Arc Flash Mitigation
Techniques and
Considerations for
Systems Design
James Lagree
Chief Engineer
Eaton
An Arc Flash - An electrical arc due to either a phase to ground or phase to phase fault.

- 80 percent of all electrical injuries are burns that result from the electric arc flash
- Arc flashes cause electrical equipment to explode, resulting in an arc-plasma fireball
- Solid copper vaporizes, expands to 67,000 times its original volume
- Temperatures exceed 35,000 degrees F
- Detected sound levels of 141.5 decibels
- Pressure levels of 2,160 pounds per square foot
Arc Flash Mitigation

Pre Arcing

Arc Prevention
- Training -Safe Work Practices
- Maintenance
- Good Design
- Remote Racking

Arc Prediction - Monitoring
- Partial Discharge
- Smoke
- Temperature
- Acoustic

Arc Containment
- Arc Resistant / Explosion Proof Enclosures: Panelboards, Switchboards, Motor Control Centers and Switchgear
- Personal Protective Equipment (PPE)

Arc Detection
- Current / Voltage signal analysis
- Ground Fault
- Light sensing

Arc Elimination
- Shorting Bar - Arc Mitigator
- Create a Parallel Arc

Arc Flash Reduction
- Differential Protection
- Zone Selective Interlocking
- Maintenance Switch

Active

Passive

Original Source: IEC SC17B
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Arc Prevention

• De-energize equipment if at all possible
• Label Equipment & Train Personnel
• Minimize Risk with Good Safety Practices
• Move People Further Away
• Closing and tightening door latches or door bolts before operating a switch
• Design the Hazard Out (Safety by Design)
  • Reduce Available Fault Current
  • Faster Clearing Times
Training
Minimize Risks with Good Safety Practices

Bad - Exposed Back of Neck

Good - All of Body Protected Toward the Arc Flash Area
• Addresses electrical safety-related work practices
• Developed in cooperation with OSHA
• Assumes an NEC compliant installation.
• 1979: First published,
• 1995: Added Flash Protection Boundary
• 2000: Focused on personal protective equipment (PPE).
• 2004: Emphasizes safe work practices.
• 2009: Energized work permits, Harmonized with CSA Z462
Good Design Practices
Current Limiting – Circuit Breakers and Fuses

Available Short Circuit Current

Peak Let-Through Current ($I_p$)

$I_{RMS}$

RMS Let-Through Current (Calculated)

$\text{Total Clearing Time}$

$\text{Available Short Circuit Current}$
Good Design
Remote Racking and Robots

VS.

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Racking MCCB Breakers

- Racking Window
- Dead-front Cover
- Dead-front Handles
## Arc Flash Mitigation

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### Arc Detection

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### Arc Elimination

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### Arc Flash Reduction

**Arc Flash Reduction**
- Differential Protection
- Zone Selective Interlocking
- Maintenance Switch

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Predictive Monitoring

• Partial Discharge Monitoring
  – Insulation Integrity
    • Switchgear
    • Generators
    • Motors
  – Transformer Bushings
Stop Switchgear Failures
Thermography – View Ports

- Traditional Infrared Thermograph survey using IR Windows or Viewports
- Visual Inspections
- Scheduled regularly for intervals between shutdown maintenance
- “snapshot” of temperature at the time of the viewing.
  - Thermographer wears appropriate PPE while in the flash boundary
IR scan identified 149.4°F hot spot temperature.

Temperature above the IEEE 1458 Standard of 130°F.

Removed from service and returned for further analysis.
Acoustic Arc Detection

• New technology that detects acoustic signature of micro-arcing of loose connections before they become dangerous.
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Arc Resistant

• Enclosures

• Provide for maximum strength during an arcing fault event.
ARC Resistant - Testing

- Test is successful if:
  - No indicators are burned
  - Doors do not open
  - No projectiles come from equipment
  - No holes are burned in the enclosure
Arc Safety– Arc Resistant Gear

65kA / 508V
Arc initiated in breaker compartment
Plenum Design

Arc projected out of plenum

No arc flash out of the front of the gear
## PPE Clothing

<table>
<thead>
<tr>
<th>Hazard Risk Category</th>
<th>Clothing Description (Number of clothing layers given in parenthesis)</th>
<th>Total Weight oz./yd²</th>
<th>Minimum Arc Thermal Performance Exposure Value (ATPV)* or Breakopen Threshold Energy (E_b)* Rating of PPE cal/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Untreated Cotton (1)</td>
<td>4.7 - 7</td>
<td>1.2</td>
</tr>
<tr>
<td>1</td>
<td>FR Shirt and FR Pants (1)</td>
<td>4.5 – 8</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>Cotton Underwear plus FR Shirt and FR Pants</td>
<td>9 – 12</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>Cotton Underwear plus FR Shirt and FR Pants plus FR Coverall (3)</td>
<td>16 – 20</td>
<td>25</td>
</tr>
<tr>
<td>4</td>
<td>Cotton Underwear plus FR Shirt and FR Pants plus Double Layer Switching Coat and Pants (4)</td>
<td>24 -40</td>
<td>40</td>
</tr>
</tbody>
</table>

Extracted from NFPA 70E-2004
Based upon maximum energy for a 2nd degree burn (1.2 cal/cm²)
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Pre Arcing | Arcing | Passive | Active
Line-to-Line-to-Line Fault

Bolted Fault

Arcing Fault
Arc Detection - AFCI

• Arc Fault Circuit Interrupter
  • UL 1699 standard – Residential
  • Standard thermal-magnetic (overload-short circuit protection) circuit breaker with AF technology.
  • Some designs contain 20mA GF protection although the standard does not require it.
Arc Detection - AFCI

Sputtering parallel arc waveform

Parallel arc

Series arc

120V ac

Cable impedance

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Arc Detection - AFCI

Standard overcurrent protection does not detect if:

- Parallel Arc Faults are sputtering – will not trip on overload because there is not enough RMS heating current.
- Parallel Arc Faults that are limited due to wiring impedances – Below the breaker’s instantaneous value.
- Algorithms for Parallel arc fault protection looking at the slope of the rise of the fault current.
- Series Arc Faults that look like load current – Ok arcs (light switch, bimetal on a skillet or coffee pot)
- Complex Algorithms for series arc faults to detect the signature of good vs. bad arcs.
Arc Detection - Ground Fault Sensing

- Different levels of protection:
  - Machinery Equipment Protection
    - 30mA Sensitivity = Equipment Protection
  - Personnel Protection
    - NEC Code says less than 6mA sensitivity required to protect people
    - IEC standard says less than 30mA sensitivity should be used.
- High Resistance Grounding
  - Reduces the level of current in arcing faults to ground
Arc Flash Light Detection Relays

- Speed, no intentional delays (2ms operate time – 52ms Trip Time)
- Sensitive, adjustable phase and ground fault current set-points from sensitive to above load
- Selectivity, trip only affected feeder(s)
- Secure, dual-sensing option (current and light) prevents false trips
- Full self-supervision
Arc Light Detection - Sensors

**EAFR-06** – Arc light plastic fiber sensor

**EAFR-07** – Arc light glass fiber sensor
Arc Light Detection - Point Light Sensor

- Wired connections provides simple installation and allows full factory testing even with shipping splits
- Current signaling based information (2mA, 20mA)
- Maximum 3 sensors in line (up to 700 feet)
- Snap-in cable connector for quick installation
- Shielded cable connection
- Three styles of different light intensity (8000, 25000, or 50000 Lux)
- 180 degrees of visibility.
# Options for Arc Flash Relay Modules

<table>
<thead>
<tr>
<th>Features</th>
<th>EAFR-110F</th>
<th>EAFR-110P</th>
<th>EAFR-102</th>
<th>EAFR-101/D</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Phase Current Detection</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Ground Current Detection</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Maximum Point Sensors</td>
<td>0</td>
<td>12</td>
<td>0</td>
<td>12</td>
</tr>
<tr>
<td>Maximum Fiber Loop Sensors</td>
<td>3</td>
<td>0</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>High Speed Outputs (2ms)</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Trip Relays (7ms)</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

![EA FR-110](EA FR-110.png)  
![EA FR-101/102](EA FR-101/102.png)  
![EA FR-101D](EA FR-101D.png)  

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Arc Detection – Light / Current

- Detect (sputtering) low power phase to ground arc faults
  - Optimal sensor sensitivity for quick detection before fault escalates.
  - Current pickup setting for high resistance sputtering fault current condition on phase or ground.

Trip Signal sent out
Arc Detection – Light Selectivity
Sensor Locations

- Point Sensors
- Arrows Point to the Fiber Loop
Arc Detection - Light Sensing

• Contact parting creates arc
• Magnetic field pulls arc into arc extinguisher
• Arc divided and cooled by steel plates
• Arc extinguishes, opening circuit
Arc Detection - Light Sensing

- Low Voltage Circuit Breakers create arc flash light when they interrupt.
- Do not want to trip the upstream circuit breaker on the light produced by the circuit breaker that is closest to the fault and is interrupting to clear the fault.
- There are light sensing relays with restrain signals to prevent nuisance trip on circuit breaker arc flash.
Fault/Arc Clearing Timing

Fault Current / Arcing Event Starts

- 2 to 7ms: Light Detected and initiate a Shunt Trip coil
- 35ms: Breaker contacts part
- 13ms: Fault Clears
- ~52ms: Light Sensor Tripping a Circuit Breaker
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Arc Quenching Devices – Shorting Bar

- Shorting bar – eliminates current flow to fault (load)
- Maximum fault current is created.
- Large stress on upstream breaker and transformer
- Dangerous arc fault is cleared in less than 7ms
- Created fault is cleared 1 to 2 cycles later by the upstream circuit breaker
Quench the Arc with another Arc
Create an Arc In Parallel

- Higher impedance fault then the Shorting Bar (quenching device).
- Less stress on the upstream circuit breaker and transformer
Fault/Arc Clearing Timing

Fault Current / Arcing Event Starts

- 4 to 7ms
  - Short Circuit eliminated
  - Quenching Device Enabled
  - Created Fault Clears

- 2 to 7ms
  - Light Detected and initiate a Shunt Trip coil

- 35ms
  - Breaker contacts part

- 13ms
  - Fault Clears

- ~5ms
  - Light Sensor Tripping a Circuit Breaker

- ~52ms
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NEC 2014’s Section 240.87

(B) **Method to Reduce Clearing Time.** One of the following or approved equivalent means shall be provided:

1. Zone-selective interlocking or
2. Differential relaying or
3. Energy-reducing maintenance switching with local status indicator or
4. Energy-reducing active arc flash mitigation system or
5. An approved equivalent means
(1) Zone Selective Interlocking

Important Clearing Time Information

Circuit Breaker Time/Current Curves (Phase Current)
Magnum, Magnum DS and Magnum SB Circuit Breakers
Response: Long Delay (I^2 T) & Short Delay Trip (FLAT & I^2 T)
This curve is for 50Hz or 60Hz applications.

Notes:
1. If Long delay memory is enabled, trip times may be shorter than indicated on this curve.
2. This curve shown as a multiple of the LONG PU Setting (I_p). The actual Pickup point is not indicated and is typically a function of the Unit Status LED on the product. The actual Pickup point occurs at 110% of the I_p current.

LongTIME Curve Equation: Trip = LongTIME * 36/I^2,
where I is a multiple of I_p. The Trip Function and the LongTIME function act independently and the entire set of LongTIME curves continue to be active even after the curves intersect.

3. With Zone Selective Interlocking enabled, max trip times w/o aux power are as follows:
   - 3-phase fault:
     - 60 Hz: 75ms
     - 50 Hz: 85ms

When only one pole is carrying current and a fault occurs, trip times increase to 95ms at 50 Hz, however with Aux power these times would be reduced by 10%.
ZSI

- zone selective interlock (ZSI): A system feature designed to reduce thermal and mechanical stress on electrical distribution equipment during short-circuit or ground-fault events. ZSI permits the nearest upstream circuit breaker to a short-circuit or ground-fault to clear the fault without intentional delay, while maintaining system coordination, see NEMA PB 2.2. Per NEMA AB3-2013
Zone Selective Interlocking Example

Zone 1

Zone 2

Zone 3
Zone Selective Interlocking

Zone 1

1.1

zone 200ms

Zone 2

1.2

zone 100ms

Zone 3

1.1

zone 100ms

Fault Current

Trip Time

M

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Zone Selective Interlocking

Zone 1
- t_{sd} = 200ms

Zone 2
- t_{sd} = 100ms

Zone 3
- t_{sd} = 100ms

Fault Current

Trip Time

Zone Trip

M

Zone 1
- ZSI

Zone 2
- ZSI

Zone 3
- ZSI

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Zone Selective Interlocking

Zone 1

Zone 2

Zone 3

\[ t_{sd} = 300\text{ms} \]

\[ t_{sd} = 200\text{ms} \]

\[ t_{sd} = 100\text{ms} \]

\[ t_{sd} = 100\text{ms} \]

Fault Current

Trip Time
Zone Selective Interlocking

- **Zone 1**
  - \( t_{sd} = 300 \text{ms} \)
  - **Zone Trip**

- **Zone 2**
  - \( t_{sd} = 200 \text{ms} \)
  - **Zone Trip**

- **Zone 3**
  - \( t_{sd} = 100 \text{ms} \)
  - **Zone Trip**

Trip Time

Fault Current

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Zone Selective Interlocking

Zone 1
- $t_{sd} = 200\text{ms}$

Zone 2
- $t_{sd} = 100\text{ms}$

Zone 3
- $t_{sd} = 100\text{ms}$

Graph:
- Trip Time vs. Fault Current
- Time delays: 1.1, 2.1, 3.1
Zone Selective Interlocking

Zone 1
- Zone Trip
- $t_{sd} = 300\text{ms}$

Zone 2
- $t_{sd} = 200\text{ms}$

Zone 3
- $t_{sd} = 100\text{ms}$
- $t_{sd} = 100\text{ms}$

Fault Current

Trip Time

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ZSI – Design Considerations

• Number of devices
• Auxiliary Power – requirement
• Length of each run
• Compatibility with other protective devices – MV
ZSI – Terminology

• ZSI on Instantaneous?

• Definition of Instantaneous: short circuit protection without an intentional time delay.

• Actually it is a second short delay function with ZSI because it has a restraining signal.
Fault/Arc Clearing Timing

Fault Current / Arcing Event Starts

- **ETU powers up**: 4 to 7 ms
- **Zone Out Signal**: 21 ms
- **Short Circuit eliminated**: 32 ms
- **Quenching Device Enabled**: ~5 ms
- **Breaker contacts part**
- **Fault Clears**: ~5 ms
- **Zone Interlock Trip**: ~70 ms
- **Light Sensor Tripping a Circuit Breaker**: ~52 ms

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(2) Differential Relaying

- Similar To Zone Selective Interlocking
- Recognizes Faults Within The Zone Of Protection
- Acts To Reduce Arc Flash
Differential Relaying

• Recognizes Faults Within The Zone Of Protection

• Current into and out of the zone must equal.

• If current is not balanced it is going into Acts To Reduce Arc Flash
Fault/Arc Clearing Timing

Fault Current / Arcing Event Starts

4 to 6ms ETU powers up

4 to 6ms ETU powers up

4 to 7ms Short Circuit eliminated

2 to 7ms Light Detected and initiate a Shunt Trip coil

25ms Trip Coil Engaged

32ms Quenching Device Enabled

35ms Light Sensor Tripping a Circuit Breaker

16ms Breaker contacts part

13ms Fault Clears

16ms Fault Clears

13ms Fault Clears

13ms Fault Clears

37ms Zone Out Signal

16ms Trip Coil Engaged

13ms Breaker contacts part

~5ms Zone Interlock Trip

~52ms Light Sensor Tripping a Circuit Breaker

~58ms Software Instantaneous Trip

~70ms Zone Interlock Trip

~5ms Quenching Device Enabled

~58ms Trip Coil Engaged

~52ms Breaker contacts part

~70ms Fault Clears

~70ms Fault Clears

~70ms Fault Clears
(3) Energy-reducing maintenance switching with local status indicator

Lockout
Tag out
Switch

Indicating Light
Arc Flash Reduction Maintenance Switch

- ARMS uses a separate bypass path that is strictly analog, bypassing all issues such as microprocessor boot up time, A/D conversion rate or code execution time saving a couple of milliseconds (and therefore calories) over something that "just" uses the instantaneous trip.

- Blue LED “Maintenance Mode” lit indicates that it is engaged.

5 Position Arc Flash Reduction Setting:
  - From R5 (10x trip rating) .... To R1 (2.5x trip rating) Reduction

- Remote Indication:
  - Power Relay Module Maintenance Mode Contact

- Remote Enable: via communications

- Lock-out/Tag-out
Arc Reduction – Maintenance Mode Switch

3 ways to enable the Maintenance Switch
1) Face of the trip unit
2) Remote Switch
3) Communications
Arc Flash Testing
IEEE 1584 Test Setup for Power Circuit Breakers

Lab Output Terminals

Circuit Breaker

Cable Connection to Downstream Test Enclosure

3/4” Diameter Copper Electrodes

7 Calorimeter Array Simulates Body Torso

Arc Flash Hazard Area

20 ”x 20” x 20” Downstream Test Enclosure With Open Front

Open Side of Enclosure

Output = Arc Flash Energy

18 AWG Shorting Wire between 3 Phase Electrodes Creates Arcing Fault

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Magnum DS Arc Flash Test Program

Eaton High Power Test Laboratory – Test configured per IEEE 1584

Circuit breaker with ARMS enabled

Enclosure with internal 3 phase fault

Calorimeter Array
Maintenance Mode Switch – MCCB Tests

Electrodes: Phase A, B, & C
Induced Low-Level Arcing Fault w/ 16 Gauge Wire
Arc Flash Reduction
Maintenance Switch (ARMS)

• ARMS uses a separate bypass path that is strictly analog, bypassing all issues such as microprocessor boot up time, A/D conversion rate or code execution time saving a couple of milliseconds (and therefore calories) over something that "just" uses the instantaneous trip.
Upon completion of the maintenance, the lock is removed, the switch is manually opened, and all previous trip unit settings are again re-activated, without need for recalibration.
Maintenance Mode Now Available for Molded Case Circuit Breakers

- Two instantaneous Maintenance Mode Settings of 2.5 and 4x In
- Five Instantaneous Normal Mode Settings of 6, 7, 8, 10 and 12 x In

MCCB Breaker with Maintenance Mode Equipped Trip Unit
Maintenance Mode Trip Curves

Typical

ARMS 2.5X

Current (pu)

Time (s)

Current (pu)

Time (s)
Fault/Arc Clearing Timing

- **Fault Current / Arcing Event Starts**

- **4 to 6 ms**
  - Analog powers up
  - ETU powers up

- **4 to 7 ms**
  - Short Circuit eliminated
  - ETU powers up

- **2 to 7 ms**
  - Light Detected and initiate a Shunt Trip coil

- **35 ms**
  - Breaker contacts part

- **13 ms**
  - Fault Clears

- **Quenching Device Enabled** ~5 ms
  - Created Fault Clears

- **4 to 7 ms**
  - Light Sensor Tripping a Circuit Breaker ~52 ms

- **Maintenance Mode Switch (ARMS) Trip** ~33 ms
  - Breaker contacts part

- **Software Instantaneous Trip** ~58 ms
  - Trip Coil Engaged
  - ETU powers up

- **Zone Interlock Trip** ~70 ms
  - Zone Out Signal
  - Trip Coil Engaged
  - ETU powers up

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**Arcing**

**Passive**

**Active**