Arc Flash in the Water/Wastewater Industry: No Longer an *Emerging* Issue

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Abstract

In the "project background" portion of its February 2006 Request for Proposal for Arc Flash Analysis, a county municipality – one that includes a major U.S. city – states:

> *The County "is taking steps to meet the highest standards for electrical safety in the workplace, established in National Fire Protection Association (NFPA) 70E, at each of its wastewater treatment facilities…In updating and building new facilities in the past three years, the County has been incorporating NFPA 70E compliance into the designs. Existing facilities that have had no electrical modifications since NFPA 70E was established need to be brought into compliance."*

While water treatment and wastewater treatment facilities have sometimes been viewed as being outside the requirements of new arc flash standards, this perception is rapidly changing. Through the years, requirements for employee safety in the workplace have come under increasing government scrutiny. In particular, worker electrical safety is one of the latest and is still evolving. Although perceived as largely a liability issue, there are benefits to the w/ww industry of an electrical safety program that includes an arc flash hazard analysis. This paper will present some of the technical portions of the safety requirements and the potential benefits.

The paper begins with an overview of the regulatory and technical requirements behind safe work electrical practices including a brief description of the applicable standards. The focus will be on facility electrical equipment and the requirement for an arc flash hazard analysis. Some of the misconceptions associated with the analyses are presented. Specific issues from recent analyses will be discussed with particular emphasis on w/ww facilities. Finally, the benefits of an electrical safety program are explained, including how an arc flash analysis can be applied to minimize liability, increase safety, protect equipment and processes, and minimize downtime.

Introduction

The National Fire Protection Association (NFPA), the National Electric Code (NEC), the Occupation Safety & Health Administration (OSHA) and others are implementing the current standards for arc flash analysis. The complete study includes a short-circuit analysis, an overcurrent device coordination study and an arc flash hazard analysis.

The short-circuit analysis evaluates the adequacy of the electrical distribution equipment in the facility based on the maximum available short-circuit current at its location. The overcurrent device time-current coordination analysis determines the suggested settings and, where appropriate, the ampere ratings and types for the electrical power system protective devices to achieve the desired system protection and electrical service continuity goals.

The arc flash hazard analysis establishes the flash protection boundary around electrical equipment within which a worker exposed to an arcing fault would expect to receive 2nd degree burns if not adequately protected. The analysis also determines the incident energy levels at specific working distances from equipment, which can be used to select appropriate personal protective equipment (PPE) to be worn when working within the flash protection boundary.

Over the past two decades the electrical industry has begun to recognize arc flash as a safety hazard in addition to electrical shock for personnel working near exposed energized conductors. The hazard was further quantified through controlled testing of 600V systems that included the effect of an enclosure in reflecting heat from the arc toward the opening of the enclosure. PPE for the arc flash hazard is the last line of defense. The protection is not intended to prevent all injuries but to mitigate the impact of an arc flash upon the individual, should one occur.

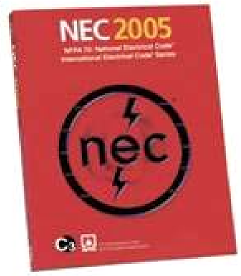
In many cases the use of PPE has saved lives or prevented injury. Adequate PPE may be required during load interruption, during the visual inspection that verifies that all disconnecting devices are open, and during the other steps necessary for placing a circuit in an electrically-safe condition, also known as lockout/tagout. Adequate PPE is always required during the tests to verify the absence of voltage after the circuits are de-energized and properly locked out/tagged out. It must be emphasized that the only way to prevent electrical injuries and fatalities is to ensure that equipment is de-energized and in an electrically safe condition. But even this act subjects the worker to potential hazards.

Background

Regulatory

The federal law that initiated worker safety was the Occupational Safety and Health Act of 1970. Title 29, Code of Federal Regulations, part 1910.132(d)(1) requires the employer to assess the workplace for hazards and the need for personal protective equipment. The law does not provide specific details or include specific standards to be met. The intent was for national consensus standards to form the specific details.

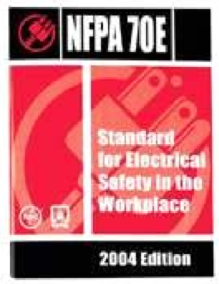
No such standard existed until the National Fire Protection Association (NFPA), publishers of the National Electrical Code, created a committee to develop such a standard. The result was NFPA 70E, Electrical Safety Requirements for Employee Workplaces. The first edition was published in 1979 but the standard was not comprehensive until the 1995 and later versions.



National Electrical Code

Governs Electrical Installations –

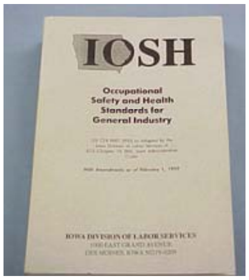
"Equipment shall be field marked…"



NFPA 70E-2004

Governs Employee Workplace Safety –

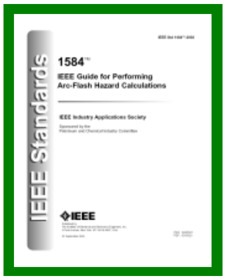
"Electrical safety standard that would serve OSHA's needs."



OSHA 29 CFR Part 1910

OSHA Standards (Iowa Shown) –

"Electrical safety related work practices shall be employed"



IEEE 1584 -2002

Guide for Performing Arc Flash Hazard Calculations –

"Based on extensive test data"

The current version of NFPA 70E (2004) covers training, electrical safety programs, lock-out/tag-out, hazard analysis, work permits, protective boundary criteria, personal protective equipment, and maintenance. The standard has become the de facto definition of compliance.

The National Electrical Code (NEC) in article 110.16 requires that many types of electrical equipment be field marked to warn of potential arc-flash hazards. It does not specify what information should be on the label. Current industry practice is to list the personal protective equipment (PPE) required and approach distances defined in NFPA 70E.

The Occupational Safety and Health Administration (OSHA) does not enforce electrical workplace hazard requirements. Like other worker safety provisions, they do not routinely look for conformance unless there has been a serious injury or death or there has been notification of unsafe work practices.

Technical

The severity of the hazard related to an arcing fault is measured by the amount of energy that an arc delivers to an exposed worker. Calculation of this "incident energy", which is commonly measured in calories per square centimeter (cal/cm^2) or joules per square centimeter (J/cm^2), provides a basis for selection of proper PPE, including flame-resistant clothing, flash suits, arc hoods, and the like. Another important value is the "flash protection boundary" and is defined as the distance from a fault source inside which the incident energy level exceeds 1.2 cal/cm^2, a level that can cause second degree burns on exposed skin.

Both the incident energy and the flash-protection boundary vary based on many parameters. Among the most important factors are:

- System voltage.
- Arcing fault current level.

- Distance from a worker to the fault source.
- Duration of the arcing fault.

As such, the hazard level depends on many system variables, including equipment type, prospective bolted fault currents, and time-current characteristics of the upstream protective devices. An analysis of the potential arc flash hazard at a given system location should be performed so that workers can select and use appropriate levels of PPE.

NFPA 70E-2004 defines five categories of protective clothing based on the degree of protection provided by each class or Hazard Category (HC), and is shown in the PPE table below. PPE is assigned an Arc Rating (cal/cm^2), which defines the "maximum incident energy resistance demonstrated by a material."

Hazard Category	Clothing Description	# of Layers	Minimum Arc Rating of PPE (cal/cm^2)
0	Untreated natural fiber clothing	1	N/A
1	Fire Resistant Shirt + Fire Resistant Pants	1	4
2	Cotton Underwear + Cat 1	2	8
3	Fire Resistant Coverall over Cat 2	3	25
4	Multi-layer flash suit over Cat 2	4	40

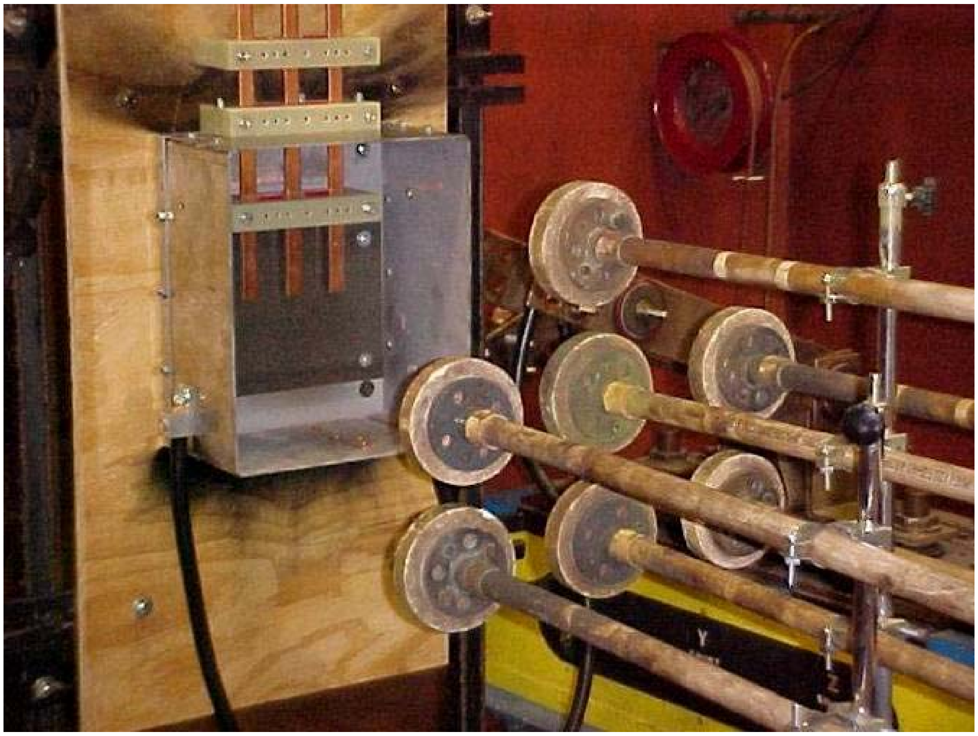
Personal Protective Clothing categories are based on the layering effect of untreated natural fiber and flame retardant clothing.

No protective classes are given for locations with energy levels exceeding 40 cal/cm^2, even though protective clothing capable of providing flash protection at incident energy levels of up to 112 cal/cm^2 is commercially available. While NFPA 70E-2004 does not explicitly prohibit work at locations with energy levels above 40 cal/cm^2, research into the potential for non-burn injuries (internal injuries, hearing damage, etc.) indicates that these other injuries become a significant concern at such high-energy locations.

At the low end of the clothing categories, note that untreated natural fiber clothing does not have a published arc rating. While this clothing is not tested in the same way as flame retardant clothing, category 0 is considered by NFPA 70E to be sufficient protection up to an incident energy of 2.0 cal/cm^2.

Recognizing the limitations of existing methods of arc flash hazard analysis, the Institute of Electrical and Electronics Engineers (IEEE) embarked on a test program in order to develop an accurate model for incident energy under simulated end-use conditions. The result, IEEE 1584-2002, IEEE *Guide for Performing Arc-Flash Hazard Calculations*, provides empirically-derived models for calculating incident energy and arc flash boundaries.

Empirical equations are given that cover systems at voltage levels ranging from 208V to 15kV and for available bolted fault currents ranging from 700A to 106kA, sufficient to cover the majority of low-voltage and medium-voltage installations. The equations are rather complex if calculations are to be performed by hand, though the equations are easily implemented in a spreadsheet or in other computer software.



IEEE 1584 arc flash calculation algorithms are based on actual test results performed to measure the incident energy of various arc flash incidents.

NFPA 70E requires either a hazard analysis or the tables in the document to be used to define the arc flash hazard at each equipment location. The tables in the standard may be used in lieu of an analysis if it has been demonstrated that the assumptions and conditions associated with the tables apply. An arc flash hazard analysis provides a more thorough and accurate characterization of the system.

Arc Flash Hazard Analysis Process

There are several steps to performing an arc flash hazard analysis. In fact, IEEE Standard 1584 identifies nine:

1. **Collect system and installation data**
2. **Determine system modes of operation**
3. **Determine bolted fault current**
4. **Determine arc fault current**
5. **Find protective device characteristic and arc duration**
6. **Document system voltages and equipment class**
7. **Select working distances**
8. **Calculate incident energy**
9. **Calculate flash protection boundary**

Step 1 can often require as much work as steps 2-9 combined! This is due to two primary reasons. One, many facilities lack up-to-date single-line diagrams that depict the actual configuration of the electrical distribution system. Two, the arc flash analysis requires additional information that is usually not available without visually inspecting the exterior and, sometimes, interior of existing power distribution equipment. This additional data includes short-circuit withstand ratings, circuit breaker settings, current-transformer ratings, fuse information, conductor type, conductor insulation, and so forth.

Step 2 offers its own set of difficulties, especially in large facilities with multiple electric utility points-of-delivery, onsite electricity generation, and multiple circuiting options. Sometimes, more than one alternative needs to be modeled in order to determine the worst-case arc flash condition. To further complicate things, the system configuration that results in the worst-case arc flash condition is usually not the same as the configuration that produces the worst-case short-circuit condition.

Data Collection Pitfalls

As suggested above, data collection is often the most underestimated portion of the overall effort. A typical w/ww plant will require *several thousand individual pieces of information* for the arc flash study. An error in any individual data element will mean one or more incorrect equipment labels. The data collection process must be rigorous, systematic and carefully executed. Knowledgeable plant personnel must work closely with the arc flash contractor to assure correct data.

To reduce costs, a facility may sometimes be tempted to collect data with its own onsite personnel. This method is strongly discouraged, for many reasons. Typically, the scale of the data collection effort and the accompanying skill set is not fully understood. Facility personnel may not be familiar with the information that is required. Plus, facility workers may not be trained and equipped to access energized equipment as is sometimes necessary to obtain circuit breaker settings, short-circuit equipment ratings, conductor sizes and insulation types. Furthermore, data collection usually receives a lower priority than keeping the facility running, and the project schedule continually slips, to the frustration of the facility and the engineering firm.

Modeling With Computer Software

Once the system data and circuit configurations have been established, these conditions and information are entered into one of many commercially-available software tools intended for performing power system analysis. These software tools then calculate the available bolted three phase short-circuit current at each equipment location.

Using the IEEE 1584 algorithms, the arcing fault current is projected and the clearing time determined from the protective device characteristic and setting. Either the as-found protective device settings can be used or they can be optimized to try to reduce incident energy.

Finally, the arc flash parameters are generated using the IEEE 1584 equations. All of the purveyors of industrial power system analysis software have integrated arc flash calculation modules into their packages to reduce the time for the evaluations. Nevertheless, it is possible to use spreadsheets to generate the results as well. Like most engineering, there are many situations during the process where engineering judgment, experience, and industry knowledge are required to perform a competent analysis. It is recommended only engineering firms with experience in the area perform such studies.

Short-Circuit Analysis

The typical arc flash analysis also includes a short-circuit analysis. An arc flash analysis is primarily concerned with calculating the incident energy to which a worker may be exposed at a given point in the electrical distribution system. A short-circuit analysis, however, is primarily concerned with the ability of electrical equipment, or electrical overcurrent protective devices, to withstand or interrupt the maximum three-phase fault current to which they could be subjected.

This analysis compares the highest calculated fault current with the ratings of each piece of electrical equipment. If a piece of equipment has been applied in the power system at a point where the power system can deliver fault current in excess of the equipment rating, it is considered “overdutied” and should be replaced or upgraded.

Time-Current Coordination Study

An overcurrent device coordination is normally included as part of the study. A coordination study develops circuit breaker settings and fuse values to protect equipment and help assure the nearest device clears the fault. Since the device settings impact fault clearing times and incident energy, a third new criterion is to try to minimize arc flash energy. Previously devices were often set high to maximize coordination where there was some margin. This was especially true of feeders where the downstream device was unknown and a high setting helped assure coordination.

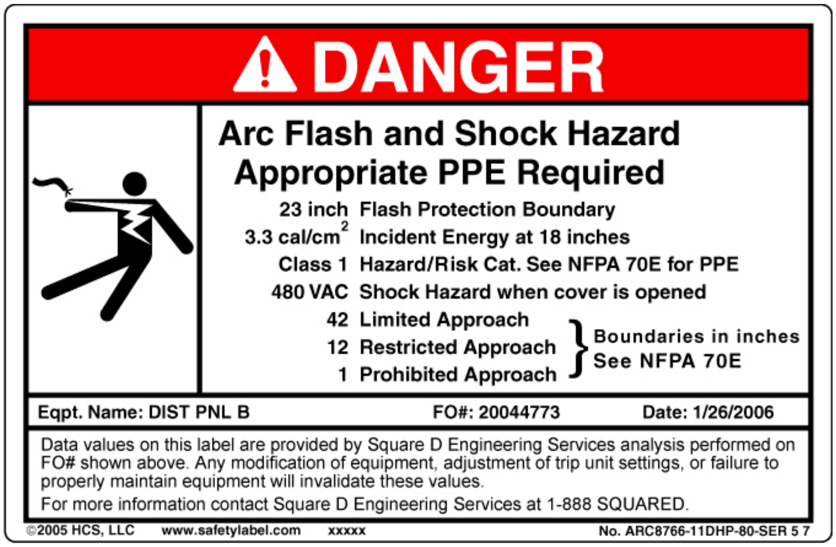
Some facilities attempt to reduce cost by omitting the coordination portion of the study. Even if a coordination study was recently performed (without arc flash), the previous settings will often result in unnecessarily high hazard categories for equipment. This can result in situations where unnecessary protective equipment is required or the equipment cannot be worked at all energized.

The results of the time-current study are usually portrayed in two ways: Settings table, and time-current figures. The settings table is often used to indicate both the as-found circuit breaker settings, and the recommended settings. This table can be used by field personnel to adjust settings to comply with study recommendations. The TCC figures display the time-current characteristics of each device in series, to graphically depict time and current selectivity. It is important that the recommended settings are implemented, especially if arc flash labels are based on these settings changes.

Arc Flash Labels for Equipment

As indicated earlier, the National Electrical Code section 110.16 requires “field marking” to warn qualified employees of electrical arc flash hazard. This field marking serves as a communication, to the facility’s properly-trained workers, of many key parameters associated with the specific electrical hazards at that point in the electrical distribution system.

These labels, therefore, contain information resulting from the arc flash analysis, and includes the incident energy value, worker approach boundary (distance from equipment at which 1.2 cal/cm^2 incident energy occurs), the voltage level (for shock hazard), and, most importantly, the personal protective equipment category. A sample arc flash label is shown below:



DANGER

Arc Flash and Shock Hazard
Appropriate PPE Required

23 inch	Flash Protection Boundary
3.3 cal/cm^2	Incident Energy at 18 inches
Class 1	Hazard/Risk Cat. See NFPA 70E for PPE
480 VAC	Shock Hazard when cover is opened
42	Limited Approach
12	Restricted Approach
1	Prohibited Approach

Boundaries in inches
See NFPA 70E

Eqpt. Name: DIST PNL B FO#: 20044773 Date: 1/26/2006

Data values on this label are provided by Square D Engineering Services analysis performed on FO# shown above. Any modification of equipment, adjustment of trip unit settings, or failure to properly maintain equipment will invalidate these values.
For more information contact Square D Engineering Services at 1-888 SQUARED.

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Typical Arc Flash Results

The following discussion is a summary of results from facility short circuit, device coordination, and arc flash studies conducted over the last five years.

Worst-Case Arc Flash Hazards

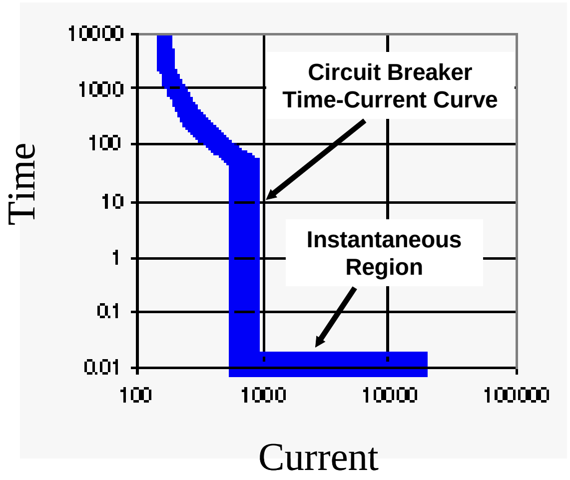
Before an analysis is performed, the expectation is that the worst arc flash hazards are at the medium voltage equipment and the low voltage switchgear. Loads after the low voltage feeders are thought to be "safe." The reality is often different.

To understand why these differences exist, it is important to understand the characteristics of overcurrent protective devices (see following figures). A typical characteristic is shown in the figure on the left. The vertical axis is the time associated with the device tripping characteristic. The horizontal axis is the magnitude of the fault current. For a given fault current, the current is found on the horizontal axis and followed vertically to the device characteristic.

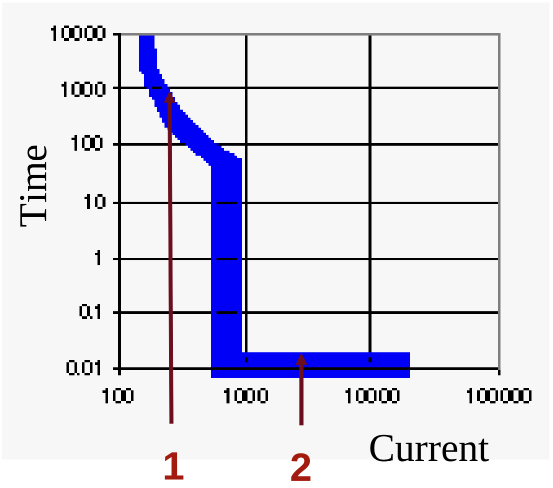
The characteristic is typically a band and the device could interrupt anywhere within the band corresponding to the current. The longest time of the band is what is conservatively selected as the clearing time. That point is followed horizontally to the vertical axis to read the clearing time. The region where there is no intentional time delay introduced is the horizontal portion of the device curve less than about 10 ms and is referred to as the instantaneous region. The greater the magnitude of the fault, the quicker the device acts to clear the fault. Fuses have similar characteristics but lack the ability of circuit breakers to adjust the shape of the curve.

One result of the general shape is that outside of the instantaneous region, a small change in fault current can have a much larger change in clearing time. The incident energy is proportional to the arcing current and the clearing time. For example, if the current is reduced by half the clearing time may be increased by ten times. The result is, even though the current has decreased, the incident energy has increased five fold.

For medium voltage systems, the available arcing fault current typically results in operation in the instantaneous portion of the curve. The fault clears quickly and the arc flash energies tend to be in the lower hazard category level.



Protective devices, like circuit breakers, are capable of clearing high overcurrents very quickly, provided the magnitude of the arcing current falls into the instantaneous region of the circuit breaker.

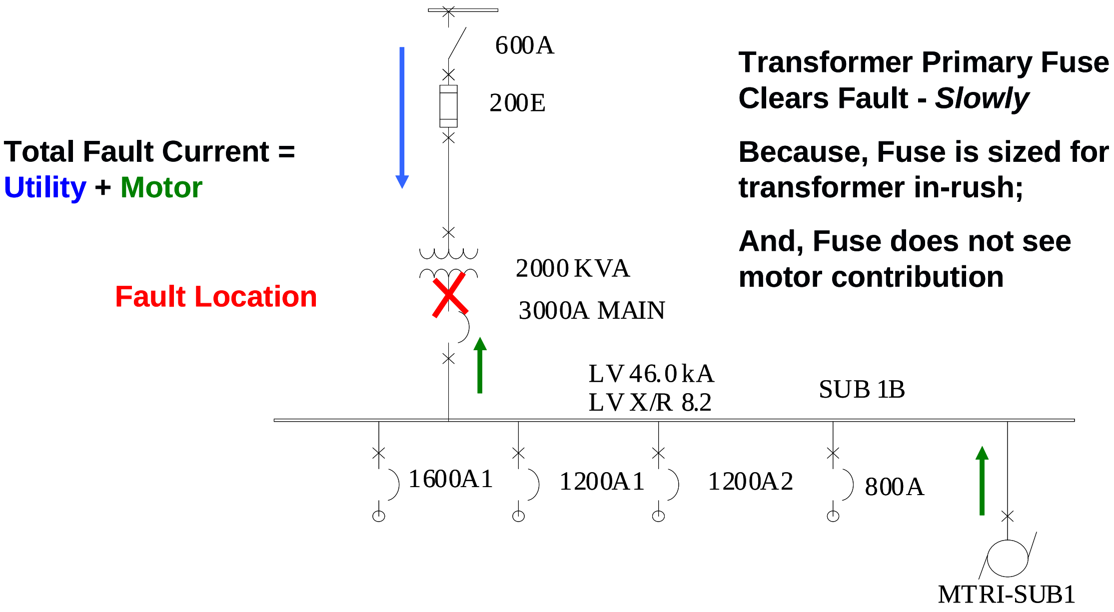


A low arcing fault current (1) may require several seconds to clear, resulting in a relatively high arc flash incident energy. A high arcing fault current (2) may fall into the instantaneous region of the circuit breaker, resulting in a low incident energy.

Other Findings of the Typical Arc Flash Analysis

- The short-circuit analysis reveals overdutied or under-rated equipment in about 60% of analyses performed.
- The overcurrent device analysis identifies protective coordination selectivity errors, or suggested improvements, in about 90% of the analyses performed.
- Arc flash incident energy levels can often be reduced without changing equipment.
- The arc flash exposure tends to be high on the line side of low voltage substation main breakers. The transformer impedance reduces the fault current for a 480 volt fault seen at the medium voltage relays often out of their instantaneous region. Consequently, the incident energies are very high and that portion of the power system is categorized as “dangerous” with no hazard category rating.

- Traditionally, substation low voltage main breakers did not have instantaneous trips installed. It was assumed most short circuits would be on the feeders and the lack of a main instantaneous trip aided selectivity. That practice guarantees high incident energies on the low voltage bus.
- Some w/ww facilities are designed so that motor control centers are served directly from a substation transformer. The arc flash exposure at these MCC's tends to be high because the high-side fuse protecting the transformer is the overcurrent device that will be required to interrupt an arcing fault in the low-voltage MCC.



Total Fault Current =
Utility + Motor

Fault Location

Transformer Primary Fuse Clears Fault - *Slowly*

Because, Fuse is sized for transformer in-rush;

And, Fuse does not see motor contribution

Arcing faults that occur in the main circuit breaker compartment of low-voltage switchboards, switchgear, or motor-control centers, often result in arc flash incident energy values well in excess of 40 cal/cm^2, as demonstrated above.

Benefits of An Arc Flash Analysis

While "taking steps to meet the highest standards for electrical safety" seems sufficient motivation, most successful w/ww facilities recognize the comprehensive benefits of the arc flash analysis process. These benefits include,

- Safer workplace, with resulting reductions in lost-time accidents, liability costs, and downtime.
- An updated set of electrical documentation for the facility, to aid in testing, troubleshooting, new-equipment feasibility studies, and maintenance.
- Identification of overdutied or misapplied electrical equipment.

- Recommendations for improving protective coordination selectivity, to reduce downtime and improve reliability.
- Identification of codes and standards errors, outdated or obsolete equipment, electrical infrastructure cost savings.

Results at a Water Treatment Facility

Overview

Square D Engineering Services performed an arc flash analysis at a water treatment facility, located in a port city on the east coast of the United States. Its power distribution system is small, fed by a single 2500-kVA utility transformer at a service voltage of 4160 Y/ 2400 V. The available fault current at the 23-kV utility delivery point is 3600 A, with an X/R ratio of 4.0.

Medium-voltage (4160-V) equipment at the facility includes several high-service pumps, ranging in size from 150-600 hp. In addition, twin engine generators provide backup power in the event of an electric utility disruption.

Arc Flash Results

Hazard Categories at the Facility Equipment

Equipment Name **	PPE Class - Electric Utility Service Only	PPE Class - Onsite Generation Only
Main 4160V Switchgear	0	1
Generator Switchgear 1	0	0
Generator Switchgear 2	0	1
Generator 1 Bus	0	N/A
Generator 2 Bus	0	N/A
4160V MCC 1	1	0
4160V MCC 2	1	0
Exist. 4160V Switchgear 1	0	0
Exist. 4160V Switchgear 2	0	0
Unit Sub 1 main breaker line side	3	3
Unit Sub 2 main breaker line side	3	3
Unit Sub 1	3	3
Unit Sub 2	3	2
MCC-1	1	1
MCC-2	1	1
MCC-3	1	1
MCC-4	0	0
MCC-5	1	1
MCC-6	1	1
** For medium-voltage equipment with arc flash category of 0, shock hazard is prevailing constraint.		

Hazard categories at the facility were acceptable, with recommendations made for improved selectivity among overcurrent devices. Unit substation main circuit breakers showed the highest arc flash incident energy, due to the transformer primary-side protection issue described earlier. In this case, the primary-side overcurrent protection was provided by a medium-voltage circuit breaker, equipped with multi-function protective relays. The transformer primary fuse was oversized to the point that this fuse would never blow (400E versus 250E), but the protective relay was capable of providing adequate protection for the transformer, as well as the low-voltage draw-out switchgear.

Another key aspect of this facility’s distribution system related to the low-voltage MCC’s. These five MCC’s were fed from circuit breakers located in low-voltage switchboards, rather than directly from a transformer secondary. This design practice greatly reduced the arc flash incident energy at the MCC’s, as compared to facility designs that eliminate the switchboards.