Protection against Thermal Hazards and Arc Flash Mitigation Studies Carried out in Electrical Sub Station

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Abstract— The nature of explosive equipment failures, and the rate of serious burn injuries in the electrical industry has been studied for many years. Detailed investigation into the arc flash phenomena by many researchers has led the NFPA to adopt arc flash guidelines in NFPA-70E (2000) for work on or near energized electrical equipment. The 2002 National Electric Code also adopted Arc Flash Hazard labeling requirements. In September of 2002, IEEE-1584 "IEEE Guide for Performing Arc Flash Hazard Calculations" was released, providing the detailed equations for determining arc flash energies. Proposed NFPA-70E (2003) due for adoption in May 2003 enhances the original 70E guidelines and adopts IEEE-1584 as the basis for determining arc flash energies. Arc-flash hazard studies require knowledge of both the electrical power system in a facility, and the systems electrical protection. Arc flash studies can be considered a continuation of the short circuit and coordination aspects of a power system, since the results for each are required to assess flash hazards. The effort required to perform an arc hazard assessment is greatly reduced the closer the integration between the short circuit, protective device coordination, and the arc-flash.

Key words: Arc Flash, Hazard Analysis

I. Introduction

In very simple terms, an arc flash is an extremely violent event. An arc occurs when the electric current uses a path through air rather than through conductive material. Where there is no firm connection between shorted conductors there is usually an arc. Arc flash is a separate hazard from electric shock, which you must also guard against when performing work associated with live equipment. The arc releases energy in the form of thermal energy and also mechanical energy. There are two basic characteristics that drive this energy release.

The arc is hotter than the temperature at the sun's surface.

When solid copper is vaporized, its volume expands 67,000 times…and that can create an immense pressure wave.

While these are the two biggest effects, there are many more caustic byproducts of an arc flash. These include deafening sound, blinding light, toxic gases, molten metal, and pieces of metal or other material explosively thrown off. Nothing about an arc flash is pleasant.

II. Methodology

A. Methodology of Arc Flash Accident Analysis

1) Objective

To provide awareness against

- Causes for Arcing Faults
- Hazards due to Arcing faults
- Injuries that result from lack of adequate Personnel Protective Equipment (PPE) and Training.

2) Scope

The Scope of the study is restricted to analysis of causes and consequences and development of protection measures arc flash incidents in ABB sites

3) Methodology

a) Methodology

The evaluation involves the following.

The study should be performed in association with or as a continuation of Short Circuit

- Study and Relay Coordination study

b) Steps

- Data Collection of the System & Installation
- System Modes of Operation
- Determination of Bolted Faulted Current
- Determination of Arc Fault Current
- Find the Protective Device Characteristics & Duration of Arc
- Document the System voltages and Class of Equipment
- Select the working Distances
- Determine the Incident Energy for all Equipment
- Determine the Flash Protection Boundary for all Equipment

The steps of the process are outlined below:

c) Calculations

The equations developed in the IEEE standard assess the arc flash hazard based on

- Available (bolted) fault current,
- Voltage,
- Clearing time,
- Equipment type,
- Grounding, and
- Working distance

Calculations are done for

- Arcing Current – Insulation Distances
- Incident Energy – Insulation Distances
- Arc Flash Protection Boundary

B. *Study Inputs*

1) *Low voltage Switch Gear*

ield Name	Field Description
Node ID	Name of the Node, Bus, MCC, Switchgear, or Generator
Node Name	Longer and more description of Node ID
Volts	Equipment Voltage Rating
Type of Device	Type of Low Voltage Device
	FUSE
	PCB (Medium Voltage Power Circuit Breaker)
	MISC (Miscellaneous)
	N/A (Not Applicable – No Short Circuit Rating)
nt Sym	Interrupting Short Circuit Current Rating in symmetrical Amperes
nt/C+L Asym	Interrupting Short Circuit Current Rating in Asymmetric Amperes or Close and Latch Rating
With Asym	Withstand Rating in Asymmetrical Amperes
ST 10 CY	10 Cycle Short Time Short Circuit Rating
nt Time	Nameplate Interrupting Time (Cycles)
Cont Part Time	Contact Parting Time
X/R Ratio	Calculated X/R Ratio of maximum fault Current
½ Cycle Sym (kA) (AC Comp)	This is the calculated maximum ½ Cycle Symmetrical Sho Circuit value
½ Cycle ASym (kA	This is the calculated maximum ½ Cycle Asymmetrical Sho Circuit value
@ Cont Parting Time	Current at contact parting time
ield Name	**Field Description**
Calc Int Value	Calculated Interrupting Value
S#	Scenario Number of the maximum fault current calculated (multiple cases are run, then there may be different case o scenarios where the fault current is higher. For exampl Scenario 1 – Normal Power, Scenario 2 – Emergency Powe

Fig. 1: Low voltage switch gear

2) *Medium Voltage Switch gear*

ield Name	Field Description
Node ID	Name of the Node, Bus, MCC, Switchgear, or Generator
Node Name	Longer and more description of Node ID
Volts	Equipment Voltage Rating
Type of Device	Type of Low Voltage Device
	ATS (Automatic Transfer Switch)
	FLVPCB (Fused Low Voltage Power Circuit Breaker)
	FUSE
	ICCB (Insulated Case Circuit Breaker)
	LVPCB (Low Voltage Power Circuit Breaker)
	MCCB (Molded Case Circuit Breaker)
	MISC (Miscellaneous)
	N/A (Not Applicable – No Short Circuit Rating)
Cat	Type of Circuit Breaker Category (See Short Circuit Devi Rating Procedure Flow Chart)
With	Withstand Rating
nt	Short Circuit Current Interrupting Rating (IAC)
X/R Ratio	Calculated X/R Ratio of maximum fault Current
½ Cycle Sym (kA) (AC Comp)	This is the calculated maximum ½ Cycle Symmetrical Sho Circuit value
½ Cycle ASym (kA	This is the calculated maximum ½ Cycle Asymmetrical Sho Circuit value
MF	Multiplying Factor to increase fault current if calculated X/ is greater than device test X/R ratio. (See Short Circu Device Rating Procedure Flow Chart)
½ Cycle Sym (kA) X MF	½ Cycle Sym (kA) current multiplied by MF (De-rates devic interrupting rating) **Use this column and compare to th equipment interrupting rating.**

Fig. 2: Medium Voltage Switch gear

C. *Calculations*

1) Arc Flash Evaluation using IEEE 1584 (2002a) / D10 assumes that the following ranges are used.
   - Range of the model
   - Bus Voltage between 208V and 15kV
   - Bolted fault current at the bus between 700A and 106kA
   - Bus bar gap between 13mm and 153mm
   - For systems outside these ranges, use the LEE equation instead
2) Determine the 3 Phase Fault at each bus in the power system, calculate or determine the Bolted Fault Current at the bus (IB) and the Bolted Fault Current through each protective device (IB br).
3) Determine the Arcing Fault Current at the bus (Ia) and through each protective device (Ia br).

For low voltage distribution systems, nominal voltage < 1 kV and 700A ≤ IB ≤ 106kA

lg (Ia) = K + 0.662 lg (IB) + 0.0966 V + 0.000526 G + 0.5588 V lg (IB) – 0.00304 G lg (IB)

lg is log10
Ia is arcing fault current at the bus
K is –0.153 for open configuration and
is –0.097 for box configuration
IB is bolted fault current – 3phase sym rms kA at the bus
V is bus voltage in kV
G is bus bar gap between conductors in mm

Calculate the Incident Energy

lg (En) = K1 + K2 + 1.081 lg (Ia) + 0.0011 G

En is incident energy (J/cm2) normalized for an arcing duration of 0.2s and working distance of 610mm
K1 is –0.792 for open configuration and
is –0.555 for box configuration (switchgear, panel, cable)
K2 is 0 for ungrounded and high resistance grounded systems and
is –0.113 for grounded systems
G is the gap between bus bar conductors in mm

solve En = 10lg En

Incident Energy is converted from normalized:

E = 4.184 Cf En (t/0.2) (610X / DX)

E is incident energy (J/cm2)
Cf is 1.0 for voltage above 1 kV and
is 1.5 for voltage at or below 1 kV
t is arcing duration in seconds
D is the working distance
x is the distance exponent

The distance exponent x based on the voltage level and equipment type shown in the table below.

x	Equipment Type	kV
1.473	Switchgear	≤ 1
1.641	Panel	≤ 1
0.973	Switchgear	> 1
2	all others	

Calculate the Arc Flash Boundary DB

DB = [4.184 Cf En (t/0.2) (610^X / EB)] ^ 1/X

DB is the arc flash boundary in mm at incident energy of EB
EB is the limit for a second-degree bare skin burn. EB = 5.0 (J/cm2)

For all current limiting fuses and breakers with the manufacturer's incident energy and flash boundary equations available, the manufacturer's current limiting equations are used instead of the above equations. The current limiting equations can be entered and are stored in the protective device library.

IE = A * Ibf + B - Incident Energy
Db = D * Ibf + D - Flash Boundary

Fig. 3: Calculations

III. RESULTS

A. Arc Flash Approach Boundaries – Low voltage

(1) Nominal System Voltage Range, Phase to Phase	(2) Limited Approach Boundary – Exposed Movable Conductor		(3) Limited Approach Boundary – Exposed Fixed Circuit Part		(4) Restricted Approach Boundary – Includes Inadvertent Movement Adder		(5) Prohibited Approach Boundary	
Less than 50	Not Specified		Not Specified		Not Specified		Not Specified	
50 to 300	10 ft 0 in.	3.05 m	3 ft 6in	1.07 m	Avoid Contact		Avoid Contact	
301 to 750	10 ft 0 in.	3.05m	3 ft 6in.	1.07m	1 ft 0 in.	304.8 mm	0 ft 1 in.	25.4 mm
751 to 15 kV	10 ft 0 in.	3.05 m	5 ft 0 in.	1.53 m	2 ft 2 in.	660.4 mm	0 ft 7 in.	177.8 mm
15.1 kV to 36 kV	10 ft 0 in.	3.05 m	6 ft 0 in.	1.83 m	2 ft 7 in.	787.4 mm	0 ft 10 in.	254 mm
36.1 kV to 46 kV	10 ft 0 in.	3.05 m	8 ft 0 in.	2.44 m	2 ft 9 in.	838.2 mm	1 ft 5 in.	431.8 mm
46.1 kV to 72.5 kV	10 ft 0 in.	3.05 m	8 ft 0 in	2.44 m	3 ft 3 in.	1 m	2 ft 2 in.	660 mm
72.6 kV to 121 kV	10 ft 8 in.	3.25 m	8 ft 0 in.	2.44 m	3 ft 4 in.	1.29 m	2 ft 9 in.	838 mm
138 kV to 145 kV	11 ft 0 in.	3.36 m	10 ft 0 in.	3.05 m	3 ft 10 in.	1.15 m	3 ft 4 in.	102 mm

Fig. 4: Arc Flash Approach Boundaries – Low voltage

B. Arc Flash Approach Boundaries – Medium voltage

(1) Nominal System Voltage Range, Phase to Phase	(2) Limited Approach Boundary – Exposed Movable Conductor		(3) Limited Approach Boundary – Exposed Fixed Circuit Part		(4) Restricted Approach Boundary – Includes Inadvertent Movement Adder		(5) Prohibited Approach Boundary	
161 kV to 169 kV	11 ft 8 in.	3.56 m	11 ft 8 in.	3.56 m	4 ft 3 in.	1.29 m	3 ft 9 in.	1.14 m
230 kV to 242 kV	13 ft 0 in.	3.97 m	13 ft 0 in.	3.97 m	5 ft 8 in.	1.71 m	5 ft 2 in.	1.57 m
345 kV to 362 kV	15 ft 4 in.	4.68 m	15 ft 4 in.	4.68 m	9 ft 2 in.	2.77 m	8 ft 8 in.	2.78 m
500 kV to 550 kV	19 ft 0 in.	5.8 m	19 ft 0 in.	5.8 m	11 ft 10 in.	3.61 m	11 ft 4 in.	3.54 m
765 kV to 800 kV	23 ft 9 in.	7.24 m	23 ft 9 in.	7.24 m	15 ft 11 in.	4.84 m	15 ft 5 in.	4.7 m

Fig. 5: Arc Flash Approach Boundaries – Medium voltage

C. Insulation Distances

Voltage	Minimum Air Insulation Distances
300 V and less	0 ft 0.03 in.
Over 300 V, not over 750 V	0 ft 0.07 in.
Over 750 V, not over 2 kV	0 ft 0.19 in.
Over 2 kV, not over 15 kV	0 ft 1.5 in.
Over 15 kV, not over 36 kV	0 ft 6.3 in.
Over 36 kV, not over 48.3 kV	0 ft 10.0 in.
Over 48.3 kV, not over 72.5 kV	1 ft 3.0 in.
Over 72.5 kV, not over 121 kV	2 ft 1.2 in.
Over 138 kV, not over 145 kV	2 ft 6.6 in.
Over 161 kV, not over 169 kV	3 ft 0.0 in.
Over 230 kV, not over 242 kV	4 ft 2.4 in.
Over 345 kV, not over 362 kV	7 ft 5.8 in.
Over 500 kV, not over 550 kV	10 ft 2.5 in.
Over 765 kV, not over 800 kV	13 ft 10.3 in.

Fig. 6: Insulation distances

D. Arc Flash Boundary as Per Calculation

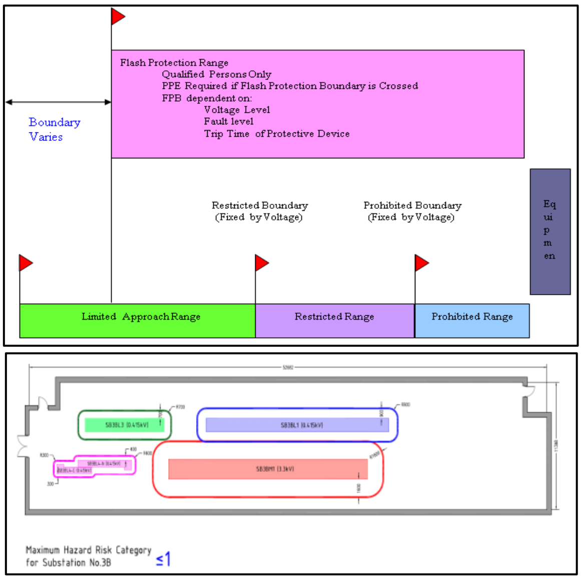

Fig. 7: Arc Flash Boundary as Per Calculation

IV. RECOMMENDATIONS

A. Combined PPE Matrix – Low Voltage

Hazard/Risk Category	Protective Clothing and PPE	PPE Clothing Characteristics and Descriptions	Required Minimum Arc Rating of PPE [J/cm2(cal/cm2)]
Hazard/Risk Category 0 Protective Clothing, Non-melting (according to ASTM F 1506-00) or Untreated Natural Fiber FR Protective Equipment	Shirt (long sleeve) Pants (long) Safety glasses or safety goggles (SR) Hearing protection (ear canal inserts) Leather gloves (AN) (Note 2)	Non-melting, flammable material (i.e., untreated cotton, wool, rayon, or silk, or blends of these materials) with a fabric weight at least 4.5 oz/yd^2	N/A
Hazard/Risk Category 1 FR Clothing, Minimum Arc Rating of 4 (Note 1) FR Protective Equipment	Arc-rated long-sleeve shirt (Note 3) Arc-rated pants (Note 3) Arc-rated coverall (Note 4) Arc-rated face shield or arc flash suit hood (Note 7) Arc-rated jacket, parka, or rainwear (AN) Hard hat Safety glasses or safety goggles (SR) Hearing protection (ear canal inserts) Leather gloves (Note 2) Leather work shoes (AN)	Arc-rated FR shirt and FR pants or FR coverall	16.74 (4)
Hazard/Risk Category 2 FR Clothing, Minimum Arc Rating of 8 (Note 1) FR Protective Equipment	Arc-rated long-sleeve shirt (Note 5) Arc-rated pants (Note 5) Arc-rated coverall (Note 6) Arc-rated face shield or arc flash suit hood (Note 7) Arc-rated jacket, parka, or rainwear (AN) Hard hat Safety glasses or safety goggles (SR) Hearing protection (ear canal inserts) Leather gloves (Note 2) Leather work shoes	Arc-rated FR shirt and FR pants or FR coverall	33.47 (8)

Fig. 8: Combined PPE Matrix – Low Voltage

B. Combined PPE Matrix – Medium Voltage

Hazard/Risk Category	Protective Clothing and PPE	PPE Clothing Characteristics and Descriptions	Required Minimum Arc Rating of PPE [J/cm2(cal/cm2)]
Hazard/Risk Category 3 FR Clothing, Minimum Arc Rating of 25 (Note 1) FR Protective Equipment	Arc-rated long-sleeve shirt (AR) (Note 8) Arc-rated pants (AR) (Note 8) Arc-rated coverall (AR) (Note 8) Arc-rated arc flash suit jacket & pants (AR) (Note 8) Arc-rated arc flash suit hood (Note 8) Arc-rated jacket, parka, or rainwear (AN) Hard hat FR hard hat liner (AR) Safety glasses or safety goggles (SR) Hearing protection (ear canal inserts) Arc-rated gloves (Note 2) Leather work shoes	Arc-rated FR shirt and FR pants or FR coverall, and arc flash suit selected so that the system arc rating meets the required minimum	104.6 (25)
Hazard/Risk Category 4 FR Clothing, Minimum Arc Rating of 40 (Note 1) FR Protective Equipment	Arc-rated long-sleeve shirt (AR) (Note 9) Arc-rated pants (AR) (Note 9) Arc-rated coverall (AR) (Note 9) Arc-rated arc flash suit jacket & pants (AR) (Note 9) Arc-rated arc flash suit hood (Note 9) Arc-rated jacket, parka, or rainwear (AN) Hard hat FR hard hat liner (AR) Safety glasses or safety goggles (SR) Hearing protection (ear canal inserts) Arc-rated gloves (Note 2) Leather work shoes	Arc-rated FR shirt and FR pants or FR coverall, and arc flash suit selected so that the system arc rating meets the required minimum	167.36 (40)

Fig. 9: Combined PPE Matrix – Medium Voltage

C. Ways to Reduce Arc Flash Energy

There are many ways to reduce arc flash energies within a facility. The best method is to de-energize the equipment before work is performed. This reduces the energy level to zero and then arc flash hazard no longer exists.

In many locations, the obvious solution above can not be implemented. Many times, breakers must be racked in and out while the equipment is energized. Sometimes, it can be extremely hazardous or expensive to de-energize or shut down the equipment. For these locations and facilities, several methods are available to reduce the arc flash energy levels.

The three major factors that affect the amount of arc flash energy at a particular location are:

1) Device Operation Time – The time it takes for the upstream device to operate.
2) Fault Current – The amount of fault current that will flow through the upstream protective device and is available at the fault location.
3) Working Distance – The amount of distance between the fault point and the worker.

It is the device operation time that effects the calculations the most, followed by fault current and working distance. In most cases, concentrating more on time reduction will result in a greater reduction in arc flash energy.

Many facilities use thermal magnetic trip units in their low voltage circuit breakers. These breakers have a fixed thermal and adjustable or fixed instantaneous function. Specifying breakers with solid state trip units using long, short, instantaneous, and ground fault functions will increase both equipment protection and coordination between devices. Tighter coordination between devices will mean a reduction in device operating times and arc flash energies.

For double ended substations using a bus tie, the mains and bus tie breaker settings can be set to the same settings. This enables the main to be set with a lower time delay which will reduce energy levels. Sacrificing the selective coordination between these devices is minor since most facilities rarely close the bus tie breakers except for maintenance purposes.

Most modern low voltage switchboards or switchgear can be equipped with trip units that are zone interlocked. If a fault occurs on the main bus, then the main and tie breakers will trip instantaneously instead of using the normal delayed coordination settings.

New trip units are being manufactured with maintenance switches. When this trip unit is switched to maintenance mode, a low instantaneous function is enabled. Should a fault occur, the breaker will quickly trip and reduce the arc flash hazard downstream. These trip units are available on new breakers or retrofit kits for old style power circuit breakers

D. Elimination Hierarchy

Arc flash energy can also be reduced by modification of the work procedures. Examples of this are listed below:

- Eliminating paralleling of transformers (reduces fault current and arc flash energy)
- Eliminating work between Transformer Secondary and Main Breaker. (Normally, the primary device must sense the fault on the secondary side of the transformer. This lower level of fault current, seen by the primary devices causes the trip time to be long. This increased trip time means larger energy levels.
- Implementing faster trip times for maintenance work (See descriptions in previous section)
  1) Circuit Breakers
  2) Relays
  3) Using infrared windows for infrared surveys
  4) Working at a greater distance
  5) Do not stand in front of electrical equipment when operating or inserting (racking in).
  6) Remote breaker racking

E. Arc Flash Label Installation Instructions

Before applying the labels to the equipment, read the important information listed below. Always clean the surface with detergent to remove all grease and dirt. Wipe surface dry before applying the label.

Where possible, apply labels at eye level on equipment covers.

The labels are CUSTOM MADE and are specific for each piece of electrical equipment. Each label has an alpha-numeric ID and Name. The name is shown in parenthesis. Care must be taken when attaching the labels to the equipment.

F. Verify That You Are Attaching The Correct Label To The Equipment!!!

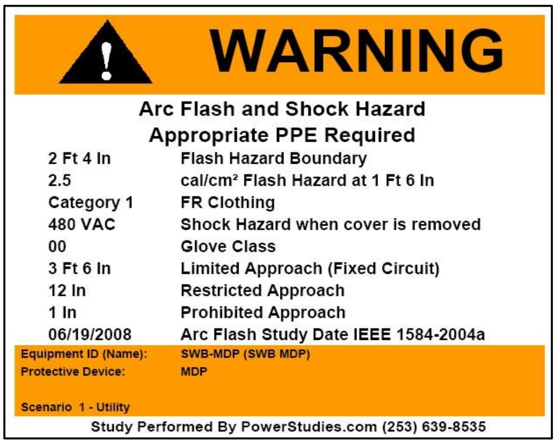

Fig. 10: Verify that you are attaching the Correct Label to the Equipment.

V. CONCLUSION

The purpose of the arc flash study was to determine the available fault current at the switchgear, switchboards, panelboards, and other equipment throughout the facility. The engineer performed the short circuit study on the existing and new equipment being supplied. The engineer compared the fault values to the equipment short circuit rating.

The engineer calculated the fault current using the SKM computer program. This program ignores the current limiting effect of the fuses. If the equipment is underrated on a fully rated basis, then the engineer applies a series rating method.

REFERENCES

[1] IEC 61482 – 1 & 2
[2] NFPA 70 E – Standard for Electrical Safety Requirements for Employee Workplaces
[3] IEEE Std. 1584-2002 - IEEE Guide for Performing Arc-Flash Hazard Calculations

