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Arc Flash Effects: A Comprehensive Review

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Abstract

The electrical breakdown of a gas occurs when the voltage gradient applied is more than the standard voltage prescribed resulting in electric arc formation and subsequent electrical discharge of a gas (arc discharge) producing visible light called "arc" which glows intensely. This paper reviews Arcing effects and terms related to Arc such as Arc Flash and Arc Blast. As per National Fire Protection Association (NFPA) 70E standards, arc flash hazards which are categorised into 5 hazard risk categories and the amount of incident energy released during an arc flash event is analysed under Arc Flash Metrics. The amount of intense light released during the arc discharge and sound effects which affect the personnel are discussed here. The arc flash calculations referred to as Fuse and Circuit Breaker are reviewed with reference to the flash protection boundary and the clearing time required for these equipment and Personnel Protective Equipment (PPE) required for different hazard risk categories is considered with examples and results are comprehended.

Keywords: Arc Blast, Arch Flash, Flash Protection Boundary, Hazard Risk Category, Incident Energy

1. Introduction

When two electrodes are brought together under sufficient voltage an electrical breakdown occurs between the electrodes and subsequent arc formation occurs. An electric arc occurs when high electric field strength (voltage gradient) is applied which causes a breakdown of dielectric material or insulator by increasing the conductivity medium. During arc discharge of gas, the ionisation of the gas molecules results in positively charged ions and electrons that encompass electric current to flow through them. When the current flows, the material becomes heated and it glows visibly and brightly in the shape of an arc as shown in Figure 1.

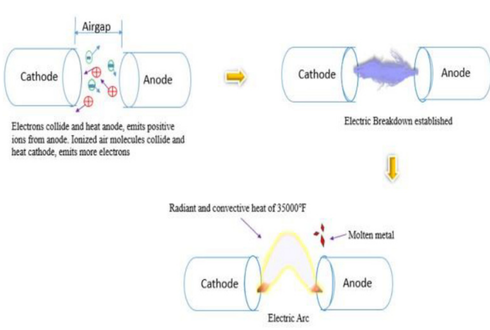

Figure 1. Arc initiation.

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Arcing Effects

- Generation of electromagnetic interference.
- Metal Transfer.
- Welding occurs on contact closure (The heat initiated in the process of arcing enables the contact surfaces to melt)
- The high energy of arcing results in the formation of corrosion products such as oxides, chlorides, sulfides, nitrides and carbon on the metal contact (Activation of contact surface).
- Arc faults give off thermal radiation and bright, intense light that can cause burns to the body, especially to the skin and eyes.
- The main hazard associated with arc flash events is heat, up to 20,000°C, which can cause burn-type injuries. The other risks associated with arc flash events are a blast (and associated debris), ultraviolet light, sound waves, hot plasma, molten metal and infrared radiation[1].

2. Arc Flash and Arc Blast

The light and heat from the massive electrical explosion during an arc fault result in an arc flash and the pressure wave which is followed by the arc flash is arc blast. An arc flash occurs when there is an unforeseen connection between live conductors and an unpredictable abrupt liberation of heat and light energy passing through the air[2].

The arc terminal of equipment can reach temperatures of 35000°F or more and 4 times that of the sun's surface temperature estimated to be 9932°F. Due to this exceeding temperature, the arc surrounded by the air and gases heats up by vapourising the conductors seen in Figure 2.

The major causes of arc faults are voltage transients and these transitions last for a few microseconds resulting in the formation of plasma arc and other lightning strikes, insulation gaps and loose connections inside the measurement device or outside[3]. When an arc flash event occurs, the current carrying capacity of the plasma arc is immense which converts the arc energy to light and heat.

An electric explosion constituted by molten and vapourised metals, high temperature of the arc leads to quick ignition of flammable materials, generation of shock waves and electromagnetic radiation. The arc current can vary up to the maximum available bolted fault current.

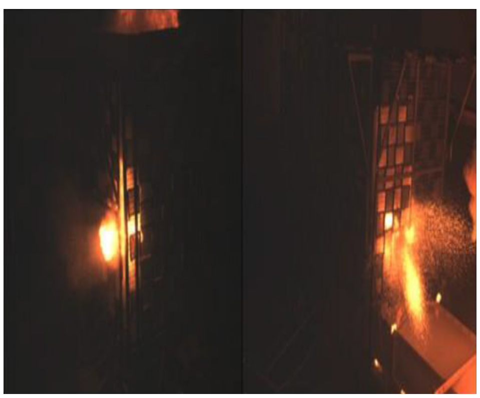

Figure 2. Arc flash

Effects

- Arc blasts due to dynamic pressure waves result in hearing loss to personnel, panels rupture, acoustic injuries, fatal shock, flying debris and physical trauma.
- Secondary effects of arcs include potential damage to electrical equipment/enclosures, release of toxic gases and airborne debris speed up to 300m/s.
- Arc flash produces intense high-energy radiation, arc plasma and ionised particles if inhaled affect the lungs and airways and superheated shrapnel produced due to droplets of molten metal can exceed up to 700MPH speed.

3. Arc Flash Metrics

At the arc point, the release of intense heat causes an arc flash and this heat energy is measured in units such as calories, joules and British Thermal Units (BTU).

The instantaneous degree of heat energy released by an arc flash is quantified as incident energy and generally expressed as calories per square centimetre (cal/cm^2). The arc distance varies with the intensity and level of incident energy. To determine the potential effects of an arc flash, the working distance from an exposed live part is calculated and this distance determines the type and degree of risk necessary for personnel protection against the hazard and arc flash boundaries are shown in Figure 3.

During an arc flash event, based on a certain amount of energy released at a definite working distance, arc flash hazards are categorised into 5 Hazard Risk Categories (HRC) as per NFPA 70E Standards referred to in Table 1.

Table 1. Classification of HRC based on incident energy[4]

Incident Energy(cal/cm^2)	Hazard Risk Category(HRC)
0 to 1.2	0
1.21 to 4	1
4.1 to 8	2
8.1 to 25	3
25.1 to 40	4

Determination of the Severity of Arc Flash.

Arc flash severity varies on certain factors such as:

- Arc gap and distance from the arc.
- System voltage.
- Available short circuit current.
- Opening time of overcurrent protective device. When Arc flash occurs, the overcurrent protective devices such as a Circuit Breaker (CB) or fuse clears the upstream fault by interrupting the current. During an arc flash, whenever the fault occurs, the degree of incident energy a worker may be subjected to is directly proportional to the clearing time (in ampere squared seconds (I^2t)) of the short circuit protective device against the fault current during the fault.

The incident energy produced will be more when high current and long time exposure takes place. So the most effective and practical way to reduce arc flash duration and arc flash incident energy is to use overcurrent breaker devices and the variable which can be controlled is the time taken by these devices to extinguish the arc throughout the electrical system[5].

4. Light and Sound Effects

4.1 Intense light

Direct sunlight is more than 100,000 lux. Considering a distance of 3m from the source, the arc flash light intensity is over 1 million lux and recent records of arc flash show 13.1 million lux which is approximately 130 times brighter than direct sunlight. Electric arcs produce high temperatures ranging up to 35000°*F* which is almost 4 times the sun's surface temperature of about 9000°*F*.

During an arc flash event, the amount of intense light generated emits harmful Ultraviolet (UV) frequencies, causing temporary or permanent blindness. To safeguard the eyes from this hazard, UV light filtering is used for face protection[6].

4.2 Blast and Sound Pressure

The sound energy from resulting arc blast effects develops a dynamic and supersonic wave augmenting pressure and reaching around 160dB rupturing eardrums and causing permanent hearing loss. The rapidly expanding gases and heated air resulting from high temperature vapourise the winding material by expanding at a rate of 67000 times its mass changing from solid to vapour.

5. Flash Hazard Analysis

Based on the available fault current and the time required to open the ground fault devices, calculations related to flash arc and hazards are determined[6,7]. The data provided for a short circuit analysis will be accurate. The latest single-line diagram and further calculations determine the arc Flash Protection Boundary (FPB) distance in feet.

FPB determines the required Distance in Feet (DC) that will produce a second-degree burn on exposed bare skin from a given arc source and varies at every end on different devices[8].

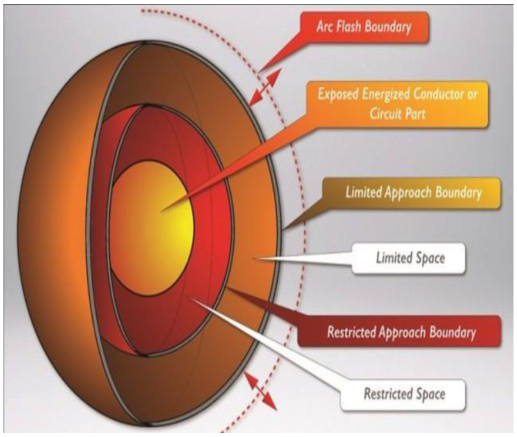

Figure 3. Arc flash boundaries[9].

According to NFPA 70E, based on Overcurrent Protection Device (OCPD) clearing time, the default flash protection boundary is 4 feet which consists of 6 cycles (0.1s) and available 50kA fault current not exceeding 5000As. The following data is required to complete the flash hazard analysis:

- One-line circuit diagram should be updated in the given electrical network.
- Max bolted fault current available and fault current available at each location from utility or generator[10].
- OCPD clearing time and minimum arcing current required for self-sustenance at each location.

6. Arc Flash Calculations

At a particular location, if the available maximum fault current is known, the OCPD analysis can be done which determines the clearing time of fault current[11]. By the above factors, the flash protection boundary and the amount of incident energy can be calculated as shown in Equations 1 and 2 respectively.

Flash Protection Boundary(Dc) is defined by the formula[10]:

$$D_c = [2.65 \text{ x } MVA_{bf} \text{ x } t]^{½} \qquad \ldots\ldots\ldots\ldots\ldots(1)$$

where,

DC = is defined as the protection boundary distance for the arc flash measured in feet.

MVA_{bf} = At fault point. The feasible bolted fault MVA is measured and rated in MVA.

MVA = Transformer capability rated in mega volt-amps.
t = The overcurrent protective device clearing time in seconds.

The short circuit current with a fault of negligible impedance (Isc) is calculated in accordance with the impedance and MVA capacity and rating of the source transformer.

Incident Energy is given by the formula[10]:

$E_{MB} = 1038.7\ D_B^{-1.4738}\ t_A[0.0093F^2 - 0.3453F + 5.9675]$ ……(2)

where,

E_{MB} =The Incident energy measured in cal/cm^2

D_B = Distance from arc electrodes, (here, usually taken as 18in).

t_A = The duration of the arc in seconds.

F = Bolted fault current available and measured in kA.

7. Examples

Calculation of HRC, incident energy, FPB for energised transformer metering section of 2000 KVA, 4160V/480V protected by either 2500A class fuse shown in Figure 4 or 2500A power circuit breaker of low voltage is shown in Figure 5 and analysed in Examples 1 and 2.

Example 1: With current limiting fuse of 5.5 % Z and clearing time of 0.01s at 43.7kA.

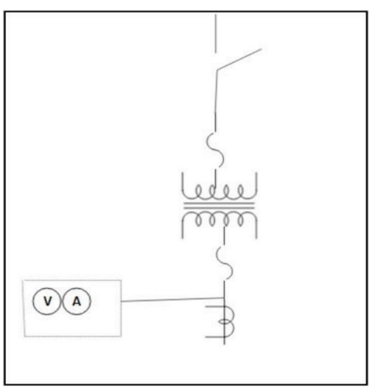

Figure 4. Arc flash calculations with respect to fuse.

- **STEP 1**: MVA_{bf} = (100/%Z)*MVA 2000 KVA=2MVA
  MVAbf = 100/5.5 * 2 = 36.4MVA
- **STEP 2**: To calculate Dc: t=0.01s
  $D_c = [2.65 \text{ x } MVA_{bf} \text{ x } t]^{½}$
  $= (2.65 * 36.4*0.01)^{1/2}$
  = 0.98ft~ 12 inches
- **STEP 3**: $I_{sc} = (MVA \times 10^6 \times 100)/(\sqrt{3} \times Vac \times \%Z)$
  = 43,738A
- **STEP 4:** $F = I_{sc}/1000$ = 43738/1000= 43.7kA
- **STEP 5:** For this calculation, Db=18 inches
  $E_{MB} = 1038.7\ D_B^{-1.4738}\ t_A\ [0.0093F^2 - 0.3453F + 5.9675]$ cal/cm^2
  = 1.27 cal/cm^2

Example 2: Transformer secondary protected with a circuit breaker of clearing time of 0.083s at 43.7kA.

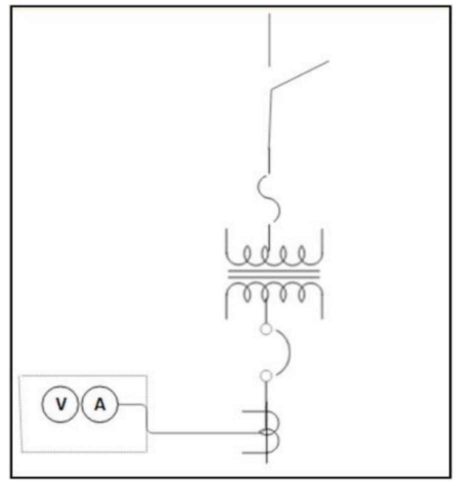

Figure 5. Arc flash calculations referred to circuit breakers.

- **STEP 1**: MVAbf = (100/%Z)*MVA
  2000 KVA=2MVA
  MVAbf = 100/5.5 * 2 = 36.4MVA
- **STEP 2**: To calculate Dc: t=0.083s

$$Dc = \sqrt{[2.65xMV\ Abf\ xt]}$$

$= (2.65 * 36.4*0.083)^{1/2}$
= 2.83ft~ 34 inches

- **STEP 3**: $I_{sc} = [MVA * 10^6 * 100]/[\sqrt{3} *Vac*\%Z]$
  = 43,738A
- **STEP 4**: F= Isc/1000 = 43738/1000= 43.7kA
- **STEP 5**: For this calculation, Db=18 inches
  $E_{MB} = 1038.7\ D_B^{-1.4738}\ t_A\ [0.0093F^2 - 0.3453F + 5.9675]$ cal/cm^2
  = 10.54 cal/cm^2

From the above calculations, it is apparent that incident energy is much less when the current restraint fuse is used analogously to the circuit breaker provided for protection[11,12].

8. Comparison of Results

The arc flash calculations with reference to OCPD are analysed and results are comprehended as shown in Table 2.

Table 2. Results of the comparison of fuse and circuit breaker

Data	Fuse	Circuit Breaker
Fault Current(Isc)	43.7Ka	43.7kA
Flash Protection Boundary(Dc)	12 inches	34 inches
Incident Energy(E_{MB})	1.27 cal/cm^2	10.54 cal/cm^2
Hazard Risk Category	1	3
Personal Protective Equipment(PPE)	1 layer of flame-resistant shirt and pants covering all	3 layers of flame-resistant shirt and pants covering all

9. Conclusion

This article presents an overview of the phenomenon of arc and summarises the effects of arc and the calculations related to arc flash' with reference to the fuse and CB analysed. The amount of incident energy addition to the clearing time of the fuse is much less to clear the arc compared to the circuit breaker and results are compared. The amount of incident energy released during an arc flash event affecting the personnel with concern to various arc flash boundaries and the hazard risk is categorised as per NFPA 70E standards. The light and sound effects of an arc flash and incident energy during an arc flash event emit harmful UV frequencies causing serious health hazards and high temperatures ranging up to 19,426°C which is almost 4 times the sun's surface temperature.

10. Acknowledgements

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