Arc Flash Considerations for Utility and Industrial Power Systems

2020 Safety/Security Panel Session

IEEE Twin Cities
Biographies
Industrial Segment

**Speaker #1 & Moderator**

Ryan Bergeron, MSEE, MBA, IEEE Senior Member
- ABB Field Application Engineer/Principal Consultant, Minneapolis, MN
- ABB CEU Certified / Authorized IACET CEU Trainer
- Phone: (612) 916-9911
- Ryan.Bergeron@us.abb.com / Ryan.Bergeron.us@ieee.org
- IEEE Twin Cities PES/IAS, Chair
  - 2019 High Performing Chapter (HPCP)
- MIPSYCON Planning Committee Member

16+ Years Experience in Power Systems
- 38kV and Below Designs
- Webinars/Presentations: EasyPower ‘18, EasyPower ‘19, MIPSYCON ‘19

**Speaker #2**

Craig Thingvold, P.E.
- Manager Power Studies and Electrical Design at Excel Engineering, St. Paul, MN
- Phone (763) 231-8566
- Craig.Thingvold@exceleng.net
- Arc Flash
- Power Quality
- Industrial Electrical Design
- Transmission System Planning and Analysis
- **13+ years experience in Power Studies**
Biographies

Utility Segment

Speaker #3

Jeff Liebsch, P.E.
- System Engineer, Power System Engineering, Minneapolis, MN
- System Planning & Studies Department
- Distribution Planning
- Operations Support
- Member: IEEE
- Phone (763) 783-5348
- liebschj@powersystem.org

15+ Years Experience in Power Systems
- Presentations: IEEE 1584-2018 Arc Flash, Motor Start and Voltage Flicker

Speaker #4

Eduardo Ramirez Bettoni, P.E. (MN)
- Xcel Energy Principal Engineer, Minneapolis, MN
- Substation & Transmission Standards Department
- IEEE PES Substations: G0 Vice-Chair, G6 Secretary
- ASTM: WK 72436 Chair, WK 70226 Co-Chair
- Member: IEEE 80, 81, 516, 1048, 1067, 1246, C37.122.1
- Member: ASTM F1506, WK 55884
- US National Committee IEC TC78 member “Live work”
- CIGRE B3.54 member “Earthing”
- eduardo.ramirez.bettoni@xcelenergy.com

18+ Years Experience in Power Systems
- 500kV and Below Design, Construction, O&M
Agenda

1) Industrial Segment
   • Ryan Bergeron and Craig Thingvold, P.E.

2) Utility Segment
   • Jeff Liebsch, P.E. and Eduardo Ramirez Bettoni, P.E.

3) Q&A Panel
Electric Industrial Segment
Panel Creation, Technical Resources, and Industry Updates
Industrial Segment for 38kV and Below

Feedback from 2019 MIPSYCON Evaluation Report

1) “Like to have a panel discussion on utility arc flash calculations.”

2) “Discussion about the changes in standards covering arc flash...between NFPA 70E-2018 and IEEE 1584-2018...how they affect arc flash safety.”

3) “Low Voltage Fuse Application”
   • **Technical Resource:** [2019 MIPSYCON Presentation for Circuit Breakers and Fuses]
     o 1-15kV Fuses: Refer to page 15
     o 0.48kV Fuses: Refer to pages 12, 13, 17-20, 22, 25, 42

Industry Updates from NFPA-70E, IEEE, etc.

1) **Major Changes to 2021 Edition of NFPA 70E – Standard for Electrical Safety in the Workplace** (every three years) in [Informational Annex D.4 IEEE 1584-2018 Calculation Method] (target page 0)

2) 35 states have adopted the 2017 NEC Code (see [NEC Adoption by State]) representing 70% of the U.S.

3) **IEEE Standards Association:** There is a corrigendum PAR (Project Authorization Request) open now as well as a revision PAR for [IEEE C37.20.7-2017]. This standard has been expanded over the years to cover significantly more equipment varieties, providing a consistent set of testing requirements over a range of product types.

4) **Historical safety note:** Legal entities back 20 years ago described that exhausting gases inside a room/enclosure may lead to legal claims from people stating they suffered by inhaling poisonous gases.
Dangerous Arc Flash Event!!

- Accidents, Fatalities, etc.
- Litigation, Fines, etc.
- Stress

Diagram:

- Conventional
- Standard
- Better
- Active

- Steel Fire
- Copper Fire
- Cable Fire
Demystifying Arc Flash Solutions
Low Voltage Arc Flash Improvements: 0.6kV and Below

Faster Time = Higher Safety

- **240.67 (B)(2) Fused**
  - Energy Reducing Switch: Modbus, Profibus, DNP3, etc.
  - 3.8 cal/cm²

- **240.87 (B)(3) Circuit Breaker**
  - Energy Reducing Switch: CAT-5e or Better, Ethernet
  - 2.7 cal/cm²

Benefits from:
- CAT-5e or Better and IEC 61850-8-1 GOOSE

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**WARNING**

Arc Flash and Shock Risk Assessment
Appropriate PPE Required

- 3' - 6''
  - Arc Flash Boundary: 1.3 cal/cm² at 24.0 inches - Arc Flash Incident Energy
  - Refer to NFPA 70E-2018 Table 130.5(O)
  - Equipment Name: LV MAIN 4000_A
  - Low Voltage Circuit Breaker Clearing Time = 42 ms

- 0.48
  - kV Shock Hazard when cover is removed
  - 3' - 6'' Limited Approach
  - 1' - 0'' Restricted Approach - Class 00 Voltage Gloves

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**WARNING**

Arc Flash and Shock Risk Assessment
Appropriate PPE Required

- 3' - 6''
  - Arc Flash Boundary: 1.3 cal/cm² at 24.0 inches - Arc Flash Incident Energy
  - Refer to NFPA 70E-2018 Table 130.5(O)
  - Equipment Name: LV MAIN 4000_B
  - Low Voltage Circuit Breaker Clearing Time = 30 ms

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*IEEE 1584-2018 Guide for Performing Arc-Flash Hazard Calculations (HCB orientations used)*
Benefits of IEEE and IEC

Improvements of Connection and Protocol Standards

1979: Modbus/Modbus RTU – 0.04 Mbps
1989: Profibus – 12 Mbps
1993: DNP3 – 12 Mbps (event based)

IEEE
Institute of Electrical and Electronics Engineers

IEC
International Electrotechnical Commission

Ethernet 802.3 Connection Standards

1995: IEEE 802.3u – 100 Mbps (CAT-5e)
1998: IEEE 802.3z – 1 Gbps
2002: IEEE 802.3ae – 10 Gbps (CAT-6)
2006: IEEE 802.3an – 10 Gbps (CAT-6)
2010: IEEE 802.3ba – 100 Gbps

IEC/IEEE 61850 Protocol Standards

2009: IEC 61850-6 Configuration to IEDs
2011: IEC 61850-8-1 Manufacturing Message Specification (GOOSE) with CAT-5e or better
2016: IEC/IEEE 61850-9-3 - Precision Time Protocol for Power Utility Automation

Applications

Medium Voltage
Low Voltage

Low Voltage
Medium Voltage

Applications

Institute of Electrical and Electronics Engineers
International Electrotechnical Commission

Ethernet 802.3 Connection Standards

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IEC/IEEE 61850 Protocol Standards

2009: IEC 61850-6 Configuration to IEDs
2011: IEC 61850-8-1 Manufacturing Message Specification (GOOSE) with CAT-5e or better
2016: IEC/IEEE 61850-9-3 - Precision Time Protocol for Power Utility Automation
## Advanced Protocol Characteristics

**GOOSE vs Sampled Measured Values (SMV)**

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>8-1 GOOSE</th>
<th>9-2LE SMV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characteristics</td>
<td>Event driven</td>
<td>Streaming</td>
</tr>
<tr>
<td>Information transmitted</td>
<td>Binary, Enum</td>
<td>Analog</td>
</tr>
<tr>
<td>Update rate</td>
<td>On data change</td>
<td>Continuous Sampling rate</td>
</tr>
<tr>
<td>Update intervals</td>
<td>1ms ... 1s</td>
<td>200-250us</td>
</tr>
</tbody>
</table>
Demystifying Arc Flash Solutions
Industrial Segment for 40kV and Below

Faster Time = Higher Safety

Players & Experience
Relay + Device
11 Years
2 Years
2 Years

QRU + UFES
(Ultra Fast Earthing System)

Arc Quenching
SiQuench

Active: 24/7

[4-5] 10

Time [ms]

0.4 cal/cm²

Arc Flash and Shock Risk Assessment
Appropriate PPE Required

 Relay + Device Clearing Time = 4 ms
### Active Arc Mitigation: 24/7

**Industrial Applications and Results**

<table>
<thead>
<tr>
<th>Circuit Breakers</th>
<th>Fuses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal-Clad Switchgear (IEEE C37.20.2)</td>
<td>Metal-Enclosed Switchgear (IEEE C37.20.3)</td>
</tr>
</tbody>
</table>

- **Transformer(s)**
- **Switchgear (UL 1558)**

<table>
<thead>
<tr>
<th>N/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Technology Not Available)</td>
</tr>
</tbody>
</table>

**WARNING**

Arc Flash and Shock Risk Assessment
Appropriate PPE Required

- 0.4 cal/cm²
- 0.4
- Arc Flash Boundary
- 24.0 Inches - Arc Flash Incident Energy
- Refer to NFPA 70E-2018 Table 130.5(G)

- Equipment Name: XF SEG 2500_B (Fed by: [Manual Time])

**Relay + Device Clearing Time = 4 ms**
System Reliability and Impacts on Arc Flash Hazards

Service life
- Not well published by manufacturers
- Environmental impacts
- Loading

Westinghouse technical bulletin
- TB-04-13

<table>
<thead>
<tr>
<th>Equipment Type</th>
<th>Expected Useful Life Period (years)¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformers</td>
<td>25 to 30</td>
</tr>
<tr>
<td>Circuit Breakers</td>
<td>20²</td>
</tr>
<tr>
<td>Switchboards/Switchgear</td>
<td>30 to 40</td>
</tr>
<tr>
<td>MCC / Motor Starters</td>
<td>20 to 30</td>
</tr>
<tr>
<td>Panelboards</td>
<td>30</td>
</tr>
<tr>
<td>Motors</td>
<td>18 to 25</td>
</tr>
<tr>
<td>Generators</td>
<td>5 to 20</td>
</tr>
<tr>
<td>UPS</td>
<td>10</td>
</tr>
<tr>
<td>Luminaire</td>
<td>20</td>
</tr>
<tr>
<td>Capacitors (Power Factor Correction)</td>
<td>17</td>
</tr>
<tr>
<td>VFDs</td>
<td>20</td>
</tr>
<tr>
<td>Cable/Wire</td>
<td>30 to 40</td>
</tr>
</tbody>
</table>

¹Life expectancy info collected from ABB, CDA, CDM, IEEE Gold Book, and Siemens.
²By year 10, 50% of circuit breakers don’t function properly per specs. By year 20, 90% don’t function properly.

System Reliability and Impacts on Arc Flash Hazards

Issues with aging Molded Case Circuit Breakers (MCCBs)

**Electrical components**
- Corrosion
- Oxidation
- Pitting
- Welding
- Increased contact resistance

**Lubrication**
- Grease
- Red Oil

**Case and Mechanical**
- Cracking/damage due to high fault current
- Damage due to overheating
- Wear from use as switch
- Corrosion due to environment
System Reliability and Impacts on Arc Flash Hazards

Recommended practices for electrical testing and maintenance:

• Manufacturer Recommendations
• NFPA 70B
• InterNational Electric Testing Association (NETA)
• National Electrical Manufacturers Association (NEMA)
• IEEE
Real World Sample Testing

- Client concerned about the reliability of MCCBs in system
- Experienced a number of circuit breaker failures
  - Breaker(s) would not open when using handle
  - Unable to close breaker after opening.
  - Contacts welded in some cases
  - Delayed opening when using the trip button
  - Failure to trip causing conductor insulation to melt and trip of upstream unit substation breaker on ground fault.
Real World Sample Testing

Sample testing

- 450 MCCB’s were removed and tested
- Single and three pole breakers
- Approximately 20% did not operate within manufacturers trip curves.
- Most were 20+ years old
- Many were sticky, difficult to operate
- Many had high contact resistance
Impact on AF Hazard due to Delayed Clearing

Panelboard
• 480V
• 800A
• 3 cycle circuit breaker
• Hazard increases 33% by one additional cycle delay

<table>
<thead>
<tr>
<th>Bus Name</th>
<th>Bus kV</th>
<th>Bus Bolted Fault (kA)</th>
<th>Electrode Config</th>
<th>Arc Flash Boundary (in)</th>
<th>Working Distance (in)</th>
<th>Incident Energy (cal/cm²)</th>
<th>% Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>PANEL (3 CYCLE)</td>
<td>0.48</td>
<td>27.73</td>
<td>VCBB</td>
<td>33</td>
<td>18</td>
<td>3.50</td>
<td>-</td>
</tr>
<tr>
<td>PANEL (4 CYCLE)</td>
<td>0.48</td>
<td>27.73</td>
<td>VCBB</td>
<td>38</td>
<td>18</td>
<td>4.67</td>
<td>33%</td>
</tr>
<tr>
<td>PANEL (5 CYCLE)</td>
<td>0.48</td>
<td>27.73</td>
<td>VCBB</td>
<td>43</td>
<td>18</td>
<td>5.83</td>
<td>67%</td>
</tr>
<tr>
<td>PANEL (6 CYCLE)</td>
<td>0.48</td>
<td>27.73</td>
<td>VCBB</td>
<td>48</td>
<td>18</td>
<td>7.00</td>
<td>100%</td>
</tr>
<tr>
<td>PANEL (7 CYCLE)</td>
<td>0.48</td>
<td>27.73</td>
<td>VCBB</td>
<td>52</td>
<td>18</td>
<td>8.16</td>
<td>133%</td>
</tr>
<tr>
<td>PANEL (8 CYCLE)</td>
<td>0.48</td>
<td>27.73</td>
<td>VCBB</td>
<td>56</td>
<td>18</td>
<td>9.33</td>
<td>167%</td>
</tr>
<tr>
<td>PANEL (9 CYCLE)</td>
<td>0.48</td>
<td>27.73</td>
<td>VCBB</td>
<td>60</td>
<td>18</td>
<td>10.5</td>
<td>200%</td>
</tr>
</tbody>
</table>
Impact on AF Hazard due to Failure of Main Device to Operate
Comparison of results based on normal operation vs failure of main protective device.
Electric Utilities Segment

Updates on Industry Standards and Tools (IEEE 1584-2018, ArcPro 3.0, etc.)
Electrode Configuration Definitions from IEEE 1584-2018
VOA, HOA, VCB, HCB, VCBB

VOA = vertical conductors/electrodes in open air
HOA = horizontal conductors/electrodes in open air
VCB = vertical conductors/electrodes inside a metal box/enclosure
HCB = horizontal conductors/electrodes inside a metal box/enclosure
VCBB = vertical conductors/electrodes terminated in an insulating barrier inside a metal box/enclosure
Arcing Current from IEEE 1584-2018
What changed?

Highest variations from bolted fault currents occur at lower voltage levels.

In old (2002) IEEE 1584 Standard:
➢ Additional calculation at 85% reduced arcing current (if < 1 kV)

In new standard (2018):
➢ Arcing Current Variation Correction Factors (208 – 15,000 V)

\[
I_{\text{arc,Var}} = 10^{(k1+1.1k2+1.9k3)\left(k4I_{\text{ar}} + k5I_{\text{arc}}^2 + k6I_{\text{arc}}^3 + k7I_{\text{arc}}^4 + k8I_{\text{arc}}^5 + k9I_{\text{arc}}^6 + k10\right)}
\]  

\[
I_{\text{arc,Var,}208} = I_{\text{arc,Var,}2700} \frac{I_{\text{arc,Var,}208} - I_{\text{arc,Var,}2700}}{2.1}\left(V_{\text{oc}} - 2.7\right) + I_{\text{arc,Var,}2700}
\]  

\[
I_{\text{arc,Var,}15000} = I_{\text{arc,Var,}2700} \frac{I_{\text{arc,Var,}15000} - I_{\text{arc,Var,}2700}}{11.6}\left(V_{\text{oc}} - 14.3\right) + I_{\text{arc,Var,}14300}
\]  

\[
I_{\text{arc,Var,}208} = I_{\text{arc,Var,}1}\left(2.7 - V_{\text{oc}}\right) + I_{\text{arc,Var,}2}\left(V_{\text{oc}} - 0.6\right) \frac{2.1}{2.1}
\]

where
- \(I_{\text{arc,1}}\) is the first \(I_{\text{arc}}\) interpolation term between 600 V and 2700 V (kA)
- \(I_{\text{arc,2}}\) is the second \(I_{\text{arc}}\) interpolation term used when \(V_{\text{oc}}\) is greater than 2700 V (kA)
- \(I_{\text{arc,3}}\) is the third \(I_{\text{arc}}\) interpolation term used when \(V_{\text{oc}}\) is less than 2700 V (kA)
- \(V_{\text{oc}}\) is the open-circuit voltage (system voltage) (kV)
Intermediate values are calculated for three voltage levels: 600 V, 2,700 V, and 14,300 V.

Final incident energy results are then calculated using interpolation equations.

Similar to low voltage calculations from old standard, the incident energy is calculated at a reduced arcing current, and the higher of the 2 values is used.

Arc flash boundary is still distance at which incident energy is 1.2 cal/cm².

\[
E_i = \frac{E_{2700} - E_{600}}{1.2} (V_{in} - 2.7) + E_{2700}
\]

\[
E_i = \frac{E_{14300} - E_{2700}}{11.6} (V_{in} - 14.3) + E_{14300}
\]

\[
E_i = \frac{E_1 (2.7 - V_{in})}{2.1} + \frac{E_2 (V_{in} - 0.6)}{2.1}
\]

where

- \(E_1\) is the first \(E\) interpolation term between 600 V and 2700 V (J/cm²)
- \(E_2\) is the second \(E\) interpolation term used when \(V_{in}\) is greater than 2700 V (J/cm²)
- \(E_3\) is the third \(E\) interpolation term used when \(V_{in}\) is less than 2700 V (J/cm²)
Box/Enclosure Dimensions from IEEE 1584-2018
More new variables! Height x Width x Depth

Width must be at least 4x the gap between conductors

Range of gap for IEEE 1584 is 19.05 mm – 254 mm (0.75 in to 10 in)

Width and height must be less than or equal to 49 inches

Depth doesn’t come into play if > 600 V

Default Box Dimensions:

➢ (30” width) x (45” height) x (30” depth), per IEEE 1584-2018 Table 8
Multiple Source Calculations

How is incident energy calculated if PD1 and PD2 don’t open at the same time?
Varying Fault Current Levels
What if a single protective device sees a varying level of fault current over time?
Manhole Calculations

What are my box dimensions??

Wait a second...I've got to think *inside* the box!
Main Takeaways

How to handle new IEEE 1584-2018 Standard??

• Results are never “dead on”!
• Incident energy calculations are good approximations as long as good engineering judgment is used.
• New variables → more complexity → fine-tuning will be needed!
• Always err on the side of caution → avoid the onset of 2nd degree burns!

Sources:
• IEEE Standards 1584-2002, 1584-2018
• Jim Phillips: brainfiller.com
• www.e-hazard.com
• “Pressure Developed by Arcs”, 1987 IEEE Paper by Ralph H. Lee
How Much Importance are Calculations in an Arc Flash Program?

Calculations are only a small component in a Company program: don’t forget hazard recognition, risk mitigation and training

Focus on elimination, substitution, engineering controls…
Focus on work tasks
Check what switching scenarios apply
Invest in a good live tool testing program
Avoid over-conservative estimates
Make arc tables and PPE levels easy to understand
Estimates are accurate enough to produce curable injuries
PPE is the last line of defense
How Much Importance are Calculations in an Arc Flash Program?

Customize your calculations to the work tasks

- Hot-sticking
- Bare-hand
- TPG
- Gloving
- Low Voltage Insulated Tools
Key Aspects on How to Estimate Arc Flash in Electric Utility Assets
Utilities are large scale systems with 1000’s of equipment spread out over a large geographical area

Challenges
- System diversity (configuration)
- Data accuracy and site confirmation
- Diversity in work methods
- Increasing fault current over time
- Refreshing calculations every X years
- Maintenance vs. construction tasks
- Upstream device rule
- Cable vault applications

Good Strategies
- First review work methods and risk assessment
- Some activities do not require estimates
- Can the system be modeled? Is testing required?
- Learn how much the calculation method is developed
- Do the results require multiplication factors?
- OSHA allows assumptions in similar systems
- Overhead systems ➔ single phase faults
- Enclosures ➔ 3ph faults
- Use 2 sec self-extraction rule
Estimating methods vs. Reality
Get familiar with how the method was produced and how far it can get you...

- 100 cal/cm² arc flash suits
- ASTM F2621 Test
- 103 cal/cm² suits
  114%
- 100 cal/cm² suits
  111%

8,221 A, 2.252 sec
90 cal/cm² target
Estimating methods vs. Reality

Get familiar with how the method was produced and how far it can get you...

- ASTM F2621 Test
- 100 cal/cm² AR Hoods
- 8,158 A, 2.169 sec
- 90 cal/cm² target

- 109 cal/cm² suits
- 121%

- 117 cal/cm² suits
- 130%
Q&A Panel

2020 Safety/Security Panel Session

IEEE Twin Cities
Thank You