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An Electrical Arc-Flash Hazard Analysis Primer: How the proper use of engineering controls can significantly reduce the severity of electrical burn injures in your facility

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Introduction

The problem of electrical workers being injured or killed by electrical arcs and blasts is the most significant safety issue in the electrical industry today. The principal hazards associated with arcs and blasts include thermal burn injuries and physical trauma from the blast concussion and flying projectiles caused by partially melted components being propelled by the force of the blast.

It is noteworthy that "engineering for safety" is a relatively new development in the Electrical Engineering realm. Obviously, Electrical Engineers considered Safety in the past but Arc-Flash Hazard Analysis (AFHA) represents one of the first times were Safety IS the focus rather than an ancillary consideration in the engineering process.

It is also important to understand that the focus of AFHA is to mitigate hazards and not merely to select Flame Resistant (FR) clothing. Many Electrical Engineers have used the methodologies discussed in this paper to calculate the "heat" associated with electric arcs but then used that information only to recommend that Electrical Workers wear higher levels of FR clothing. The appropriate approach would be to first exhaust reasonable attempts to make engineering changes to the system to reduce the "heat" and THEN select the appropriate FR clothing for the Residual Risk that cannot be adequately controlled through engineering interventions.

History of AFHA

The electric utility industry was the first non-academic group to study Arc-Flash (AF) hazards when they noted that high voltage workers often received the most severe burns from their clothing igniting and continuing to burn long after the initiating arc had extinguished. In particular, "man-made" fibers such as Polyester, Nylon and Rayon were known to melt and "stick" to the worker's skin following an AF and this resulted in burns many times worse than had the injured worker been wearing no clothing at all.

Duke Power Company began high-energy testing of fabrics in 1986 following a high-voltage AF accident. Duke Power management initially tried to find studies relating electrical arcs to burn injuries but they noted that most studies related to house fires or other fires caused by common combustibles. The problem with these studies was that the heat produced from a house fire increased very slowly in comparison to that caused by an electrical arc. The temperatures of an arc could reach values many times hotter than the surface of the Sun in less than 0.5 seconds and this very rapid heat gradient had never before been studied in relation to burn injuries.

The Duke Power studies revealed the following:

1. The heat produced by AF was unique in its magnitude and heat gradient. Electric arcs were second only to the LASER as the hottest heat source on earth.
2. Man-made fibers would support combustion and should not be worn by electrical workers.
3. The Force produced by AF could “breakthrough” normal-weight clothing resulting in the clothing being blown-off of the worker’s body. This resulted in the clothing providing no insulating value to the worker.
4. “Layering” clothing provided the best method to insulate workers from AF hazards. The studies also revealed that NO man-made fibers could be worn even underneath 100% “natural fiber” clothing such as cotton, wool, silk or linen. The studies revealed that man-made fibers would ignite and burn even underneath natural-fiber clothing.
5. “Heavy Weight” clothing provided the best breakthrough protection for electrical workers. Clothing made of fabrics of at least 11 oz./yd would generally stay intact and continue to insulate workers during AF events. (1)

Much of the subsequent federal Electrical Safety regulations were based upon the Duke studies, although the Duke studies were apparently influenced by the paper: “The Other Electrical Hazard: Electrical Burns and Blasts” published in 1982 by Ralph Lee (2).

The first federal safety standard for electrical workers was promulgated by the Occupational Safety and Health Administration (OSHA) in 1991. The Electrical Safe Work Practices standard (29 CFR 1910.331-.335) (3) largely ignored the Arc-Flash Hazard (AFH) issue focusing instead on electrical shock injuries.

In 1994, OSHA promulgated the Electric Power Generation, Transmission and Distribution standard (29 CFR 1910.269) (4) which specifically identified the AFH issue for the first time. This standard, known euphemistically as the “Utility Maintenance Standard” (UMS) because of its focus on maintenance activities, based its AFH recommendations on the Lee paper and the Duke Power high energy research.

In 1995, the National Fire Protection Administration (NFPA) Electrical Safe Work Practices (70E) standard recognized arc-flash hazards and established “Limits of Approach” and “Flash Protection Boundary” requirements requiring that electrical workers use FR Personal Protective Equipment (PPE) when coming closer than voltage-dependent distances from exposed energized parts. The NFPA 70E is not part of the OSHA regulations as it is a “consensus” standard written by a private organization, the NFPA. However, OSHA can cite organizations for violations to the NFPA 70E via the General Duty Clause of the OSHact (5).

In 2002, the Institute of Electrical and Electronics Engineers (IEEE) published the: “IEEE Guide for Performing Arc-Flash Calculations” paper which has become the primary reference for AF Hazard Analysis (AFHA) in the United States. The IEEE Guide included recommendations from the 1584 committee that was charged with studying AF hazards and the Guide is now often referenced as the “1584 Method” for AFHA.

Although the 1584 method represents a significant step forward in electrical safety, the methodology has certain inherent deficits that prudent engineers must take into account when evaluating electrical systems. For example, the 1584 methodology measured only the radiant heat associated with the arc and ignored the “molten plasma” caused by melted conductors, insulation and part of the enclosure during an arc-blast. The heat associated molten plasma is thought to comprise as much as 10 percent of the total heat in an arc-blast (6). Therefore, it can be correctly inferred that most calculations using only the 1584 methodology are understated by a value up to 10 percent.

In 2002, the NFPA 70E added a “tabular method” that provided a simplified method for selecting FR PPE based upon voltage classifications, class of equipment and task-specific criteria. The tabular method was derived from the IEEE Guide and can only be used on systems within certain Fault Current and System Protection parameters.

In 2004, the NFPA 70E-2004 formally adopted the IEEE AFHA methods. The National Electrical Code (NEC), also known as the NFPA 70, adopted the IEEE AFHA methodology in 2002 and required that equipment with AF hazard potential to be “field marked” (110.16) to warn electrical workers of the AF hazards. The labeling requirement subsequently was enhanced to include information on Incident Energy levels and the Flash Protection Boundary. Similar text was also added to the NFPA 70E-2004 document (400.11) as well.

Numerous papers have been published in the last 15 years that amplified Lee’s work and suggested approaches to managing AF hazards in the work place. This paper will provide an overview of the AFHA process and will highlight important considerations that Electrical Engineers should consider when protecting Electrical Workers in the work place. Before discussing this topic further, the reader must understand the following terms:

1. Arc Clearing Time: The time from the onset of the arcing current to the moment the arc is extinguished. The clearing time is comprised of three separate variables; the time it takes for the protective device to “sense” the fault, the mechanical operating time of the protective device (circuit breakers or fuses) and the time it takes for the protective device to extinguish the arc.

2. Arcing Fault Current: A fault current (See definition #9) flowing through an electrical arc plasma, also called arc fault current and arc current.

3. Arc-In-A-Box: The estimated Incident Energy for an arc in a cubic enclosure with sides of 20 inches.

4. Arc Rating: The maximum Incident Energy resistance demonstrated by a material (or a layered system of materials) prior to break-open or at the onset of a second-degree skin burn. Arc Rating is normally expressed in calories per square centimeter.

5. Available Fault Current: The electrical current that can be provided by a serving utility and facility-owned generation devices and large electrical motors, considering the amount of impedance in the current path.

6. Bolted Fault Current: A short circuit or electrical contact between two conductors at different potentials in which impedance between the conductors is essentially zero.

7. Electrical Hazard: A dangerous condition in which inadvertent contact or equipment failure can result in shock, arc-flash burn, thermal burn or blast.

8. Exposed: Capable of being inadvertently touched or approached nearer than a safe distance by a person. It is applied to parts that are not suitably guarded, isolated or insulated.

9. Fault Current: A current that flows from one conductor to ground or to another conductor through an abnormal connection (including an arc) between the two.

10. Flame Resistant (FR): The property of a material whereby combustion is prevented, terminated or inhibited following the application of flaming or non-flaming source of ignition, with or without removal of said flaming source.

11. Flash Hazard Analysis: A method to determine the risk of personal injury as a result of exposure to incident energy from an electrical arc flash.

12. Flash Protection Boundary: An approach limit at a distance from live parts that are un-insulated with which a person could receive a second-degree burn. This is defined as Incident Energy levels of 1.2 cal/cm^2 or more.

13. Incident Energy: The amount of energy impressed on a surface, a certain distance from the source, generated during an arc event. Incident Energy is measured in joules per square centimeter or calories per square centimeter.

Overview of the AFHA Process

Perhaps the best starting place for discussion of engineering controls is with the engineers themselves. Any engineer who will attempt an AFHA will likely need additional training. AFHA integrates both Electrical Engineering and Safety Engineering. Unless the Electrical Engineer performing AFHA is fluent with proper methods of Hazard Analysis and Systems Safety principles, they will be at a deficit when determining appropriate methods to address Safety issues in an AFHA.

A question often arises as to whether an effective AFHA requires that it be conducted by a degree Electrical Engineer. I believe the answer to that question is an unequivocal “yes.” Further, the person conducting AFHA must have great depth of experience in Power Systems because there are many occasions where the AF calculations will provide erroneous results and the engineer must have enough knowledge and experience to identify when reasonable results are produced or when investigation is needed to identify why an erroneous value was produced during calculations.

The necessity for conducting AFHA is established because the heat generated by an electrical arc often results in fatalities or permanently disabling injuries to workers. Therefore, there are few opportunities to "learn from previous mistakes" in the electrical business and the premium is placed on anticipating and controlling AF hazards before they result in an accident. Studies have shown each arc-fault to be a "unique" event (7) that could not be recreated (due to the complexity of the variables involved) and therefore studied. This makes devising systems to protect Electrical Workers from AF injuries a daunting task for Electrical Engineers.

The AFHA Process Defined

An AFHA consists of 4 distinct engineering functions, including:
Stage 1: System Modeling
Stage 2: Data entry and validation
Stage 3: System Analysis
Stage 4: Reporting and Recommendations
A brief description of each phase follows.

Stage 1: System Modeling

Given that all subsequent analysis of the project hinges on the accuracy of the front-end information (GIGO) it is critically important to accurately capture the electrical system in a commercially-available AFHA software. This step involves physically gathering data relative to the system components and settings on electronic system protective devices such as Power Circuit Breakers, protective relays and fuses.

The initial evaluation captures the facility electrical system in its "normal operating state" (As Built) which includes the normal position of bus ties, generator operation and feeder contribution from the Utility.

Stage 2: Data Entry

Stage 2 includes populating the AFHA software with the needed information to predict system function in both normal operation and during faulted conditions. An added benefit of Stage 2 is that an accurate schematic diagram of at least the main feeders of the facility is created as a natural output of the study.

From a practical standpoint, Stages 1 and 2 constitute about 2/3 of the total time involved in an AFHA. Further, the graphical representation of the facility (schematic diagram) must be verified before proceeding to the Analysis process because the software program uses the diagrams in engineering calculations.

Stage 3: Analysis

The Analysis section includes evaluation of the system from several perspectives, including:

1. Short Circuit Analysis: The amount of Short-Circuit Current (SCC) generated by the system during faulted conditions at each "node" (location) in the facility. This information is valuable for ensuring protective devices are properly rated to interrupt the available short circuit current and also for selecting the properly sized grounding cables. SCC is mostly a function of the Mega-Volt-Amperes (MVA) ratings of the source generators and transformers from the Utility company, however, many modern industrial

customers have extremely large internal generation systems (>50 MVA) and AFHA must take the internal generation capabilities into account when performing AFHA.

2. Protective Device Duty Analysis: One key element of the SCC analysis is a report known as the "Protective Device Duty Analysis". This report compares the capability of protective devices (fuses, circuit breakers) to interrupt SCC to which it is subjected. In cases where the SCC exceeds the interrupting rating of the protective device, a "through-fault" results which means the protective device operates but is unable to interrupt the flow of SCC. The result is the same effect as not having a protective device in the circuit and the SCC must then be interrupted by the next protective device in series with the system "upstream" toward the source. This results in much slower arc-clearing times which in turn translate into far greater Incident Energy exposures for Electrical Workers. See the Coordination discussion below for more detail.

3. Coordination Analysis: Coordination analysis involves evaluating the Time Current Curves (TCC) of the protective devices to ensure that the electrical system will clear faults in an orderly or "coordinated" manner. A TCC refers to the speed at which a device will "clear" SCC as a function of the amount of SCC to which it is exposed. In general, the higher the SCC, the faster the protective devices will operate. This reality often explains why systems with low SCC can actually have MORE Incident Energy because the time an arc continues to "burn" determines how much heat eventually develops.

The Coordination study evaluates two scenarios that will later appear in reports. The first scenario evaluates the coordination of the current configuration (the "As Built" Case) of the system. The second scenario evaluates the system once the recommended engineering changes have been implemented (Revised Case). The "recommended engineering changes" can involve any combination of the following:

a) Reducing trip times on adjustable circuit breakers

b) Using Current-Limiting fuses

c) Reducing fuse sizes of non-Current-Limiting fuses

d) Replacing fuses with other styles of fuses that have different TCC characteristics

e) Changing Protective Relay settings on systems where an electronic relay actuates a separate circuit breaker. These systems are far more expensive but provide maximum flexibility for engineering interventions because many different relays can be connected to a single circuit breaker. This means the protective systems can be "smarter" than simply sensing magnetism or heat as is the case in a simple thermal-magnetic circuit breaker found in a home.

f) Inserting additional protective devices in series with existing devices. Often the use of Motor Overloads in series with fuses can result in much lower values of Incident Energy because fuses can be set to interrupt only SCC while relying on the overload sensors to interrupt "overloaded" conditions.

4. Incident Energy Calculations: AFHA is always a delicate “balancing act” between safety and reliability. The focus is to optimize Safety while maintaining Reliability. The normal approach to making Incident Energy calculations is to use commercially available software programs that have essentially “automated” the use of the IEEE 1584 Arc Calculation spreadsheet.

The most impressive use of this software is in the area of adjusting System coordination. The engineer can adjust an individual protective device and any related system elements simultaneously update with new values. This allows the engineer to “test” different scenarios and receive instantaneous results. Needless to say, the AFHA software is worth the price in terms of man-hours of engineering time.

Stage 4: Reporting

The Reporting stage of an AFHA typically includes 5 sections:

1. Tabular data from the study: It is very important to provide tabular data for each section of the report because doing so allows critical review by other engineers and allows others to catch data entry mistakes in equipment labeling, etc.

2. Protective Device Duty Analysis: Identifies devices at or near their interrupting duty ratings. Some software programs produce an “Equipment Duty Report” which is synonymous with PDDA.

3. Incident Energy calculations: Highlights areas where incident energy levels exceed 10 cal/cm^2. We recommend using a10 cal/cm^2 threshold because studies have shown that 3rd degree burns result from exposures to 10.7 cal/cm^2 (unprotected skin) or more.

4. Recommended Engineering Interventions: Including revised breaker/relay settings when those changes will result in satisfactory outcomes. This section also includes a cost-benefit section for recommended interventions that necessitate either equipment replacement or significant retro-fitting of equipment to lower Incident Energy exposures.

5. Equipment Labeling. The National Electrical Code (110.16) requires that all equipment with AF hazard potential (i.e. >1.2 cal/cm^2) be “field marked” to warn Electrical Worker of the hazardous condition. This label normally includes the Incident Energy calculated value and other important safety information needed to safely work on the equipment.

It is important to note that the science AFHA is still evolving and is therefore a somewhat imprecise endeavor. The first page of the IEEE 1584 Guide for performing AFHA clearly explains that the authors assume that future studies will address deficits in the 1584 methodology. This reality requires that AFHA be conducted by an experienced engineer who can properly interpret the results of the calculations and offer recommendations of System modifications that will result in better protection of workers. In many cases, circumstances may warrant that protective systems “exceed minimum requirements” due to extenuating circumstances such as equipment configurations that place workers in enclosed spaces such as manholes or vaults.

For example, an 8 cal/cm^2 arc that occurs in an open space is far less dangerous than the same arc occurring in a manhole. This is so because the manhole has limited volume and the arc-energy will more quickly precipitate a significant rise in temperature when there is a smaller volume of air to “heat” so to speak. The 1584 calculations do provide for calculating an “arc in a box” which is construed to mean a cubical box with 20” sides. However, in situations where equipment configurations place workers in confined areas but not technically fitting the “arc in a box” definition, the wise engineer will take the calculated values as “only one data point” in their overall decision-making process regarding proper design of protective systems.

Avoiding “Traps” In AFHA

There are several common “traps” that inexperienced engineers (or non-engineers) performing AFHA have experienced over the years and a discussion of the more common traps appear below.

1) Hyper-focus on High Voltage (>600 volt) Systems: There is a general belief that HV systems present a much greater threat from the AF perspective than do Low Voltage (<600 volt) systems. The tabular approach in the NFPA 70E contributes to this misunderstanding because the tables in the 70E require high levels of FR clothing for HV systems and relatively little FR clothing for LV systems. There are numerous occasions when LV systems represent significantly HIGHER Arc-Flash Hazards (AFH) to workers than do HV systems. One reason for this is that most HV work is performed using Insulated sticks that can range from 4 feet in length to over 35 feet in length. The increased Working Distance when using insulated sticks often renders the actual Incident Energy exposures to values far less than working on LV circuitry.

   Another reason to avoid “HV hyper-focus” relates to “employee exposure” to HV systems. In the Commercial/Industrial realm, most Electricians or Maintenance Workers only interface with HV systems perhaps once per year. Many organizations will use a “phased approach” to AFHA due to costs and they almost invariably devote scarce resources to the HV system first. This is the antithesis of what should be done. By far, Electrical Workers interface with LV systems more often than HV systems and the focus of AFHA should first be to mitigate AFH on the LV system in most organizations.

2) Modeling the System Based Upon Voltage Levels: A dangerous practice in AFHA is to model the electrical system to only a certain voltage-level rather than to model the system based upon AF Hazards. The most common practice is to stop at the 480 volt level of the system, assuming that lower levels of the system do not present an AF hazard. Experience teaches that some of the highest Incident Energy in a facility is on the 208 volt side of 480v./208v. dry transformers. There are literally thousands of examples where there were Incident Energy levels of only 0.1 cal/cm^2 on the 480 volt side of the transformer and Incident Energy levels of as high as 600 cal/cm^2 on the 208 volt side of the same transformer.

3) Stopping Analysis when Low Incident Energy Levels are Achieved: In many cases, once Incident Energy has been reduced to acceptable levels at one level of the system, it is often true that lower levels of the system <u>on the same circuit</u> do have the same or lower Incident Energy levels. However, a good practice to follow when performing AFHA is to “sample” downstream circuits just to ensure downstream circuits do in fact have low Incident Energy levels as expected.

   A recommended way of “sampling” would be to model each style of circuit breaker or fusible element on lower level circuits. The reason for this approach is that SCC levels usually decrease as one moves to lower levels of the system. The Clearing Times on Protective Devices will increase in response to the lower SCC levels. In some cases, Incident Energy levels can actually increase when SCC levels dip below the level where a protective device will operate. This results in arcs that can last for several seconds and this often translates into dangerously high Incident Energy levels.

4) Blindly Accepting Computer-generated Results: As previously discussed, only competent Electrical Engineers should perform AFHA because the software is not perfect and it will occasionally produce erroneous results. In these cases, it takes someone with both experience and Engineering training to first recognize the error and then "hand-calculate" the correct results. Another difficult step requires the engineer to re-integrate the correct results into the software program for use with the rest of the study.

   As example of when AFHA software can produce erroneous results relates to interconnected (a.k.a. "looped") systems. Looped systems can present a challenge for AFHA software because algorithms in the software may "look" for certain mathematical results when determining the "source" for a fault. This can also happen when generators are involved. In these cases, erroneous results can sometimes be produced by the software because these situations usually require more than one Protective Device to operate in a specific order to clear the fault. If the software "picks" the wrong source or if it doesn't properly calculate the "sequence of events" in the fault-event, it will produce erroneous results.

   It is also important to note that AFHA software programs often do not include comprehensive "reasonability check" systems to verify that inputted results are "reasonable" for the system being modeled. Once again, the responsibility for catching these situations rests with the engineer doing the analysis. Clearly, not having a properly qualified person doing the analysis increases the likelihood of erroneous results.

Conclusion

The hazards represented by electrical arc-blasts have been identified as a significant hazard for many years. Previously, the preferred method for protecting Electrical Workers from Arc-Flash hazards was through the use of Personal Protective Equipment such as Flame Resistant clothing, face shields, etc. However, many accidents revealed that Incident Energy levels could easily reach values for which there was no PPE capable of providing adequate protection and it was necessary to reduce Incident Energy to manageable levels through the use of Engineering Controls.

The use of formal engineering studies such as AFHA represents a significant improvement for protecting Electrical Workers from Arc-Flash hazards in the workplace. The IEEE 1584 methodology has emerged as the standard for AFHA in America since it's publication in 2002. Although the 1584 methodology is very powerful, there are inherent weaknesses in the methodology that qualified Engineers must consider when determining the best methods to protect Electrical Workers.

There are a number of commercially-available AFHA software programs that make AFHA significantly easier. These programs allow an engineer to easily test different coordination scenarios which results in better Systems Analysis and improved recommendations. Automating the many calculations needed to perform AFHA reduces mathematical errors and again improves the end product.

In the final analysis, Safety Professionals and Engineers alike must remember that AFHA is about <u>people</u> and not engineering calculations or OSHA regulations. A miscalculation by an engineer or errors in data gathering <u>can result in death of a human being</u>. Therefore, all parties must maintain great diligence in ensuring that every facet of AFHA is performed to the highest standards possible.

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