# UNDERSTANDING THE EFFECT OF ELECTRODE CONFIGURATION ON INCIDENT ENERGY AND ARC-FLASH BOUNDARY

Copyright Material IEEE
Paper No. ESW2020-45

Adam Reeves, P.E.
Member, IEEE
Eaton
7451 Coca Cola Drive
Hanover, MD 21076
USA
AdamReeves@eaton.com

Mark Freyenberger, P.E.
Member, IEEE
Eaton
50 Soccer Park Drive
Fenton, MO 63026
USA
MarkAFreyenberger@eaton.com

Michael Hodder, P.Eng.
Member, IEEE
Eaton
610 Industrial Drive, Unit #2
Milton, ON L9T 5C3
Canada
MichaelBHodder@eaton.com

***Abstract*** – The 2018 update to the IEEE Std. 1584 Guide for Performing Arc-Flash Hazard Calculations has introduced new electrode configurations that can drastically affect incident energy calculations and labeling. The electrode configurations discussed in this paper are: Vertical conductors/electrodes inside a metal box/enclosure (VCB), Vertical conductors/electrodes terminated in an insulating barrier inside a metal box/enclosure (VCBB) and Horizontal conductors/electrodes inside a metal box/enclosure (HCB). It is generally understood that at typical working distances, HCB will produce a higher incident energy than VCBB, which will produce a higher incident energy than VCB with all other parameters equal. However, there is a counter-intuitive trend for the arc-flash boundary, such that the boundary distance for HCB is often lower than the boundary for VCBB and VCB. The electrode configuration will also affect the magnitude of arcing current, which may result in varying fault clearing times depending on which electrode configuration is selected. This paper will discuss arcing fault current, incident energy, and arc-flash boundary results for each enclosed electrode configuration that challenge the assumption that HCB will always yield the worst-case incident energy and arc-flash boundary.

*Index Terms* — Arcing fault current, arc flash, arc-flash boundary, arc-flash hazard analysis, electrode configuration, HCB, IEEE 1584, incident energy, VCB, VCBB, working distance.

## I. INTRODUCTION

NFPA 70E-2018 [1]. Annex D encourages users to consult the latest version of the IEEE Std. 1584 document.

IEEE Std. 1584-2002 [2] did not include electrode configuration as an input variable to the arc-flash calculation model. However, equipment modeled as “arc in a cubic box” using IEEE Std. 1584-2002 equations is equivalent to the VCB configuration in IEEE Std. 1584-2018 [3]. Other electrode configurations discussed in IEEE Std. 1584-2018 that are inside a metal “box” enclosure include VCBB and HCB.

It is possible for electrical equipment to have multiple electrode configurations and in some cases even within the same compartment. When multiple electrode configurations are considered, it is not always intuitive which electrode configuration will result in the highest calculated incident energy and arc-flash boundary at a single location. The effects of electrode configuration are now required to be considered when the worst-case incident energy and arc-flash boundary are reported in an arc flash report and label. The relationships discussed in this paper are valid for enclosed equipment ≤ 600 V. The effects on equipment locations above 600 V and for open air electrode configurations are not discussed.

## II. ARCING FAULT CURRENT

### *A. Electrode Configurations*

The calculated arcing fault current is dependent on the selected electrode configuration. In general, the arcing fault current of a VCBB fault will have a higher magnitude than the arcing fault current of a VCB or HCB fault, with all other parameters equal.

It is expected that during a VCBB fault, the insulating barrier will collect and contain the arc plasma at the ends of the conductors. The containment of arc plasma near the fault location creates a lower impedance arc which results in a higher arcing fault current magnitude. During a VCB or HCB fault, there is no barrier to contain the arc plasma, so the arc can bow out away from the fault location, creating a longer arc with greater impedance.

The arcing current for a VCB fault is generally similar to the arcing current for an HCB fault. The only difference between the VCB and HCB configurations is the orientation of the conductors to the calorimeters that IEEE Std. 1584-2018 used to measure incident energy. The energy measured by the calorimeters do not affect the arcing current calculations.

### *B. Sample Arcing Fault Current Calculation*

Consider a sample arcing fault current calculation for a switchgear work location with the parameters in Table I.

TABLE I
SAMPLE CALCULATION PARAMETERS

| Input Parameter | Value |
|---|---|
| Voltage | 480 V |
| Gap | 32 mm |
| Working Distance | 24 in |
| Height | 20 in |
| Width | 20 in |
| Depth | n/a |
| $I_{bf}$ | 50 kA |
| Fault Clearing Time (FCT) | 2000 ms |

978-1-7281-6438-0/20/$31.00 ©2020 IEEE

Authorized licensed use limited to: Eaton Corporation. Downloaded on June 22,2022 at 18:55:41 UTC from IEEE Xplore. Restrictions apply.

Table II shows the arcing current results using the calculation parameters of Table I.

TABLE II
ARCING CURRENT RESULTS

| Electrode Configuration | Value |
|---|---|
| VCB | 30.6 kA |
| VCBB | 35.0 kA |
| HCB | 30.1 kA |

The results in Table II show that the VCBB arcing fault current is higher than the VCB and HCB current as expected. Fig. 1 plots this trend across the entire bolted fault current range of IEEE Std. 1584-2018 and confirms that VCBB generally yields a higher arcing fault current with all other parameters equal.

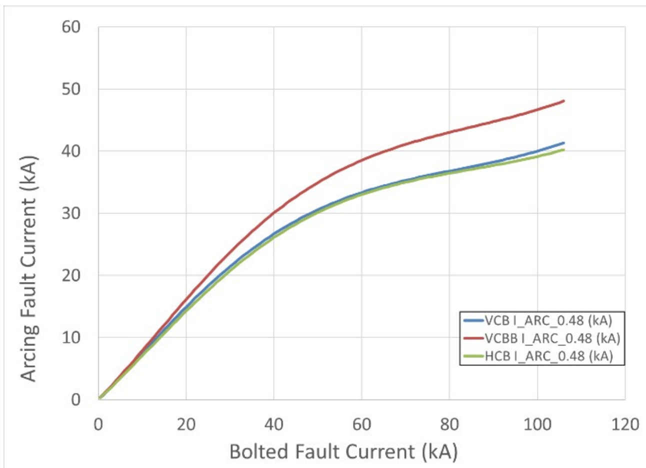


Fig. 1 Arcing Fault Current vs. Bolted Fault Current

## III. INCIDENT ENERGY

### *A. Electrode Configurations*

The calculated incident energy is also dependent on the selected electrode configuration. VCB will yield the lowest incident energy at a typical working distance with all other parameters equal. VCBB will yield the next highest incident energy, followed by HCB.

1) *VCB*: During a VCB fault, the arc will move away from the source, and the plasma will be directed off the ends of the conductors, parallel to the enclosure opening.

2) *VCBB:* During a VCBB fault, the arc is expected to move away from the source and terminate at an insulating barrier. The barrier will direct some of the arc plasma towards the enclosure opening, resulting in a higher incident energy than VCB.

3) *HCB:* During an HCB fault, the ends of the conductors are pointed directly towards the enclosure opening. When the arc moves away from the source, the plasma will be directed out of the enclosure opening and will yield a higher incident energy than both VCB and VCBB.

### *B. Sample Incident Energy Calculation with Fixed Clearing Time*

Table III shows the incident energy results from a sample switchgear installation with same parameters of Table I.

TABLE III
INCIDENT ENERGY RESULTS

| Electrode Configuration | Value |
|---|---|
| VCB | 105.0 cal/cm$^2$ |
| VCBB | 145.3 cal/cm$^2$ |
| HCB | 188.6 cal/cm$^2$ |

The results in Table III show the HCB incident energy is higher than the VCBB and VCB incident as expected. Fig. 2 plots this trend across the entire bolted fault current range of IEEE Std. 1584-2018 and confirms that HCB yields a higher incident energy with all other parameters equal.

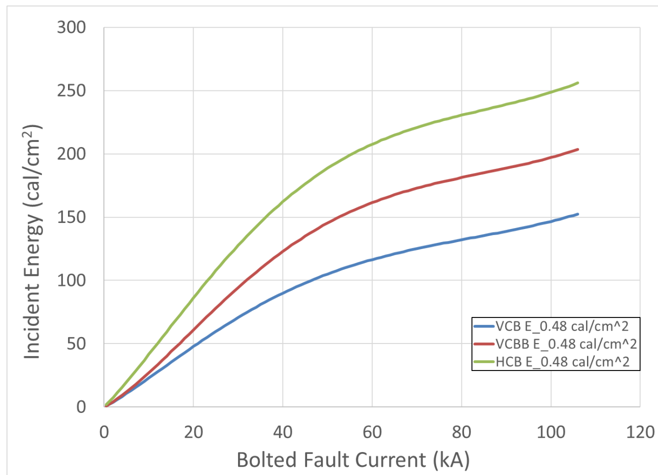


Fig. 2 Incident Energy Plot vs. Bolted Fault Current with Fixed Clearing Time

### *C. Sample Incident Energy Calculation with Varied Clearing Time*

The calculations in Fig. 2 assume a fixed fault clearing time over the entire range of bolted fault current, which is not realistic in distribution systems. As the fault current varies, the line-side protective device response time will change the fault duration based on the device tripping characteristics.

For example, a 50 kA fault will likely result in an instantaneous response of a circuit breaker, whereas a 20 kA fault may take longer to clear due to an intentional delay for coordination. A 20 kA fault that lasts for a longer time may result in a higher incident energy than a 50 kA fault that clears instantaneously. Even though VCB is intuitively expected to have a lower incident energy, the higher arcing fault current from VCBB may result in a faster clearing time. This may cause the VCBB result to have a lower final incident energy than VCB.

Fig. 3 plots the incident energy result over a range of bolted fault currents, but instead of a fixed fault clearing time, it considers the response of an upstream protective device with an electronic trip unit with Short Time and Instantaneous responses enabled. Table IV shows the device settings for this sample



Authorized licensed use limited to: Eaton Corporation. Downloaded on June 22,2022 at 18:55:41 UTC from IEEE Xplore. Restrictions apply.

calculation. Note that pickup values shown in Table IV include typical trip unit tolerance.

TABLE IV
SAMPLE CIRCUIT BREAKER SETTINGS

| Input Parameter | Value |
|---|---|
| Trip Setting | 4000 A |
| Short Time Pickup | 4x (16,800 A) |
| Short Time Delay | 300 ms |
| Instantaneous Pickup | 6x (26,400 A) |

Fig. 3 shows that the electrode configuration that yields the lowest incident energy will change based on the varying bolted fault current, which impacts arcing fault current and clearing time.

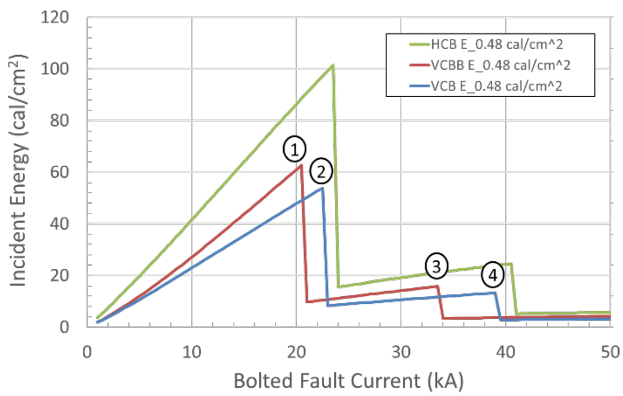


Fig. 3 Incident Energy Plot vs. Bolted Fault Current with Varied Clearing Time

- Point 1 – The VCBB fault reaches the STPU
- Point 2 – The VCB fault reaches the STPU
- Point 3 – The VCBB fault reaches the INST
- Point 4 – The VCB fault reaches the INST

The first observation is that HCB yields the highest incident energy over the entire fault current range. This is expected because the HCB arcing current is less than or equal to the VCBB and VCB arcing current, so the clearing time for HCB will always be greater than or equal to the VCBB or VCB clearing time.

The second observation in Fig. 3 is that at times the VCBB incident energy is greater than the VCB incident energy, and at other times the VCB incident energy is greater than the VCBB incident energy. Consider the following points on the plot:

- For fault currents up to point 1, both the VCB and VCBB arcing fault currents are below the Short Time Pickup (STPU) of the protective device. In this example, a maximum of 2 second fault clearing time is considered. For a fixed clearing time, VCBB is higher than VCB.
- At point 1, the VCBB arcing fault current causes an STPU response of the overcurrent protective device. The lower arcing fault current of VCB has not yet reached the STPU, so from points 1 to 2, VCB has a higher incident energy because of the longer clearing time.
- At point 2, the VCB arcing fault current exceeds the STPU of the protective device. Between points 2 and 3, both VCBB and VCB have the same clearing time of 300 ms. For a fixed clearing time, VCBB has a higher incident energy.
- At point 3, the VCBB arcing fault current causes an instantaneous response before the VCB arcing fault current exceeds the instantaneous pickup. Between points 3 and 4, VCB has a higher incident energy because of the longer clearing time.
- Finally, at point 4, the VCB arcing fault current exceeds the instantaneous pickup. For fault currents past point 4, both configurations have the same instantaneous clearing time. For a fixed clearing time, VCBB has a higher incident energy.

## IV. ARC-FLASH BOUNDARY

### *A. Electrode Configurations*

The calculated arc-flash boundary is also dependent on the selected electrode configuration but does not follow the same trend as incident energy. Depending on the bolted fault current and clearing time, an HCB fault could either yield the highest arc-flash boundary, or the lowest arc-flash boundary.

Prior to the introduction of electrode configurations, incident energy was always positively correlated to the arc-flash boundary. This is still true when only considering one electrode configuration. However, due to differences in arc behavior, the highest incident energy does not always correspond to the highest arc-flash boundary when multiple configurations are considered in IEEE Std. 1584-2018.

As the distance from the arc increases, the incident energy will decrease. Because the arc-flash boundary is defined as the distance at which the incident energy is calculated to be 1.2 cal/cm$^2$, a higher incident energy will correspond to a higher arc-flash boundary with all other parameters equal. However, as working distance increases, the rate at which the incident energy decreases is not the same for each electrode configuration.

The HCB incident energy decreases at a faster rate as distance increases, so at a large enough distance from the arc, HCB will no longer yield the highest incident energy and will have the lowest boundary. The VCBB incident energy decreases at a faster rate than VCB, so at a large enough distance from the arc, VCBB will have a lower incident energy than VCB and a lower boundary.

### *B. Sample Arc Flash Boundary Calculation with Fixed Clearing Time*

Table V shows the arc flash boundary results from the sample switchgear installation with parameters of Table I.

TABLE V
ARC-FLASH BOUNDARY RESULTS

| Electrode Configuration | Value |
|---|---|
| VCB | 394.1 in |
| VCBB | 340.2 in |
| HCB | 289.9 in |

The results in Table V show the VCB arc-flash boundary is higher than the HCB and VCBB arc-flash boundaries. Fig. 4 plots this trend across the entire bolted fault current range of IEEE Std. 1584-2018 and confirms that HCB yields the lowest arc-flash boundary for most bolted fault current values with a fixed 2000 ms fault clearing time.



Authorized licensed use limited to: Eaton Corporation. Downloaded on June 22,2022 at 18:55:41 UTC from IEEE Xplore. Restrictions apply.

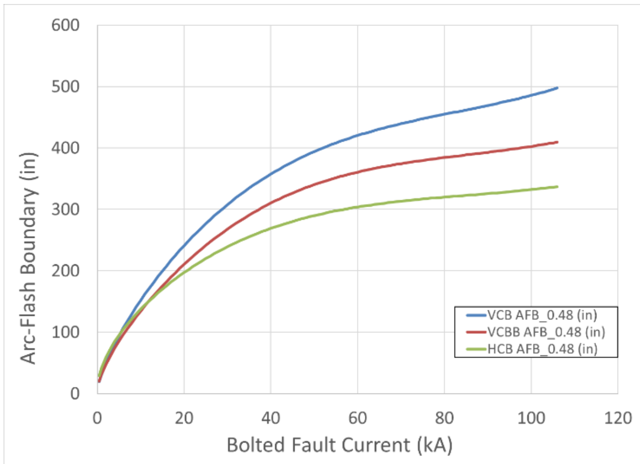

Fig. 4 Arc-Flash Boundary vs. Bolted Fault Current with Fixed Clearing Time

### *C. Sample Arc-Flash Boundary Calculation with Varied Clearing Time*

Fig. 4 assumes a fixed fault clearing time over the entire range of bolted fault current, which is not realistic in distribution systems. As the fault current varies, the upstream overcurrent protective device operating response will vary the fault duration.

Fig. 5 combines the previous incident energy (I.E) plot with the arc-flash boundary (AFB) results when considering the effect of an upstream protective device with settings shown in Table IV. Results for the arcing fault current and reduced (MIN) arcing fault current are plotted and HCB has been removed for simplicity.

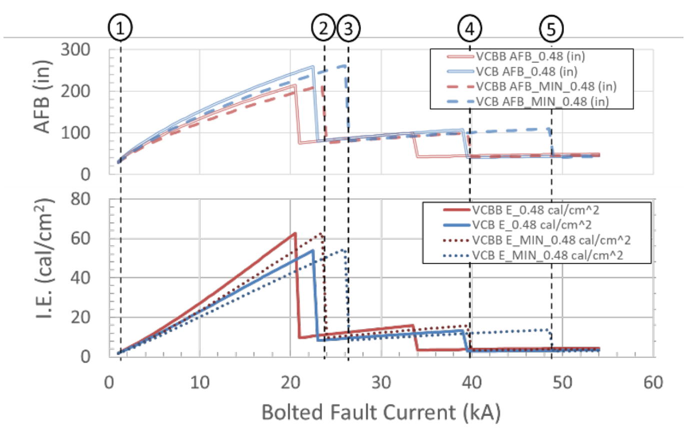

Fig. 5 Combined Plot with Varied Clearing Time

Fig. 5 illustrates that when VCBB and VCB are considered, the worst-case arc-flash boundary and the worst-case incident energy are not associated with the same electrode configuration for most fault current ranges.

- Between points 1 and 2, VCBB yields the highest incident energy, but VCB yields the highest arc-flash boundary.
- Between points 2 and 3, VCB yields both the highest incident energy and arc-flash boundary.
- Between points 3 and 4, VCBB yields the highest incident energy, but VCB yields the highest arc-flash boundary.
- Between points 4 and 5, VCB yields both the highest incident energy and arc-flash boundary.

## V. WORKING DISTANCE

At typical working distances, HCB is always expected to have the highest incident energy because the arc plasma is forced directly towards the calorimeters in the IEEE Std. 1584-2018 tests. However, this arc plasma is quickly dissipated, and the effect of the HCB is lessened as distance increases. As distance increases, the HCB incident energy will decrease faster than the VCBB and VCB incident energy. This implies that at some distance from the arc, HCB will no longer have the highest incident energy.

Fig. 6 illustrates how the incident energy will decrease as working distance increases for each electrode configuration. Note that the y-axis is plotted on a logarithmic scale. This calculation is performed at a typical switchgear location with a fixed bolted fault current of 50 kA and fault clearing time of 500 ms.

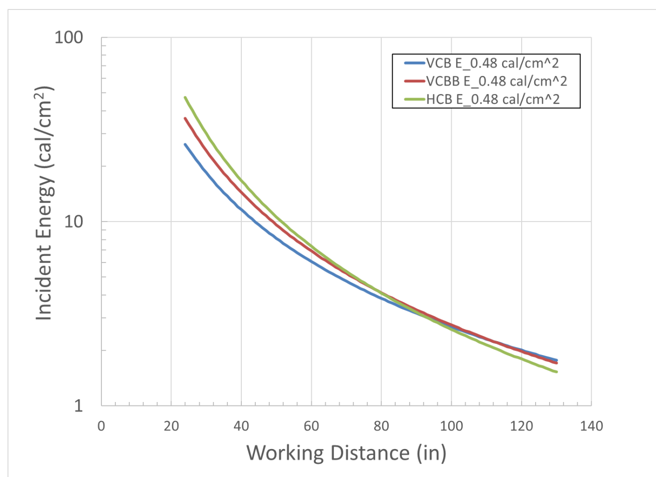

Fig. 6 Incident Energy vs. Working Distance

The incident energy for each configuration decreases at a different rate. Fig. 7 expands an area of Fig. 6 to show the points where the incident energy lines for each electrode configuration intersect.



Authorized licensed use limited to: Eaton Corporation. Downloaded on June 22,2022 at 18:55:41 UTC from IEEE Xplore. Restrictions apply.

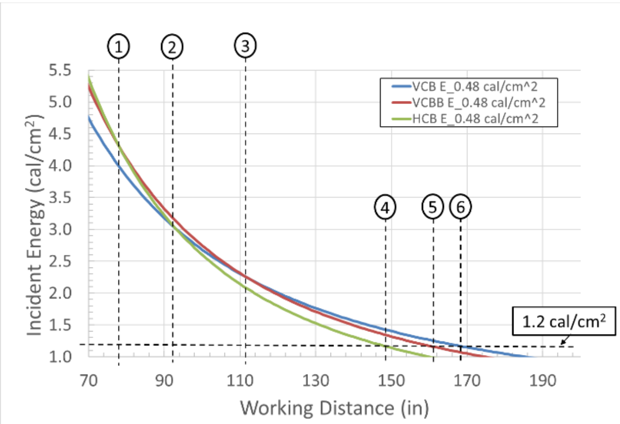

Fig. 7 Incident Energy vs. Working Distance

- Prior to point 1, the HCB incident energy is highest, followed by VCBB and VCB.
- At point 1, the HCB incident energy decreases and is now lower than the VCBB incident energy, but higher than the VCB incident energy.
- At point 2, the HCB incident energy decreases further and is now lower than both the VCBB and VCB incident energy.
- At point 3, the HCB and VCBB incident energy decrease further and VCB now yields the highest incident energy.
- At point 4, the HCB is the first electrode configuration to reach 1.2 cal/cm$^2$ at a distance of 146 in.
- At point 5, the VCBB incident energy reaches 1.2 cal/cm$^2$ at a distance of 158 in.
- At point 6, the VCB incident energy reaches 1.2 cal/cm$^2$ at a distance of 165 in.

The distances at which each configuration is calculated to have an incident energy of 1.2 cal/cm$^2$ are defined as the arc-flash boundary. In this example and many other cases, the HCB configuration has the smallest arc flash boundary, even though it has the highest incident energy at a typical working distance.

## VI. CONCLUSIONS

### A. *Worst Case Incident Energy*

When multiple electrode configurations are considered at an equipment location, determining the electrode configuration that results in the highest incident energy is not always intuitive because it depends on the conditions for which the incident energy is being calculated.

HCB will always yield a higher incident energy than VCBB and VCB for a typical working distance with all other parameters equal. The next highest incident energy can be either VCBB or VCB, depending on the arcing fault current and device clearing time and cannot be easily determined without detailed calculations.

At larger working distances, HCB may no longer yield the highest incident energy because as distance from the arc increases, the HCB incident energy decreases at a faster rate than the VCBB and VCB incident energy.

### B. *Worst Case Arc-Flash Boundary*

When multiple electrode configurations are considered at an equipment location, the configuration that results in the largest arc-flash boundary is not always the one that yields the highest incident energy for specific tasks.

At lower bolted fault current values and/or lower fault clearing times, HCB will generally yield the highest arc-flash boundary. At higher bolted fault currents and/or higher fault clearing times, VCB or VCBB will generally yield the largest arc-flash boundary.

The electrode configuration that yields the worst-case arc-flash boundary will change depending on the system parameters. In addition, the electrode configuration that yields the largest arc-flash boundary does not always correspond to the electrode configuration that yields the worst-case incident energy.

### C. *Reporting Incident Energy and Arc-Flash Boundary Results*

IEEE Std. 1584-2018 requires the selection of at least one electrode configuration for each arc flash calculation. It is likely that many real-world equipment installations contain more than one configuration. This requires the qualified person performing the arc-flash study to perform multiple calculations for a single location. It can be tempting to use typical rules and assumptions to ignore results for a single configuration, but the variations in arcing current and arc-flash boundary make it difficult to determine which configurations will yield a higher result without performing detailed calculations.

It is critical that the qualified person performing the arc-flash study understand the electrode configurations used for each calculation and consider not only the worst-case incident energy, but also the worst-case arc-flash boundary when reporting results in an arc flash study report and label.

## VII. ACKNOWLEDGEMENTS

The authors would like to thank the IEEE1584 working group for their work in updating IEEE Std. 1584-2018 Guide for Performing Arc-Flash Hazard Calculations, as well as previous presentations and tutorials presented at the IEEE Electrical Safety Workshop (IEEE ESW) and IEEE IAS Petroleum and Chemical Industry Committee (IEEE PCIC) conferences that have facilitated discussions that have led to this paper.

## VIII. REFERENCES

[1] NFPA 70E-2018, *Standard for Electrical Safety in the Workplace*, Quincy, MA: NFPA

[2] IEEE Std 1584-2002, *IEEE Guide for Performing Arc-Flash Hazard Calculations*, New York, NY: IEEE.

[3] IEEE Std 1584-2018, *IEEE Guide for Performing Arc-Flash Hazard Calculations*, New York, NY: IEEE.

## IX. VITA

Adam Reeves received a BSEE from the University of Maryland and joined Eaton in 2012. Mr. Reeves is currently working as Lead Power Systems Engineer for Eaton's Electrical Engineering Services and Systems. His main responsibilities include performing power system studies and training regarding short circuit, coordination, arc flash, and power quality. Mr.



Authorized licensed use limited to: Eaton Corporation. Downloaded on June 22,2022 at 18:55:41 UTC from IEEE Xplore. Restrictions apply.

Reeves is the Chairman of Eaton's Arc Flash Committee and is responsible for the standardization and improvement of arc flash methods at Eaton Electrical. He is a member of the IEEE and a registered Professional Engineer in the State of Maryland.

Mark Freyenberger received a BSEE from Kansas State University in 2007 and joined Eaton in 2013. Mr. Freyenberger is currently working as Power Systems Engineer Project Leader for Eaton's Electrical Engineering Services and Systems. His main responsibilities include performing power system studies, training regarding electrical safety, and project management for national accounts. He is a member of the IEEE and registered Professional Engineer in six states.

Michael Hodder received a BASc in Electrical Engineering from the University of Waterloo in 1977. Mr. Hodder is currently working as an Advisory Power Systems Engineer for Eaton's Electrical Engineering Services and Systems. His main responsibilities include performing power system studies and training regarding electrical safety and power system studies. Mr. Hodder is a member of Eaton's National Safety Council. He is also a member of the Technical Committee on Workplace Electrical Safety (CSA Z462). He is a member of the IEEE Industrial Application Society and is a registered Professional Engineer in the province of Ontario.



Authorized licensed use limited to: Eaton Corporation. Downloaded on June 22,2022 at 18:55:41 UTC from IEEE Xplore. Restrictions apply.