245	310	155/ 155	185/ 155	245/155 185/185	245/185 310/155	310/185 245/245	310/ 245	310/ 310
		DISTANCE FROM PROSPECTIVE FAULT [millimetres (mm)]									
1,000	0.1	50	50	45	40	40	40	40	35	30	30
4,000	0.1	120	110	100	90	90	80	80	80	70	70
7,000	0.1	160	150	140	130	120	110	110	100	100	100
10,000	0.1	200	180	170	160	150	140	130	130	120	120
12,000	0.1	220	200	180	170	160	150	150	140	130	130
14.000	0.1	240	220	200	190	180	170	160	150	150	140
16,000	0.1	250	230	220	200	190	180	170	160	160	150
18,000	0.1	270	250	230	220	200	190	180	180	170	160
20,000	0.1	290	260	240	230	220	200	190	190	180	170
25,000	0.1	330	300	280	260	240	230	220	210	200	200
30,000	0.1	360	330	310	290	270	260	240	230	220	220
35,000	0.1	390	360	330	310	290	280	270	260	250	240
ESTIMATED HEAT FLUX [calories/square centimetre (cal/cm^2)]		**10**	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**26**	**28**

A similar table based on the same equation is also provided in NENS 09 for HV (>1kV) systems. The only difference is that the HV table has a fault duration of 0.5s instead of 0.1s.

As per IEEE 1584 case studies, most arc flash incidents in LV switchboards involve more than one phase. For example, the most common incidence involved measuring phase to phase voltage with a faulty voltmeter. Also, as per IEEE 1584, an arcing condition will quickly ionise the surrounding air and results in a three phase arcing fault. Hence, to provide adequate arc flash protection in the case of switchboards, it is necessary to consider three phase faults. It can be noted that NENS 09 does provide for calculation of heat flux for three phase faults. However, the results obtained for three phase faults are not of much use in practice. This is illustrated by the following example.

An example (Clause A5.1 Example 1) has been included in NENS 09 to illustrate arc flash heat flux calculations. However, it is interesting to note that even for this example provided in NENS 09, the maximum specified clothing in Table 8 cannot provide adequate protection for three phase faults. This example considers an 11kV/400V, 250kVA transformer with 5% impedance. This corresponds to a fault current of 7000A on the 400V side of the transformer. As per the calculations, this results in a heat flux of 12 cal/cm2 for fault duration of 0.1s at a working distance of 150mm. This can be verified from Table 8, referring to row 3 and column 2 of clothing weights. As per Table 8, 245 gsm cotton drill clothing provides adequate protection for a phase to ground arcing fault. However, for a three phase fault, the calculated heat flux is

3 x 12 = 36 cal/cm^2. Referring to Table 8, it can be noted that the clothing has been specified only up to maximum heat flux of 28 cal/cm^2.

The example provided in NENS 09 recognises the above problem and provides the following suggestions.

- Use appropriate equipment that will ensure only phase to earth faults are possible.
- Ensure that multiphase faults can only develop at remote distances, so that the selected cloth heat flux with-stand is not exceeded.

Obviously, the above suggestions are not feasible when a person is carrying out tests in a LV switchboard using a voltmeter.

It can also be noted that the example system considers only a 250kVA transformer. However, in a typical industrial site, 11kV/415V transformer ratings are normally 500kVA, 1MVA and 1.5MVA. Many new substations have 2 MVA transformers. Hence, it is not feasible to use Table 8 for arc flash protection at these substations.

Finally, there is a serious anomaly between NENS 09 and NFPA 70E arc flash PPE specification. As per NENS 09 table, adequate protection for 10 cal/cm^2 heat flux is provided by 185 gsm cotton drill clothing. This is the normal every day work wear in Australian industrial sites. However, as per NFPA 70E, incident heat energy of 10 cal/cm^2 requires Hazard Risk Category 3 FR clothing along with arc flash suit hood. This is a huge difference. To the best of knowledge of this author, there has been no serious criticism in the available literature with regard to NFPA 70E arc flash protection PPE specifications.

It can be noted that heat flux equations in NENS 09 do not consider concept of ‘arc current’ which can be much lower than bolted fault currents in LV systems. It is also not clear whether these equations are for ‘open air’ or ‘arc in a box’. NENS 09 does not provide adequate documentation on the research background for the equations specified for heat flux calculations.

In conclusion, major revisions to NENS 09 arc flash protection specification and heat flux calculation equations are necessary before it can be used effectively by Australian industries.

Canadian Arc Flash Standard – CSA Z462

Canadian Arc Flash Standard CSA Z462 has been developed by Canadian Standards Association (CSA) in collaboration with NFPA of United states. Hence, CSA Z462 is essentially an adaptation of NFPA 70E standard. Technical content of CSA Z462 is in conformity with NFPA 70E – 2009 edition.

Conclusion

An overview of various arc flash standards for arc flash protection and arc flash hazard incident energy calculations has been presented.

NFPA 70E is a well recognized standard for specification of arc flash personal protective equipment. This standard has been updated at regular intervals to provide for developments in technology. The latest edition NFPA 70E – 2009 provides simpler and comprehensive technical information on arc flash protection and provides a good overview of arc flash hazard calculations.

Arc flash protection materials specified in NFPA 70E need to be tested as per the procedure specified in ASTM F 1959 to establish the Arc Thermal Performance Value (ATPV) of the material.

Canadian Standard CSA Z462 has been developed based on NFPA 70E and the technical content of Z462 is in conformity with NFPA 70E – 2009.

At present IEEE 1584 – 2002 is the widely used standard for arc flash incident energy calculations. However, there is considerable criticism in Australia with regard to its methodology and test set up. Further research on IEEE 1584 arc flash calculations will be carried as collaborative effort of NFPA/IEEE with an invited member from Australia in the Technical Committee. Hence, it is expected that future revisions will address the criticism of existing IEEE 1584 methodology.

In Australia, ENA NENS 09 provides guidelines for selection of arc flash PPE and also equations for arc flash heat flux calculations. However, this standard needs to be revised before it can be used effectively by Australian industries.

AS 3000 – 2007 edition has incorporated specifications for the design of switchboard enclosures to contain internal arcing faults. This specification is not relevant for arc flash calculations and arc flash PPE when the switchboard is open and the personnel are exposed to energized parts. Hence, details of AS 3000 – 2007 revisions have not been included in this paper.

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