ARC FLASH CALCULATIONS

An Important Tool in Fire & Electrical Accident Investigations

BY JOHN C. PFEIFFER, P.E., LOUISVILLE, KENTUCKY—The annual average number of fires due to electrical failures was more than 81,000 between 1994 and 1998[1]. These fires are the result of insulation breakdown, high heat due to bad connections and arcs, to name a few. Arcs produced by an electrical fault have been studied for a long time but little has shown up to allow us to calculate the amount of energy produced by an arc for a specific incident. In the 1980s Ralph Lee published an IEEE paper tilted *The Other Electrical Hazard: Electric Arc Blast Burns*[2] that basically quantified the energy produced by an electrical arc and its effect on persons in the vicinity of the arc. From his data, standards have been developed relating to electrical safety and the protection of personnel while working on energized electrical equipment.

- *NFPA 70E-2004 Standard for Electrical Safety Requirements for Employee Workplaces*[3].
- *IEEE Standard 1584-2002 Guide for Performing Arc Flash Hazard Calculations*[4].

As a person involved in fire and accident investigation, I have been limited in my ability to equate an apparent arc event to the amount of heat produced and thus the amount of damage or injury that has resulted. But now, there are recognized safety standards that can be extended to fire/accident investigations. These calculations are not simple but can be accomplished by an electrical engineer who has experience in the area of power distribution systems and with the aid of software. What follows is a brief description of what can be calculated and what is basically required in these calculations. I will begin with a brief introduction to Arc Flash.

What is Arc Flash?

Arc Flash is the result of a rapid release of energy due to an arcing fault between a phase conductor and any of the following: another phase conductor, a neutral conductor or a ground. This type of fault is an accidental connection of energized electrical conductors and/or even the earth and are created by mechanical failures, failures of insulation, or accidentally while a person is working on an energized electrical system. This type of short circuit is the result of a brief contact of energized conductors, such as a metal part falling onto an electrical circuit. The initial short is of relatively low impedance but the impedance begins to increase as the arc is produced when the air becomes the conductor. These arc faults are generally limited to systems where the voltage is in excess of 120 volts. At 120 volts and below, the fault will normally not sustain an arc. An arc fault is similar to the arc obtained during electric welding and the fault has to be manually started by something creating the path of conduction or by a failure, such as a breakdown in insulation.

The cause of the short normally burns away during the initial flash and the establishment of highly conductive plasma then sustains the arc fault. The plasma will conduct as much energy as is available and is only limited by the impedance of the arc and the overall electrical system impedance. This massive energy discharge burns the bus bars or wiring, vaporizing the copper or aluminum and thus causing an explosive volumetric increase. The arc flash is a blast and is conservatively estimated as an expansion in volume of 40,000 to 1. Vaporizing copper produces a volume increase of 67,000 to 1[5] and vaporizing water has a volume increase of 1,670 to 1 as it boils. This fiery explosion devastates everything in its path, creating deadly shrapnel and droplets of molten metal flying in many directions.

The arc terminal has a temperature estimated to be in excess of 35,000° F[6] with plasma of vaporizing metal having a temperature of 23,000° F. Unbelievably hot since the sun's surface temperature is only 10,000° F and an atomic bomb, after 0.3 seconds reaches only 12,600° F.

The high heat and volume expansion produces a pressure wave that can literally knock a person over, producing sound at a level that can damage hearing. It's a fireball with shrapnel exploding outward. Injury and fires resulting from such an event is primarily the result of the radiant heat produced and by the molten metal rather than by the arc itself.

The arc fault current that is produced during an arc flash is usually much lower than the available bolted fault current that occurs during a direct short circuit. Thus, it is often below the rating/setting of the protecting circuit breaker or fuse. Unless these protective devices have been selected to handle the arc fault condition, they normally will not trip or trip fast enough to minimize the full force of an arc flash. The amount of energy produced at the point of the arc is a function of the voltage and current present as well as the time that the arc is sustained. And this time is the most important part of this energy equation, every second matters greatly. The transition from the arc fault to the arc flash takes a finite time, increasing in intensity as a pressure wave develops. The challenge to protect against an arc flash is to sense the arc fault current and shut off the current in a timely manner before it develops into a serious arc flash condition.

Example

During a fire at a 50,000 sq. ft. facility, a maintenance mechanic dies. The worker suffered severe head injuries and third degree burns over large portions of his body and was found five feet from an electrical panel that was heavily damaged. This area is believed to be the point of origin. The front of the panel was laying several feet away and other equipment in the area was destroyed. There was evidence of flammable liquids in the area along with storage containers for the liquids. During the investigation it was determined that the dead worker had been in a severe argument with another worker several days before. Could this be murder that was covered up by arson or another cause? An arc flash current (I_{AF}) equaling 17,300 amps was calculated based upon 31,100 amps of bolted fault current (I_{sc}). The fuse protecting the panel was determined to have opened after four seconds based upon the fuse's trip characteristic curve. Calculation of the arc flash incident energy, 18 inches from the panel, it was determined to be 191 cal/cm^2 and produced with a blast force of 117 lbs/ft^2. The radiant heat produced, along with the force produce, was found to be sufficient to severely burn the victim and to have propelled the victim several feet where he hit his head on nearby equipment. The molten metal from the arc flash ignited the nearby flammable liquids causing the fire to spread. After presenting this evidence, the fire was ruled accidental.

So, what is the significance of the numbers? An arc flash would have sufficient force to propel a person several feet and the heat was sufficient to cause severe second and third degree burns. The upper body of an average man is about 2.2 sq. ft. This would result in 257 pounds of force hitting him in the chest. Next, radiant heat of 1.2 cal/cm^2 is enough to produce second degree burns and 4 cal/cm^2 will ignite a cotton shirt. 191 cal/cm^2 is lethal.

The data used in this example was taken from an actual accident. However, the circumstances of the accident were considerably different. The results was that an electrician died from burns, 40 percent of his body with second degree burns and 20 percent of his body with third degree burns. This type of accident could occur due to the maintenance mechanic testing an energized conductor in the power panel. A slip of a tool is all it takes if sufficient energy is available.

The Resultant Calculations

The IEEE (Institute of Electrical and Electronic Engineers) standard provides the formula for the calculation of arc fault energy expressed in calories per cm^2 or joules per cm^2. Further, the energy levels can be calculated at any distance from the point of an arc. These calculations are used today as part of electrical safety programs to determine the amount of Personnel Protection Equipment (PPE) required to protect a worker who has to work on energized electrical systems.

These same calculations can be applied to fire and accident investigation to determine the amount of heat energy a person or object is subjected to at a distance from the arc event.

The calculations consist of three steps:

1. Calculate the Bolted Fault Current at the point of the arc flash. From the bolted fault current, the Arc Fault Current is calculated.
2. Determine how fast the up-stream circuit overcurrent protective device opens based upon the calculated arc fault current, (i.e. circuit breaker or fuse).
3. Based upon the calculated bolted fault current and protective device opening time, the incident energy can be calculated at a set distance from the point of the arc.

Determining the bolted fault current is the most time intensive task to performed and must be performed using actual data for the equipment located in the facility involved in the accident. The data required consists of items such as transformer size, rating and impedance, wiring types and distances run to name a few. There are a number of software products that help to speed the process of performing these calculations, particularly for large facilities. Manual methods can also be used and are defined in various IEEE publications.

Once the bolted fault current is determined, its value can be entered into a spreadsheet that can be obtained from the IEEE to calculate the arc fault current.

Arc Fault Current[7]:

For V < 1 kV,

$\text{Log } I_a = K + 0.662 \text{ Log } I_{bf} + 0.0966\, V + 0.000526\, \text{Gap} + 0.5588 (\text{Log } I_{bf})\, V - 0.00304 (\text{Log } I_{bf})\, \text{Gap}$

Once the arc fault current is determined a time-current characteristic curve for the over current protective device, (i.e. fuse or circuit breaker), is used to determine how fast the protective device will open. This time along with the distance to the point of interest is used to calculate the Incident Energy and the resulting force.

Incident Energy (Cal/cm^2)[8]:

$E_{mb} = (1038.7\, D_b^{-1.4738}\, t_a)\ (.0093\, F^2 - .3453\, F + 5.9675)$

D_b = Distance from arc in inches
t_a = arc duration in seconds
$F = I_a$ or Arc fault energy

Incident Force[9]:
$\text{Lbs/ft}^2 = (11.5 \times I_a/1000) / (\text{Distance in Ft})^{0.9}$

Significance

Arc flash energy at levels equivalent to the example will not be found in the average residential home and in general 120v circuits do not have sufficient capacity to generate large arcs. However, as a facility increases in size from that of an average residence to 50,000 sq. ft and larger, the potentials do exist. As a rule of thumb, you might start to consider arc flash energies where you have electrical services supplied by a transformer of 500 kVA or larger. This is true for 120/208V services as well as 480v services. Why base this on transformer size? Transformers act as a choke points in electrical systems. That is, they only let so much current flow even under severe situations. The limiting factor is the impedance of the transformer.

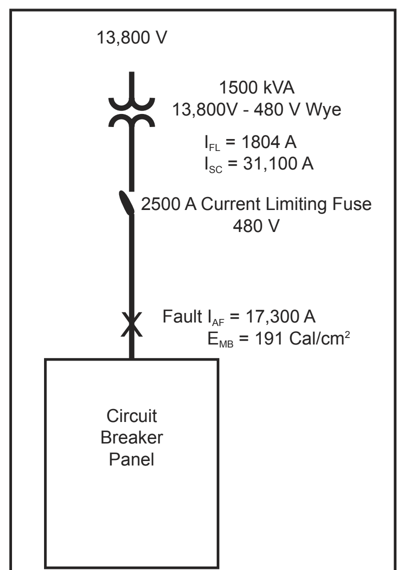

Figure 1: Arc Fault

Today, when unusual heat patterns or force exist near large electrical panels or other large electrical systems, the investigator may want to use arc flash calculation methods to better understand the forces at work surrounding an arc flash. These calculations would also be useful in analyzing injury potential due to someone closing a circuit breaker and having the circuit breaker arc or explode. It's a means of quantifying arc faults in terms of heat, force and the extent of burns that can result.

Definitions:

Bolted Fault—Short circuit current resulting from conductors at different potentials becoming solidly connected together.

Arc Fault—Short circuit current resulting from conductors at different potentials making a less than solid contact. This results in a relatively high resistant connection with respect to a bolted fault.

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