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ABSTRACT

A robust, reliable, and safe electric power system is essential to productive industrial operations. Plant personnel must maintain and operate the electric power system without exposure to dangerous electrical hazards. The arc flash that accompanies electrical system faults and operator errors exposes workers to high temperature plasma, pressure shock waves, toxic gases, and blast fragments. Arc flash can be deadly to personnel, cost millions of dollars to repair, and idle industrial facilities. Without arc flash analysis and mitigation strategies, workers must wear cumbersome personal protective equipment that can resist maximum arc energy or work only on de-energized equipment. This paper surveys the computation methods and mitigation technologies used to quantify and control arc flash hazards in industrial power systems. A review of analysis techniques compares algorithms used currently to determine incident energy. A presentation of current mitigation technologies identifies their advantages and disadvantages in the control of incident energy. A final section proposes future directions for research and development on arc flash safety.

INTRODUCTION TO ARC FLASH HAZARDS

Arc flash is an electrical fault (short circuit) that propagates through air producing high temperature plasma. Arc flash temperatures exceed 5000° F creating an intense light, a pressure shock wave, toxic gases, and blast fragments. Arc flashes produce concentrated radiant energy that can cause severe burns to unprotected workers (Fischer, 2004). The numerous physical hazards and high energies associated with arc flash make it a dangerous and costly industrial accident. Proper system design and work rules can minimize the impact of an arc flash incident on both workers and equipment (Hill, Bruehler, & Chmura, 2004).

Arc flash analysis determines the incident energy exposure workers encounter at various locations in an industrial electric power system. Incident energy values determine the level of personal protective equipment (PPE) that workers require to prevent serious burns. Analysis methods must produce reliable values of arc energies that do not grossly overestimate actual conditions. Over protecting workers limits their ability to operate and maintain electrical systems efficiently, but under protection exposes them to unnecessary risks. Arc flash mitigation uses modified electrical equipment, protective device settings, and work rules to restrict worker exposure to high energy levels. These modifications reduce the required level of PPE. The goal of arc flash analysis and mitigation is to provide a safe work environment while operating and maintaining industrial electrical systems with minimal disruption.

Arc flash is a significant safety hazard addressed by the Occupational Safety and Health Administration (OSHA) standards since its inception in the 1970's. These standards evolved over the last 33 years into NFPA 70E-2004 and IEEE 1584-2002. One standard, NFPA 70E-2004, sets protective clothing requirements, defines the flash-protection boundary, and includes calculation procedures for incident energy. The second standard, IEEE 1584-2002: "Guide for Performing Arc-Flash Hazard Calculations", presents mathematical models and formulas derived from empirical data for determining incident energy levels. In 2002, the National Electrical Code (NEC) included labeling requirements for electrical equipment to warn workers of the arc flash hazard and list protective clothing requirements (Ammerman, Sen & Nelson, 2007). All these standards have the same goal of reducing worker injuries due to arc flash burns.

Arc flash accidents are high-cost/low probability events that make cost justifications for detailed studies and extensive retrofitting difficult (Fischer, 2004). A review of OSHA incidents shows that human error causes up to 80 percent of electrical incidents. (Inshaw, & Wilson, 2005) The policies and procedures included in arc flash standards give industrial managers the framework to promote safety by defining the training, tools, warning labels, and PPE required to minimize injuries and comply with OSHA guidelines. Even though arc flash accidents are unlikely, they are costly when they occur. Analyzing and mitigating the arc flash hazard makes economic sense when the analysis includes the costs of lost production, equipment repair, and company liability. Arc flash analysis and mitigation schemes limit personal injury and electrical equipment damage to reduce repair and lost production costs (Wilson, Harju, Keisala, & Ganesan, 2007).

Arc flash standards set PPE guidelines based on the incident energy levels near the arc flash. These guidelines define how workers should be clothed to protect them from burns (Das, 2005). The threshold limit is 1.2 cal/cm^2 , the onset of a second-degree burn. Table 1 shows arc thermal performance values (ATPV) of protective clothing classes required for increasing levels of incident arc flash energy. The standards do not define PPE for incident energy levels greater than 40 cal/cm^2. Incident energy levels at or above this level require work on de-energized electrical equipment. These guidelines are only for burn protection and do not address other hazards of arc flash.

Table 1. Protective Clothing Classes

Description	Class (HRC)	Weight (oz/yd^2)	ATPV (cal/cm^2)
Untreated cotton	0	4.5-7	N/A
Flame retardant (FR) shirt and pants	1	4.5-8	5
Cotton underwear plus FR shirt and pants	2	9-12	8
Cotton underwear plus FR shirt, pants and coveralls	3	16-20	25
Cotton underwear plus FR shirt, pants, coveralls and multilayer flash suit	4	24-30	40

(Excerpt from Table 3-3.913 NFPA 70E-2004. ATPV is the incident energy that just causes the onset of a second degree burn.)

Arc mitigation schemes should increase worker safety without compromising the reliability of the electrical system. Practical mitigation schemes may temporarily sacrifice system reliability to lower incident energy levels and relax worker PPE requirements. The goal of arc flash analysis and mitigation is to find incident energies throughout the industrial power system and then reduce these values to the lowest level. This will allow workers to maintain and operate plant electrical systems without excessive PPE. High classes of PPE restrict mobility and visibility. The heavy weight fabrics and the full flash suit specified for class 4 PPE locations rapidly fatigue workers due to retained body heat (Doan, 2009).

ARC FLASH ENERGY COMPUTATION METHODS

Industrial electric power systems are typically radial connected and fed from medium voltage (15 kV class) systems. Transformers reduce this voltage to secondary medium voltages (4.16 and 2.4 kV) for operating large motors and further distribution to low voltage motor control centers (MCC's). Industrial low voltage is typically 480 V. Industrial power systems have low impedance and operate at low voltage resulting in high fault currents and arc energies. Figure 1 shows a one-line diagram of a simple industrial power system with a three-phase fault located at point F1. Current standards require arc flash analysis and hazard classification labeling throughout industrial power systems.

System voltage, fault current levels, time, and proximity are all factors in determining arc flash intensities. (Buff and Zimmerman, 2008) Relays, fuses, molded-case (MCCB) and low-voltage power circuit breakers (LVPCB) provide fault protection in most industrial power systems. In radial systems, fault current magnitudes diminish as the fault location moves further from the source. System designers achieve protection coordination by selecting devices that have time-current characteristics that intentionally introduce delay in device operation.

Figure 2 shows fault current decay in a radial system as a function of distance from a source. Proper protection coordination requires that the highest current levels at breaker 1 have the longest time delay (Mason, 1956).

ARC HAZARD ANALYSIS USING NFPA-70E-2004

Both arc flash standards include algorithms for computing incident energy. The detailed algorithms in each standard require short circuit calculations and protective device settings to determine incident energy levels. The NFPA 70E-2004 standard includes tables of common tasks and simple formulas to determine the PPE category without detailed calculations.

The first step in the NFPA-70E-2004 algorithm is to determine the task personnel will perform. The next step is to calculate the flash protection boundary and determine if work on energized equipment falls within this distance. This standard uses the product of bolted three-phase fault current and the total clearing time to determine the flash protection boundary. If the time-current product is less than 300 kA-cycles then the flash-protection distance is 4 feet. Equations 1 and 2 compute the flash-protection boundary for electrical system and transformer faults respectively.

$$D_c = \sqrt{2.65 \cdot MVA_{bf} \cdot t} \tag{1}$$

$$D_c = \sqrt{53 \cdot MVA \cdot t} \tag{2}$$

where:

D_c = distance that will just cause a second-degree burn on a person (ft),

MVA_{bf} = bolted three-phase fault power (MVA),

MVA = power rating of transformer (MVA). For transformers with power ratings below 750 kVA, multiply transformer power rating by 1.25

t = total clearing time (Sec)

Once the flash boundary is computed, one of three methods finds the necessary level of PPE for workers within this distance. Figure 3 shows the basic steps in these methods. Methods 1 and 2 are tabular techniques for finding the hazard risk category (HRC). Method 1 uses Table 130-7(C)(9)(a) in the NFPA 70E-2004 to associate common work tasks with an HRC (0-4). Method 2 uses a simplified table that determines the appropriate level of PPE. These tabular methods can substitute for more detailed arc flash analyses but they must be applied carefully.

Figure 1. Typical Industrial Power System Showing Protective Devices.

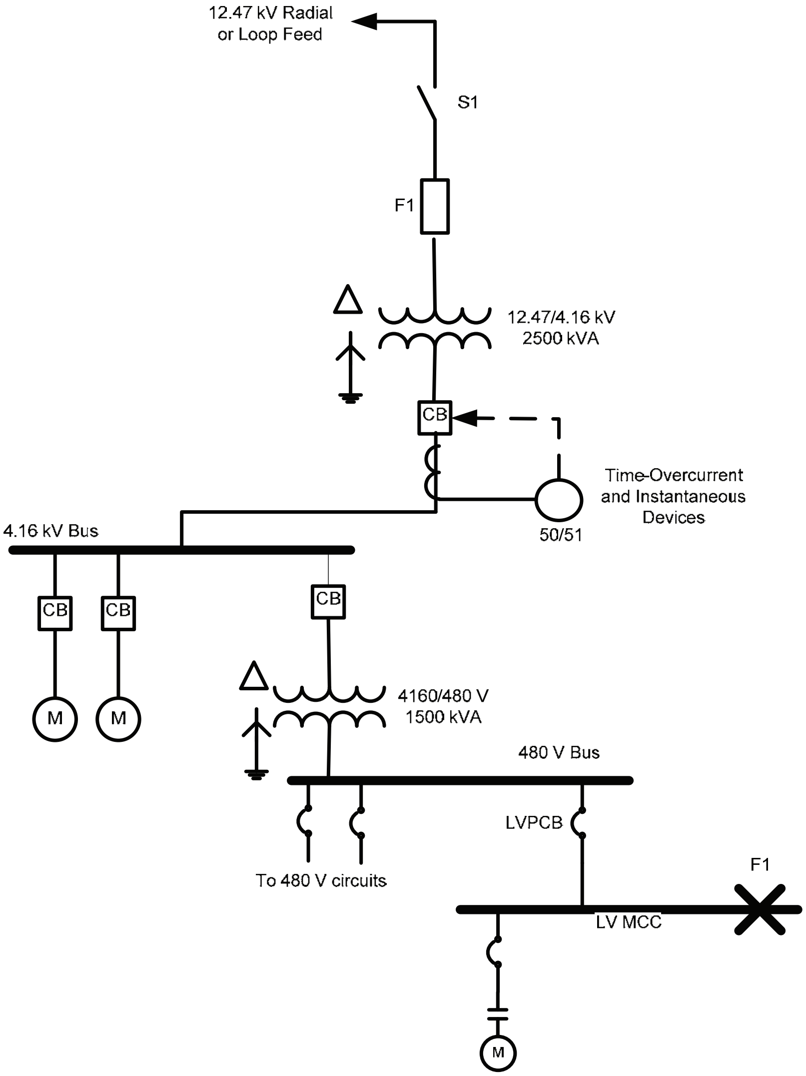


Figure 2. Current-Distance Relationship in Radial Systems and Associated Coordination Curves.

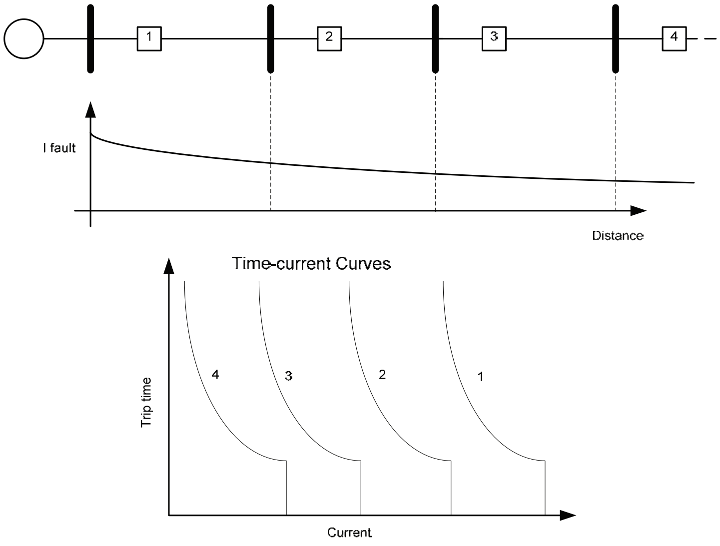
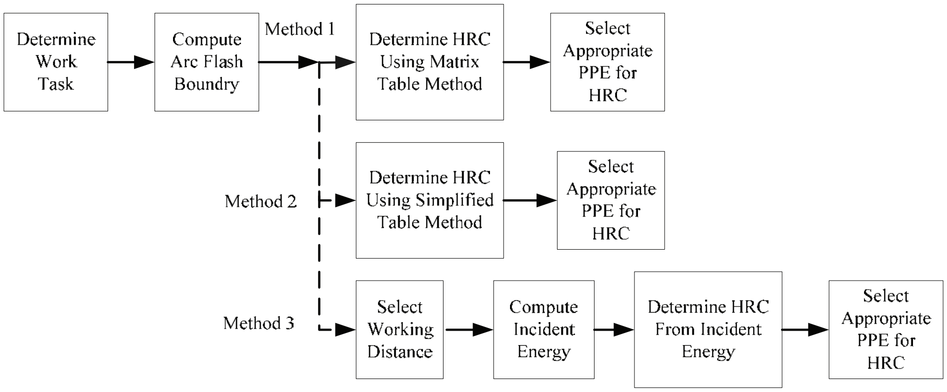


Figure 3. Steps for Finding the HRC Using the NFPA-70E-2004 Standard.



The tables only apply to listed tasks under the specified assumptions and cannot be extrapolated to other situations and circumstances (Graham, Hodder, & Gates, 2008). These assumptions place limits on fault current and protective device operating time. Analysis using method three is necessary when fault currents and device operating time violate these limits.

The third method for conducting an arc flash analysis in NFPA 70E-2004 requires detailed system data but gives the most precise results. This algorithm finds the incident energy level in calories/cm^2. The resulting incident energy then determines the PPE category from Table 1. The steps for detailed arc flash analysis using the NFPA 70E-2004 standard are:

1. Use Equations (1) or (2) to determine the flash-protection boundary.
2. Determine the minimum worker approach distance to electrical equipment for the designated task. If the minimum approach is within the boundary then continue with the analysis.
3. Find the bolted three-phase fault current at the work location. Use maximum and minimum arc-sustaining current values for the remaining steps. (NFPA 70E-2004 defines minimum arc sustaining current at 480V as 38% of available fault current.)
4. Find total fault clearing time for the values in step 3.
5. Determine if work will be done in open air or inside an enclosure. Use the appropriate formula below to compute incident energy.

Open air: $$E_{MA} = 5271 D_A^{-1.9593} t_A (0.0016F^2 - 0.0076F + 0.8938) \quad (3)$$

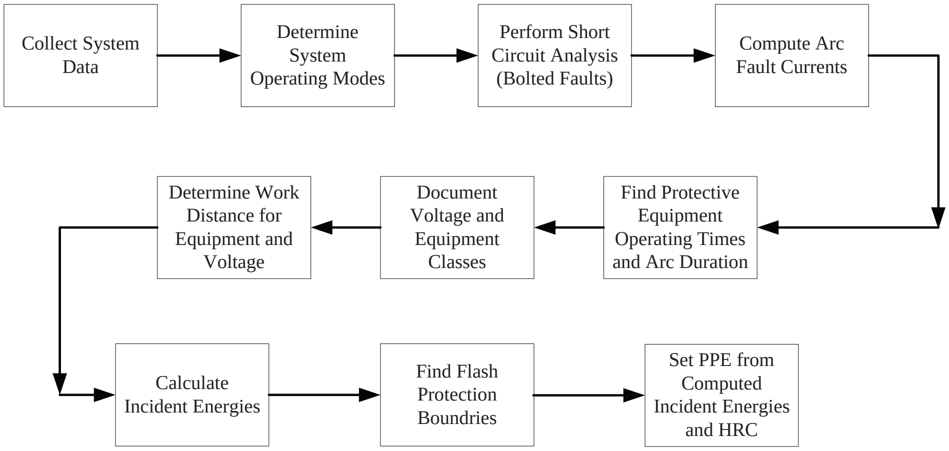
Enclosure: $$E_{MB} = 1038.7 D_B^{-1.4738} t_A (0.0093F^2 - 0.3453F + 5.9675) \quad (4)$$

Where: E_{MA} = incident energy in open air (calories/cm^2)
E_{MB} = incident energy for enclosed box (calories/cm^2)
D_A = distance from electrodes (inches)
t_A = maximum arc clearing time (Sec)
F = short circuit current (kA, range 16-50 kA)

6. If incident energy calculated from above is less than 1.2 Cal/cm^2, flame retardant clothing may not be required to prevent burns although protection may be needed for other hazards (Graham, Hodder, & Gates, 2008).
7. Determine the HRC and select the proper level of PPE from the incident calculations.

Calculations for the NFPA 70E-2004 standard produce conservative results for incident energy that tend to over-protect workers (Ammerman, Sen, & Nelson, 2007). Equations (3) and (4) are based on theoretical concepts and models derived from a small test data set. Electric arcs are complex phenomena that are difficult to model precisely (Stokes & Oppenlander, 1991), The standard is based on research conducted using simplifying assumptions (Lee, 1982) that may not be suitable in general application.

Figure 4. IEEE 1584-2002 Algorithm for Finding Arc Flash Hazards.



ARC HAZARD ANALYSIS USING IEEE-1584-2002

The IEEE 1584-2002 standard presents another method for detailed arc flash analysis. Figure 4 shows the steps in this algorithm with the following explanation.

1. Gather power system and electrical equipment data.
2. Review system topology to determine different operating modes.
3. Calculate minimum and maximum fault currents and X/R ratios at work locations.
4. Find arc fault currents. This value is different from fault currents due to arc resistance. Equations (5a) and (5b) compute this value for system voltages under 1 kV.

$$\log_{10}(I_{arc}) = K_A + 0.662\log_{10}(I_{BF}) + 0.0966V\ldots \\ \ldots + 0.000526g + 0.5588V\log_{10}(I_{BF}) - 0.00304g\log_{10}(I_{BF}) \qquad (5a)$$

$$I_{arc} = 10^{\log_{10}(I_{BF})} \qquad (5b)$$

Where: K_A = -0.153 for open air or -0.097 for enclosure
I_{BF} = bolted three-phase fault current (kA)
V = system voltage, (kV)
g = electrode gap (mm)

5. Use protective device characteristics to find total arc clearing time.
6. Determine working distance to energized equipment.
7. Equations (6a) and (6b) determine normalized incident energy at each work location. The equations are normalized to an arc time of .200 second and a working distance of 610 mm.

$$\log_{10}(E_n) = K_1 + K_2 + 1.081\log_{10}(I_{arc}) + 0.0011g \qquad (6a)$$

$$E_n = 10^{\log_{10}(E_n)}\ (\mathrm{J/cm^2}) \qquad (6b)$$

Where: K_1 = -0.792 for open air and -0.555 for enclosure
K_2 = 0 for grounded and -0.113 for ungrounded systems

Applying specific case values of clearing time and working distance converts this value to actual incident energy values. Distance exponents for different types of equipment model energy dissipation with distance (Buff & Zimmerman, 2008).

The following formula computes the actual incident energy for specific arcing time and personnel distance.

$$E = 4.184C_f E_n\left(\frac{t}{0.2}\right)\left(\frac{610^x}{D^x}\right) \qquad (7)$$

Where:
E = incident energy (J/ cm^2)
E_n = normalized incident energy (J/ cm^2)
C_f = calculation factor
t = arcing time (seconds)
D = distance from arc point to person (mm)
x = distance exponent from table in standard

8. Determine flash protection boundary using equation (8)

$$D_B = \left[4.184C_f E_n\left(\frac{t}{0.2}\right)\left(\frac{610^x}{E_B}\right)\right]^{\frac{1}{x}} \qquad (8)$$

Where:
D_B = Boundary distance from arc (mm)
E_B = Incident energy level at boundary (J/ cm^2). This is usually set to the value of 5 J/ cm^2, which is the burn threshold energy.

9. Select proper PPE category based on incident energy and flash protection boundary.

The IEEE 1584-2002 method is quite complex and requires extensive calculations. The standard comes with spreadsheet software for making these calculations.

The equations in IEEE-1584-2002 derive from fitting extensive test data statistically to a model. The relationship of the variables produces a good fit to the data but also results in anomalous results for certain ranges of parameters (Wilkins, Allison, & Lang, 2005).

Both detailed analysis techniques presented above use approximations and simplifications of the problem to arrive at the incident energy. The electric arc in open air is difficult to represent mathematically (Stokes, & Oppenlander, 1991). A mathematical model must include randomness, arc interruptions, and plasma characteristics to represent accurately an electrical arc in air. The standards use a combination of theoretical models (Lee, 1982) and laboratory tests. The algorithms omit contributions from induction and synchronous motors. They also use symmetrical fault current values that ignore DC offsets. The existing algorithms rely on symmetrical, three-phase fault current, but most faults start as line-to-ground faults and progress into a three-phase fault. Significant energy dissipates during the transition that is damaging to equipment and dangerous to personnel.

COMPARISON OF METHODS AND CONTINUING RESEARCH

Tables 2 and 3 compare the methods of determining HRC presented in the NFPA-70E-2004 and IEEE-1584-2002 standards based on data requirements, required variables and computational effort and limitations.

Table 2. Arc Fault Analysis Comparison

Analysis Method	Data Requirement	Computational Effort	Limitations
NFPA-70E-2004 Method 1 - Matrix Table	Low	No Calculation Required	Must not violate given assumptions. Does not cover all work tasks
NFPA-70E-2004 Method 2 - Simplified Table	Low	No Calculation Required	Must not violate given assumptions. Does not cover all work tasks.
NFPA-70E-2004 Method 3 – Detailed Analysis	Moderate	Moderate	Must apply energy formulas within specified fault current ranges. Need total device operating time and work distance
IEEE-1584-2002 Arc Hazard Analysis	Moderate	High	Voltage range: 208V to 15 kV. Current range: 700 – 106,000 A

Table 3. Comparison of Required Variables for Arc Analysis Methods

Required Variable	NFPA-70E-2004 Method 1	NFPA-70E-2004 Method 2	NFPA-70E-2004 Method 3	IEEE 1584-2002
System Voltage, V, V (kV)	X	X	X	X
Fault Current, F, I_{bf} (kA)	X	X	X	X
Arcing Time t_A, t (seconds)	X	X	X	X
Working distance (mm)			X	X
Open/enclosed Equipment				X
Conductor gap, G (mm)				X
System Grounding factor, K				X
Calculation factor, C_f				X
Distance Factor, x				X

The two tabular methods presented in the NFPA standard require no calculations to find the incident energies but do require information from fault and protection studies. The tabular methods only apply within specified limits of operating time and fault currents, which restricts their application. The detailed analysis from the NFPA standard computes arc flash energies with some additional data requirements above the tabular methods. This method requires working distances, protective device operating times and fault currents. The method requires two calculations for each work location and only applies to fault currents ranging from 16 – 50 kA.

The IEEE standard covers a wide range of voltages and fault current levels but requires several computational steps to determine the incident energy levels. This method requires conductor gap distances, system grounding, and working distance values along with fault and protection data to compute the incident energy. The IEEE method requires six computations to find incident energy and boundary distances for a single work location.

Figures 5 and 6 compare the two computations methods from the NFPA and IEEE standards for a range of fault currents on a 480 volt solidly grounded system. Working distance is 24 inches and conductor gap distance 25 mm. The total protective device operating time is 0.3 seconds. Figure 5 compares the incident energy calculations for a fault current range of 16-46 kA. The method produces nearly the same results over the fault current range of 20-30 kA. Beyond this range, the NFPA method over-estimates the incident energies with respect to the IEEE method. This over-estimate leads to conservative values of HRC and tends to overprotect workers.

Figure 6 compares the arc flash protection boundaries produced by the NFPA and IEEE methods. The boundary values from the IEEE computations are all significantly larger than corresponding value from the NFPA methods. This gives the IEEE method a more conservative result with respect to worker safety. The flash protection boundary distance sets the minimum approach distance of unprotected workers to the electrical work zone. The NFPA method uses the flash protection boundary to determine if any further analysis must take place. If personnel perform work within this distance, the standard specifies application of one of the three methods to determine the HRC and level of PPE required.

Several researchers address issues related to the analysis algorithms presented in the current standards. The algorithm in IEEE 1584-2002 is complex and requires a computer spreadsheet provided with the standard for effective use. Ammerman, Sen, and Nelson (2007) conducted a sensitivity analysis on the IEEE 1584-2002 equations. The results were simplified regression equations that are ideal for prescreening work locations. Wu (2008) addressed the absence of contributions from rotating machines in medium voltage arc flash analysis by developing modified equations that include fault current decay factors. These equations compute lower values of incident energy than the IEEE 1584-2002 method. The equations find fault current magnitudes that decay over time which reduces arc energy.

Time domain analysis gives detailed solutions of faults and includes factors omitted from the standards. Wilkins, Allison, and Lang (2005) developed a time domain model that includes current limiting fuses. Their work modeled the arc with a non-linear V-I characteristic. Computations using this model combined with system time domain formulas give circuit currents, voltages, powers, and energy. The model results correlate well with experimental data.

Figure 5. Incident Energy Computation Comparison.

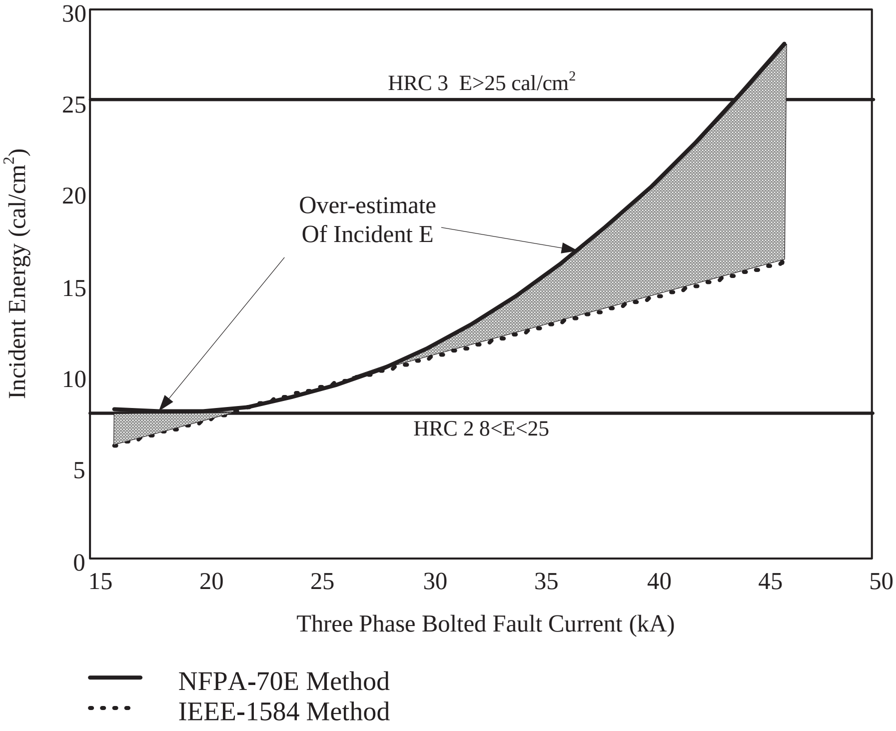
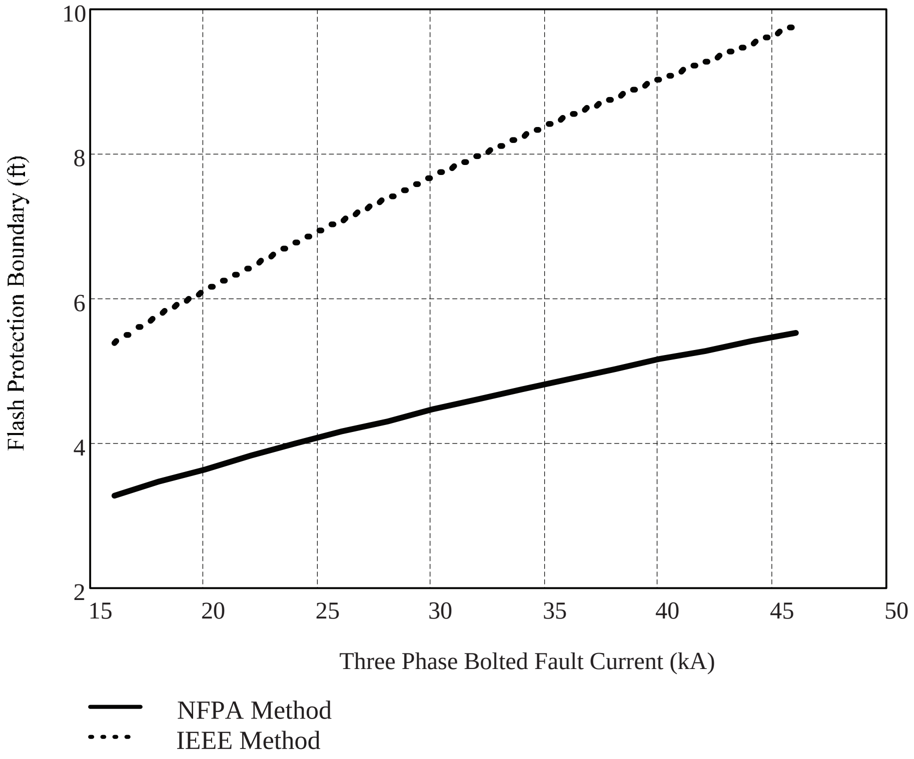


Figure 6. Comparison of Arc Flash Boundaries Produced by NFPA and IEEE Methods.



ARC FLASH MITIGATION TECHNIQUES

Arc flash energy depends on three key factors: system voltage, fault current magnitude and arc time. Industrial power system owners have limited control over the first two factors, leaving only arc time as a controllable variable. Protective relays, fuses, LVPCB, and MCCB are the devices commonly used to provide fault protection in industrial power systems. These devices all have an inverse time relationship where higher currents cause the devices to operate faster (Gregory, Lyttle, & Wellman, 2003).

A properly designed protection scheme will clear system faults with minimum interruption to electric supply. This requires a time delay between protective devices that increases as the device nears the fault current source. A properly coordinated protection system has the longest time delays nearest the utility source, which is where the highest fault currents occur. Figure 2 shows the relationship between fault current magnitudes and protection system time delay. High fault currents produce large incident energies and require the most stringent level of arc flash PPE.

Table 4 summarizes arc flash mitigation techniques commonly applied in industrial power systems (Buff & Zimmerman, 2007). Most of these techniques reduce arc flash incident energy exposure by shortening the protection system response time to the fault current. Bus differential relaying, fast bus tripping, current limiting fuses, and arc flash detectors all reduce incident energy by shortening the tripping time for a fault current. Arc flash detectors respond to the high intensity light emitted from arc flashes and give the fastest response of all these schemes. Current limiting fuses can reduce fault-clearing times to 8.3 ms or less, but only within a specified range of fault currents (Doughty, Neal, Macalady, Saporita, & Borgwald, 2000).

Other techniques in Table 4 modify work rules or equipment settings to reduce the energy exposure a worker encounters. Increasing the distance between the worker and live electrical protective equipment reduces the incident energy as the square of the distance. "Hot sticks," remote control tripping, and racking of breakers are all methods that reduce arc flash hazards.

Table 4. Arc Flash Mitigation Techniques

Technique	Advantages	Disadvantages
High impedance grounding (Wilson, Harju, Keisala, & Ganesan, 2007)	Limits fault currents on line-to-ground faults. Lowers fault currents.	Lowering fault currents without changing protection settings slows device response and leads to higher arc energies. Has no impact on three-phase faults.
Current-limiting fuses (Doughty, Neal, Macalady, Saporita, & Borgwald, 2000).	Very fast clearing time. Less than 8.3 ms. Interrupting fuse adds resistance and lowers arc current.	Fuses are only current-limiting within specific range. Limited number of current-limiting fuse types.
Arc resistant switchgear (Hopper & Etzel, 2008)	Special design redirects arc blast away from workers.	Must be included in design. Expensive to retrofit.
Reducing relay coordination times (Buff & Zimmerman, 2008)	No changes in equipment or design. Uses existing protective devices	Expenses are associated with coordination study. Cost high relative to trip time decrease. Could be unpractical for LVPCP's and MCCB's due to trip time uncertainty.
Increase working distance (Inshaw & Wilson, 2005)	Requires no changes in electrical equipment. Reduces arc energy as the square of the distance change.	May be impractical for some cases. Expenses associated with special tools and equipment. Longer times required to complete tasks due to working at distance.
Arc flash detectors (Inshaw & Wilson, 2005)	Very fast tripping times. (2-9 ms) Respond to high-intensity light produced by arcs. Operates independently of overcurrent protection.	Must be supervised by instantaneous tripping device. Only applies to enclosed switchgear. Requires communication between flash detectors and existing protection.
Bus differential relaying (Buff & Zimmerman, 2008)	Fast response (< 24 ms). Operates for any type of fault.	Requires additional relays, current transformers and wiring. Expensive.
Fast bus tripping (Buff & Zimmerman, 2008)	Uses overcurrent protection and a communication channel to block downstream faults but applies fast tripping to bus faults. Maintains sensitivity and security of protection.	Requires communication channels and special relays. Expensive
Enable special protection settings during maintenance	Operators enable instantaneous tripping. Low cost modification to existing systems.	Risk of larger system outages due to higher relay sensitivity during maintenance.

Modifying system protection settings either permanently or temporarily to reduce operating times also reduces the arc flash energy (Buff & Zimmerman, 2008). The use of maintenance settings on protective devices gives instantaneous (<20 ms) tripping of breakers while workers are near energized electrical equipment. Reducing device coordination times can also reduce incident energy but may produce small reductions relative to the cost.

Lowering fault currents by using high impedance grounding can increase rather than decrease arc energies. Reduced fault currents increase the response time of inverse time protective devices. This increased time causes increased incident energies that can lead to greater worker hazards. This technique must be accompanied by a detailed analysis of protective device coordination times.

New or redesigned industrial power systems can employ new equipment technologies that reduce arc flash hazards. Arc resistant switchgear redirects arc blasts away from workers. Installing main breakers in MCC's adds another level of protection and reduces fault-clearing times, resulting in lower incident energy levels (Hopper & Etzel, 2008). Incorporating arc flash safety into new designs and retrofits of existing systems gives the best results with the least cost.

FUTURE TRENDS IN ARC FLASH ANALYSIS AND MITIGATION

The goal of arc flash analysis and mitigation is to provide workers with enough protection to prevent second-degree burns but to avoid over-protecting workers so that they do not encounter a greater risk of heat stress and other injuries due to poor visibility and limited movements. The current standards use algorithms based on experimental data acquired from laboratory tests. These algorithms include simplifying assumptions to make the problem tractable and tend to over-estimate incident energy levels. This results in selecting higher PPE categories that over-protect workers. A time domain representation that uses non-linear time-varying resistance to model arcs can give more precise estimates of arc currents and incident energies.

Computer simulation programs such as the Alternative Transients Program (ATP) (Canadian/American EMTP User Group, 2008) and MatLab with Simulink (Mathworks, 2009) allow engineers to build complex time-domain representations of electrical networks. These tools also have control systems modeling capabilities to represent protective device behaviors. It is possible to create a time domain models of an arc flash and system protective devices using these tools, but field-testing must verify the results. Work should focus on the evolution of line-to-ground faults into three phase faults so that fault exposure time can be minimized.

Increasing the working distance is a simply way of reducing the incident energy in an industrial electric system. Secure wireless operation of breakers would allow maintenance workers to stay outside the flash protection boundary while operating energized electrical equipment with incident energies greater than 40 cal/cm^2. These devices will be part of the next generation of electrical maintenance tools.

Many of the mitigation techniques must have communication channels to transfer tripping and trip-blocking information to other parts of the electrical system. Innovations in secure wireless communications between protective devices will help reduce the costs of implementing these schemes. Using ad hoc wireless networking would allow low cost expansion of protection schemes with less set-up time.

Continued development of digital relays can extend to LVPCB's and MCCB's that have greater capabilities and more flexibility than today's models. Application of low-cost microcontrollers to produce alternatives to time-overcurrent protection in industrial power systems will give designers more choices in designing and retrofitting protection schemes. Implementing impedance relays using this technology in low voltage systems can achieve high speed tripping over 80 to 90 percent of distribution feeders at low cost. Hall-effect current sensors that do not saturate when subjected to high currents can take the place of current transformers with reduced cost and greater flexibility in retrofitting.

Technology cannot take the place of worker training and skill. Reducing the high percentage of electrical accidents attributed to personnel errors must be a priority. All maintenance personnel and system operators must have continuing training on electrical safety procedures and current industry practices regarding locking and tagging of industrial electrical equipment for de-energized service. Worker training should emphasize completing tasks in the safest way, not the easiest or fastest. Industrial maintenance supervisors and management must make electrical safety a priority. Industries should maintain electrical system diagrams in an "as-build" or "as-operating" state to prevent accidents due to undocumented system changes. These drawings should be available to workers as needed. Communication between maintenance, operations and engineering personnel on the current state of the electrical system should promote a safe and efficient industrial operation and reduce the risk of arc flash accidents.

This paper surveys the available literature on arc flash hazard analysis and mitigation techniques. This topic produces a large number of articles and research each year. This paper covers the main topics and a fraction of the ongoing work in the field. A comprehensive review of all topics and research is beyond the scope of this paper.

CONCLUSION

Arc flash accidents are very dangerous industrial safety hazards that subject plant personnel to life-threaten levels of energy. These energy levels can produce severe burns leading to death for those within close proximity of the arc flash. Two industry standards address these hazards and give guidelines for computing incident energy, selecting personal protective equipment, and labeling equipment to alert workers of arc flash dangers. Different levels of analysis exist for computing arc flash incident energy. The algorithms presented in the standards derive from test data and tend to produce conservative values. The goal of arc flash analysis and mitigation is to limit worker energy exposure through the use of appropriate levels of protective equipment. Overly conservative values lead to over-protected worker who are at risk of other injuries due to heat, visibility, or mobility. Future work on arc flash analysis should include further development of time-domain models of system faults supported by high-power test data. New models should produce better estimates of incident energy values, which will provide workers with adequate protection without requiring excessive PPE. Designing industrial power systems for arc flash safety is the least expensive method of complying with current safety standards. Continued development of innovative low-cost, digital communication and protective devices will give plant management lower cost alternatives for retrofitting existing systems to achieve compliance.

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