

Protection Considerations to Mitigate Arc-Flash Hazards

Technical Report to the Substation Subcommittee of the Power Systems Relaying Committee
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Assignment—Write a technical report to the Substation Subcommittee on protection tools that mitigate the effects of arc flash and how arc flash issues impact protection.

I. INTRODUCTION

Recently enacted guidelines and regulations regarding arc-flash hazards have focused industry attention on quantifying the dangers of arc-flash events when qualified persons are working near exposed, energized electrical equipment. [1], [2], [7] In order to comply with these guidelines and regulations, arc-flash studies are developed to estimate incident energy if a short circuit occurs and to provide guidance as to the level of arc thermal performance value-rated personal protective equipment (PPE) required. Incident energy from an arcing fault is related to the arc clearing time, the magnitude of short-circuit current, the arc length, and the working distance. Reducing the arcing time, reducing the magnitude of short-circuit current, and increasing working distance can reduce incident energy and thereby reduce PPE level requirements.

This report reviews the terms used in arc-flash discussions, reviews how the electric power industry perceives the arc-flash problem, and reviews recently developed applicable standards and regulations pertaining to arc-flash analysis. After presenting an understanding of the issues, the report continues with ways to mitigate the problem. Several relay schemes are discussed with specific emphasis on how these schemes can be used or modified to mitigate the arc-flash problem. Another approach discussed senses the light emitted by the arc to initiate fast breaker tripping to lessen the amount of incident energy.

In addition, several nonprotective relay methods to mitigate the hazard are listed, including current-limiting fuses and arc-resistant switchgear.

This document is solely intended to provide a resource to describe protection considerations to mitigate arc-flash hazards.

II. DEFINITION OF ARC-FLASH AND RELATED TERMS

Arc-flash hazard: a dangerous condition associated with the release of energy caused by an electric arc. [1]

Electric hazard: a dangerous condition in which inadvertent or unintentional contact or equipment failure can result in shock, arc-flash burn, thermal burn, or blast. [1]

Flash protection boundary: an approach limit at a distance from exposed live parts within which a person could receive a second-degree burn if an electrical arc flash were to occur. [2]

Incident energy: the amount of energy impressed on a surface, a certain distance from the source, generated during an electrical arc event. One of the units used to measure incident energy is calories per centimeter squared (cal/cm^2). [2]

Limited approach boundary: an approach limit at a distance from an exposed live part within which a shock hazard exists. [2]

Qualified person: one who has skills and knowledge related to the construction and operation of the electrical equipment and installations and has received safety training on the hazards involved. [2]

Restricted approach boundary: an approach limit at a distance from an exposed live part within which there is an increased risk of shock, due to electrical arc over combined with inadvertent movement, for personnel working in close proximity to the live part. [2]

Prohibited approach boundary: an approach limit at a distance from an exposed live part within which work is considered the same as making contact with the live part. [2]

Working distance: the dimension between the possible arc point and the head and body of the worker positioned in place to perform the assigned task. [1]

III. SUMMARY OF APPLICABLE STANDARDS

There are several standards that identify requirements related to working with live electrical parts and specifically arc-flash protection. Some standards are OSHA (Occupational Safety and Health Act) 29 Code of Federal Regulations (CFR) Part 1910 Subpart S, NEC (National Electrical Code) 2005 NFPA 70, NFPA (National Fire Protection Association) 70E Standard for Electrical Safety in the Workplace 2004 Edition, IEEE Standard 1584 2002 Guide for Performing Arc-Flash Hazard Calculations, and NESC 2007 (National Electric Safety Code). While a summary of several applicable standards is included in this report, refer to each standard for the specific scope and specific application of the standard. In some cases, the standard applies to industrial or commercial electrical systems and not utility electrical systems. Further, the adoption of a standard and regulation will depend on the electrical system's location.

A. OSHA Title 29 Code of Federal Regulations Part 1910 Subpart S

OSHA's function is to regulate practices in the workplace for both the employer and the employee. Included in these practices is one to prevent electrical shock or other injuries that could result from coming in contact with live electrical parts either directly or indirectly. OSHA requires that for work to be performed on electrical parts, the parts must be de-energized, locked out and tagged as such, except for special circumstances. If de-energizing the electrical part is not possible because continuity of service is required or if de-energizing it would create other hazards, then OSHA will allow work to be carried out on the live electrical parts.

B. NEC 2005 NFPA 70E

The NEC is utilized mainly for design, construction, installation, and inspection. For example, it identifies the required clear working space around live electrical parts. The standard is very detailed and complex. The standard does identify specific requirements for arc-flash protection. It requires that electrical panels, enclosures, etc. that would typically require access while energized be marked with signage warning qualified personnel of potential electric arc-flash hazards. This signage is to be in plain view of qualified personnel prior to work being performed. The standard references the NFPA 70E standard for further specific measures.

C. NFPA 70E Standard for Electrical Safety in the Workplace 2004

This standard provides specific details on working with electrical parts. It identifies the definition of a qualified person who plans to work on the electrical parts, the need for an Electrical Safety Program and Procedures, and the need for a Hazard/Risk Evaluation Procedure. It goes on to identify specific steps and identifies practices for working on or near live parts. This includes specific information on the appropriate boundary requirements and personal protective equipment necessary in order to minimize the possibility of

electrical shock or injury. This document references the IEEE Standard 1584 for further details.

D. IEEE Standard 1584 Guide for Performing Arc-Flash Hazard Calculations

This standard provides calculation details for the Flash Protection Boundary, the level of PPE required, and the anticipated incident energy level.

E. National Electrical Safety Code Standard C2-2007

This standard covers basic provisions for safeguarding of persons from hazards arising from the installation, operation, or maintenance of (1) conductors and equipment in electric supply stations and (2) overhead and underground electric supply and communications lines. Per Section 41, paragraph 410.A.3, effective as of January 1, 2009, the employer shall ensure that an assessment is performed to determine potential exposure to an electric arc for employees who work on or near energized parts or equipment.

F. CSA Z462 Arc-Flash Safety Standard

This is a Canadian standard that covers many issues covered by NFPA 70E.

IV. PROTECTIVE RELAYING TOOLS TO REDUCE THE IMPACT OF ARC-FLASH – REDUCE TRIP TIMES

The following sections describe protection schemes that, when applied properly, can reduce trip times, and consequently, mitigate the arc-flash hazard. To apply properly, the user must be aware of some protection fundamentals:

- Each relay scheme is designed to detect faults within its zone of protection (e.g., a current differential scheme operates only for faults within its differential zone).
- Each relay scheme, when actuated, must be designed to operate all of the source interrupters (e.g., it may be necessary to open a transformer high-side switch or breaker to clear a low-side fault if the fault is between the transformer and low-side main breaker).

Specific settings may be required on each scheme (e.g., an overcurrent pickup setting may need to be reduced to achieve faster trip time).

A. Reduce Coordination Intervals of Existing Time-Overcurrent Relays

Fig. 1 shows a typical coordination of feeder relays. Most engineers and many software programs use a 0.3-second minimum coordination interval (CI) between tripping characteristics of series-overcurrent devices. Reducing coordination intervals exceeding 0.3 seconds is a direct and simple way of reducing tripping times. Most engineers do not recommend a margin less of than 0.3 seconds unless very specific testing and analysis is performed.

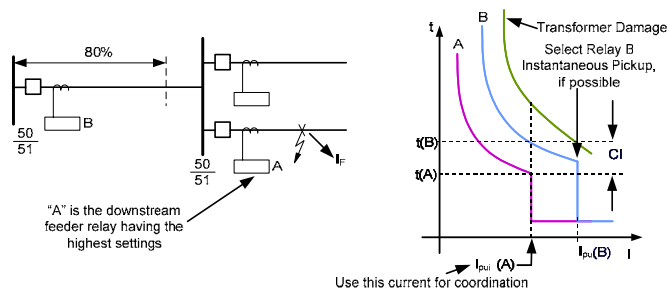


Fig. 1. Time Current Coordination

Note that setting an instantaneous overcurrent at B is desired (e.g. 125% of maximum fault current at A), but instantaneous element coordination is not possible if there is no difference in the fault current at A and B.

Fig. 2 shows fault current and relay-operate times based on fault location. We can see that fault current is highest at the source. If the distance between coordinating devices is low, the effect is that the “delta Ts” continue to add. Thus, we end up with the highest fault currents and longest trip times closest to the source, where personnel are most likely to be working.

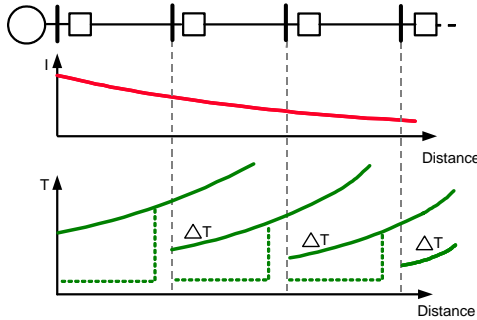


Fig. 2. Fault Current and Operate Time as a Function of Electrical Distance from Source

For some systems, it may be possible to lower pickup settings and thus reduce trip times by applying voltage-restrained or voltage-controlled overcurrent protection.

In summary, time-overcurrent relay settings can be lowered to minimum coordination intervals, which has the advantages of using existing relays and no electrical design changes are required. The disadvantages are the cost of the coordination study and field setting application and often only a small decrease in trip times may be achieved.

B. Zone Interlocking Scheme Using Overcurrent Relaying

Fig. 3 shows a zone interlocking scheme. The arrows indicate the direction of current flow for a radial system. Fig. 3 shows the use of digital communications to transmit blocking and tripping signals. Alternately, these signals can be hard-wired.

Scheme operation:

- Feeder relays send “block” signal to low-side main breaker for feeder faults.
- Main breaker set to trip with short (2- to 3-cycle) delay to allow time to receive block signal.

- Maintains sensitivity and security even when CTs approach saturation.
- Can be applied with nondirectional or directional overcurrent elements.

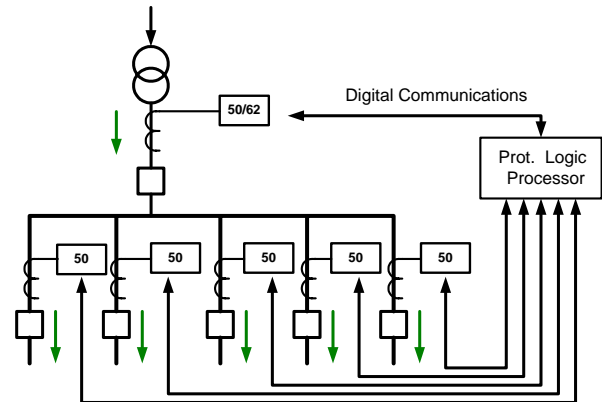


Fig. 3. Zone Interlock Scheme

One consideration is that if a fault occurs in one of the feeder breakers, the feeder relay on the faulted line will block the fast-tripping element. Thus the scheme will perceive this as a feeder fault and block the zone interlocking scheme. If no other measures are taken, back-up, time-delayed (e.g. 51) protection is required to clear the fault.

C. Bus Differential Scheme

A bus differential scheme is a method of protecting a bus that relies on Kirchoff’s Law that the sum of all currents entering and exiting a node must add to zero. Currents taken from CTs surrounding a bus are added together. If the sum of the currents or differential current is not zero, then the relay declares an internal fault and operates. Any fault between the CTs and the bus is considered in the zone, and the relay will operate. Any fault on the line side of the CTs is considered external and is outside of the zone of protection.

1) High-Impedance Bus Differential

Dedicated CTs are required for this scheme because all of the CT inputs are paralleled and then connected to a high-impedance input in the relay. The relay measures the voltage across its internal impedance—typically about 2000 ohms.

The relay is set such that, for the external fault, the voltage measured across the impedance is less than the pickup, and the internal fault is above the pickup.

This scheme is fast and secure but relatively costly because of the need for the dedicated CTs and the additional wiring and testing required to validate the scheme.

Fig. 4 shows a connection for a high-impedance bus differential scheme. The arrows show the direction of load current for a radial system.

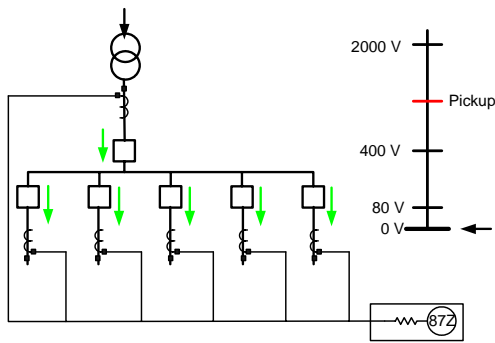


Fig. 4. High-Impedance Bus Differential Scheme

2) Low-Impedance Bus Differential

A low-impedance bus differential scheme is fast and secure and does not require dedicated CTs (i.e., additional relays, meters, transducers, etc. can be connected to the same set of CTs). Relay settings are typically slightly more complex than a high-impedance differential scheme because each input has an independent CT ratio and connection. Like the high-impedance scheme, this scheme requires some additional commissioning testing. For the fault shown in Fig. 5, the differential scheme should not trip.

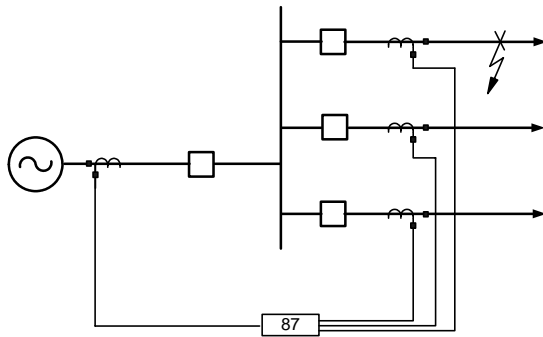


Fig. 5. Low-Impedance Bus Differential

D. Enable Instantaneous Element during Maintenance

Another solution is to require maintenance personnel to enable a sensitive instantaneous element whenever live work is performed. This scheme would require adding a control switch or pushbutton, cabling, and associated logic. This could be added to new or old installations for a relatively low cost.

Like any lockout tag-out procedure, this could be added to operations and maintenance plans for switchgear or electrical equipment. Just as workers are expected to wear appropriate PPE for the application, they would be required to enable fast tripping on the bus relays.

During maintenance periods, there is a risk of overtripping, but statistically, it is a small risk. For example, if we assume that 80 hours per year of live work is performed, the probability of overtripping during maintenance is $80/(24 \cdot 365) = 0.91\%$ per year. The potential cost associated with the small risk could be significant enough to justify the installation of one of the more secure and more costly alternatives.

On many systems, especially at industrial facilities, high-fault currents, low-ratio CTs, and high-system X/R ratios conspire to cause CT saturation during faults with dc offset.

Thus, it is important to apply instantaneous overcurrent elements that detect the waveforms produced by CT saturation [4].

The CTs for this overcurrent element should be upstream of any of the arc-flash area of concern so that all faults can be detected quickly.

E. Optical Sensors (Device AFD: Arc-Flash Detector)

One method of detecting an arc is through the use of optical sensors. Optical sensor use is possible because the arc emits a very high-intensity light. This light is detected by the optical sensor and trips the upstream breaker.

There are two types of optical sensors used:

1. Continuous fiber loop
2. Point sensor

The continuous fiber loop employs a nonjacketed glass fiber that is routed through the piece of equipment that is to be protected. An example of this as applied to a switchgear lineup is shown below. [5]

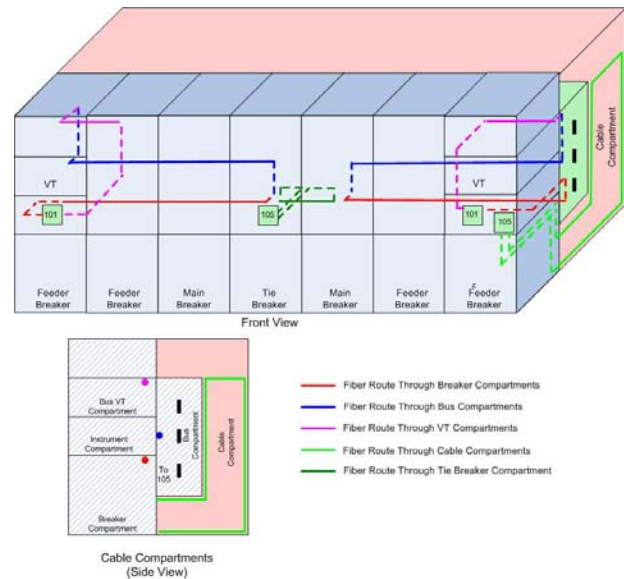


Fig. 6. Example Continuous Fiber Loop in Switchgear

Any light that is incident to the fiber will be detected, since this is a loop back to the receiver. The receiver monitors the loop for integrity. Should the fiber break, alarms can alert the appropriate people.

The other method employs an optical sensor mounted on the wall of a cubicle. Again, any light incident to the sensor will be transmitted to the receiver where the appropriate upstream breaker(s) will be tripped.

The advantage of an optical scheme is that it does not have to coordinate with downstream devices. The operate time of an optical scheme with a solid-state output is as low as 2 to 2.5 milliseconds.

For additional security, the optical scheme can be supervised by a current detector, if one does not want to rely on light alone for detection. The CT should be located upstream from the switchgear so that it will sense current for any switchgear fault, and the overcurrent element must be extremely fast so as to minimize delay.

F. Summary of Protective Relaying Methods to Reduce Arc Flash

TABLE I
SUMMARY OF SCHEME ADVANTAGES AND DISADVANTAGES TO REDUCE ARC-FLASH HAZARD [6]

Clause Number	Protection Scheme Description	Advantages	Disadvantages
IV.A	Reduce coordination intervals of existing time-overcurrent relays	Existing hardware, existing technology.	Cost of coordination study and field settings application, trip times are still likely to be high (0.5–2 s*, depending on coordination issues), only marginal improvement can be achieved.
IV.B	Zone interlocking	Use of existing main and feeder overcurrent relays. Faster than TOC (typically 3–5 cycles*), secure. Communications-assisted scheme monitors scheme integrity. Relatively low cost to install communications hardware.	Settings more complex. CTs on bus side of breaker would result in delayed tripping for faults in the feeder breaker. Communications-assisted scheme requires additional communications hardware.
IV.C.1	High-impedance bus differential	Fast (less than 1.5 cycles*) and secure for any fault type, easy to set.	Requires additional relay, dedicated CTs, wiring installation. Testing more complex. Does not operate for faults outside differential zone.
IV.C.2	Low-impedance bus differential	Fast (less than 1.5 cycles*) and secure for any fault type.	Requires additional relays, wire, CTs. Settings, testing more complex. Relay may not be available for larger buses. Does not operate for faults outside differential zone.
IV.D	Enable instantaneous overcurrent protection, block reclosing during maintenance	Use of existing main and feeder overcurrent relays. Fast (less than 1.5 cycles*). Low cost to install control switch, wiring.	Lose selectivity during maintenance periods, could over trip. Introduces change in maintenance procedures. Additional relaying may be required.
IV.E	Optical sensors	Fastest (less than 1/4 cycle*), sensitive, easy to set and apply.	Cost of installing fiber loop or point sensors, not applicable to open/ outdoor substation designs.

* Does not include breaker/interrupter operate time.

V. SUMMARY OF NONPROTECTIVE RELAYING METHODS OF REDUCING ARC-FLASH

Many nonrelaying methods exist to reduce the arc-flash hazards associated with electrical equipment. These methods generally involve some combination of 1) reducing the amount of available fault current, 2) reducing the time required to clear a fault, or 3) removing the operator from the hazard/removing the hazard from the operator. These methods are considered beyond the scope of this report but are briefly mentioned here for reference.

Methods that reduce the available fault current include:

- Current limiting fuses
- Reduced transformer sizes
- Increased transformer impedance
- Current limiting reactors
- Electronic current limiters
- Installation of variable frequency drives on large motors
- Bus arrangements (tied vs, split)
- Impedance grounding

Methods that reduce the time required to clear a fault include:

- Installation of faster operating breakers
- Optical fault sensing via fiber or lens sensors

Methods that remove the operator from the hazard include:

- Arc-resistant switchgear (directs energy away from personnel)
- Remote breaker operation (e.g., use of wireless communications)
- Remote breaker racking
- Operating de-energized

VI. CURRENT UTILITY PRACTICES

The majority of utility distribution substations consist of either open-air buswork or enclosed switchgear buses. Protection devices range from power fuses to overcurrent relaying to a combination of differential with overcurrent backup relaying. The protection devices are installed to limit the damage that occurs to the equipment under fault conditions. Normally, there is no autorestitution after an extended outage for substation faults without some form of system operator intervention.

The application of high-side fuses provides the most economical protection to the utility. However, fuse protection has limited flexibility because of fixed time-current curves and an inability to change the protection configuration for system maintenance.

Mitigating the effect of arc flash is an important activity for many utilities. Here is a summary of actions being taken. Utilities are:

- Reviewing schemes with respect to arc flash and performing arc-flash studies.
- Implementing faster tripping schemes when possible (bus differential, etc.).
- Using alternate settings on existing schemes to achieve faster tripping.
- Disabling reclosing during maintenance.
- Willing to sacrifice coordination during live work conditions.
- Increasing the use of methods to remotely operate breakers (e.g., wireless communications, time delays, or umbilical remote switch).
- Using hot-sticks or lengthened tools to increase working distance.

- Performing an increasing amount of work with equipment in a de-energized state.
- Using higher levels of PPE where needed.

VII. SUMMARY

Arc-flash hazards are separate and distinct from shock/electrocution hazards and must be addressed with appropriate work practices and personal protective equipment. The degree of the arc-flash hazard depends on the available short-circuit current, the clearing time of the protective devices, and the working distance from the potential arc location. The level of protection required depends on the degree of hazard.

If other variables remain constant, the degree of arc-flash hazard increases with higher fault current, longer clearing time, or closer working distance. It should be noted that commonly applied time-overcurrent responsive relays will result in a longer fault clearing time at lower fault current. Despite the mitigating effect of the lower fault current, the arc-flash hazard may actually be more severe at the lower current as a result of the longer fault clearing time. Arc-flash hazard analysis should include evaluation of low-current faults as well as high-current faults, with appropriate fault clearing times included for each.

Means of reducing the arc-flash hazard amount to reducing the magnitude of fault current (without increasing the fault clearing time, see above), reducing the duration of the arc, or increasing the working distance. Where possible, equipment should be de-energized before performing work. Where not possible to de-energize, the choice of protective relaying schemes employed and appropriate coordination of these may provide faster fault clearing time with a resultant decrease in the arc-flash hazard.

Several protective relaying methods of reducing the arc-flash hazard were reviewed in this document. It may be possible to reduce fault clearing time with existing relays if review of the coordination shows that the pickup time may be reduced without risk of miscoordination or false trip. Zone interlocking schemes may be considered to provide fast response for in-zone faults with delayed response for backup of out-of-zone faults. Differential relaying schemes often offer faster response to some fault conditions than time-overcurrent relays. It may be possible to reduce the arc-flash hazard by temporarily foregoing coordination and applying or enabling instantaneous elements (that is, elements that do not have any intentional time delay) while work is being performed. Flash detectors (optical sensors) might also be considered to provide a fast response to arcing faults. With faster clearing time, the arc-flash analysis may indicate that the lower level of PPE is required. It should be remembered that relay response time is only a portion of the total fault clearing time—the circuit breaker interrupting time must be added to the tripping time to get the total clearing time.

This document also lists in summary several nonprotective relaying methods of reducing the arc-flash hazard. The interested reader is directed to other sources for detailed discussions, which are beyond the scope of this document.

VIII. BIBLIOGRAPHY

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IX. APPENDIX A: ARC-FLASH ANALYSIS

A. Background

An Arc Flash Hazard Analysis consists of three major steps: (1) determination of the available incident energy; (2) Determination of the minimum required PPE based on that incident energy; and (3) additional engineering, if required, to mitigate high levels of incident energy to manageable levels. There are several tools which are available for determining arc flash incident energies; including but not limited to NFPA 70E/IEEE 1584, NESC C2-2007, and commercially available software. Care should be taken when selecting an arc flash incident energy calculation methodology since these tools have limitations based on the system voltage levels and type of equipment. For example, it may be necessary to use different methodologies for calculating incident energies for enclosed switchgear above and below 15KV, for open type substations, and for overhead and underground power lines. Calculation inputs and assumptions such as fault current, working distances, arc gap distances are also important considerations. Whenever possible, it is always best to use actual system information, rather than conservative assumptions.

B. Examples

1) Enclosed Switchgear

For switchgear 15 kV and below, IEEE 1584 [1] provides an accepted method of calculating arc-flash energy. Using IEEE 1584, we can calculate incident energy.

For example, let us assume an infinite bus on the high side of a transformer to provide a maximum fault current on the low side of a transformer. A typical example might be a 1000 kVA, 13.8/480 kV transformer with a self-impedance of 6% will give approximately 20,000 amperes fault current at 480 volts (assuming an infinite bus on the high side of the transformer). Let us further assume that using an instantaneous element, we can achieve a total clearing time of

0.11 seconds. Using an 18-inch working distance, the calculated incident energy is 4.4 cal/cm^2 . After a thorough analysis of the system, let us say the fault current is closer to 10 kA, due to the actual system source impedance. If that current is below the instantaneous trip level, the clearing time increases to 2.5 seconds. Under these conditions, the incident energy increases to 53.2 cal/cm^2 . Thus, we may choose to lower the instantaneous trip level, or enable a faster tripping scheme during maintenance.

2) *Overhead Line*

For overhead lines, we instead use NESC C2-2007 [7]. This standard provides tables to assist in determining Arc-Flash energy. Using Table 410-1 from the standard, for a 34.5 kV line with 10,000 ampere fault current, the maximum fault clearing time must be 0.147 seconds or less to limit incident energy to 4 cal/cm^2 .