WHITE PAPER

Reducing arc flash energy levels on dry-type secondary substations using metal-enclosed switchgear with vacuum breakers

A basic protection scheme involves replacing the fuse set in an existing high voltage load-break interrupter switch (LIS) with a compact vacuum breaker and installing an overcurrent protection relay and a primary set of current transformers in the LIS.

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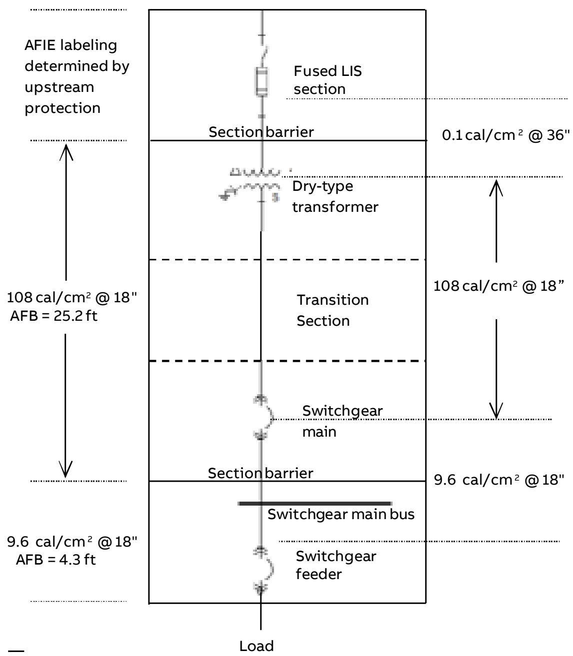
Abstract
Dry-type secondary substations can be found in a variety of settings, including manufacturing facilities, commercial buildings, data centers and medical facilities. These substations are commonly located inside such facilities, and, due to their physical design, the arc flash incident energy is typically well above the extreme danger level as defined by NFPA 70E when the primary protection is a fused switch. Numerous power distribution equipment manufacturers offer metal-enclosed switchgear with fixed mounted vacuum breakers as well as retrofit packages that replace the fuse set in a high voltage load-break interrupter switch with a vacuum breaker and overcurrent relay. The vacuum breaker and overcurrent relay combination can greatly reduce the arc flash incident energy on the typical dry-type secondary substation, as compared to primary fuse protection. This paper discusses both basic and advanced application of metal-enclosed vacuum breaker switchgear for reducing arc flash incident energy and, at the same time, improving the protection scheme for the dry-type secondary substation.

Index terms
Dry-type secondary substation, load-break interrupter switch (LIS), arc flash incident energy (AFIE), extreme danger level, metal-enclosed vacuum breaker switchgear

Introduction
Dry-type secondary substations typically consist of a single enclosure with a high voltage LIS section that is close-coupled to a dry-type transformer section. The transformer section is close-coupled to a transition section and low voltage switchgear sections. No internal barriers exist between the transformer section, the transition section and the first switchgear section. Ventilation openings are located at the top and bottom of every section of the substation enclosure.

The open construction of dry-type substations allows for the possibility that an arcing fault event will propagate to other locations in the substation.

Consequently, the substation must be labeled with the worst-case arc flash incident energy level. For transformers of sufficient capacity using primary fuse protection, the worst-case arc flash incident energy is typically in excess of 40 calories/cm^2, which is the threshold for the extreme danger level as defined by NFPA 70E.



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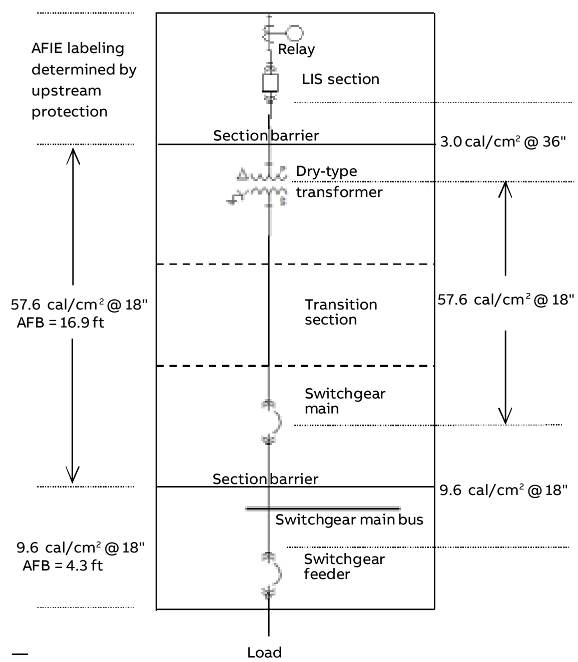
01 Enclosure arrangement and arc flash calculations for a typical 2,500 kVA, dry-type secondary substation

Figure 1 shows the enclosure arrangement and the arc flash hazard calculations for a typical 2,500 kVA, dry-type secondary substation when a fuse provides the primary protection.[1] The arc flash incident energy results shown on the right-hand side of the figure are for specific regions of bus. In figure 1 and in all other cases presented in this paper, it is assumed that the section barriers shown are adequate to justify independent labeling of the neighboring sections. The secondary gear is assumed to be of switchgear, not switchboard, construction. The expected labeling of the enclosures based on the highest incident energy within the section is shown on the left-hand side of figure 1. The arc flash incident energy is over 2.5 times the 40 calories/cm^2 extreme danger threshold. With the lack of internal barriers and the ventilation openings in some enclosures, it is essential to reduce the arc flash incident energy on all parts of the substation.

Various techniques are available to mitigate or reduce the arc flash incident energy in this typical substation. Some techniques can retain the use of the primary fuse when a high-speed grounding switch and relay are added. [2] [3] This paper will examine the arc flash energy reduction when the fuse is replaced by a vacuum breaker in metal-enclosed construction.

Basic protection using LIS with vacuum breaker
A basic protection scheme involves replacing the fuse set in an existing high voltage LIS with a compact vacuum breaker and installing an overcurrent protection relay and a primary set of current transformers (CTs) in the LIS. Metal-enclosed switchgear is also available assembled at the factory in this configuration. Figure 2 illustrates this protection arrangement and the resulting arc flash energy.[2]



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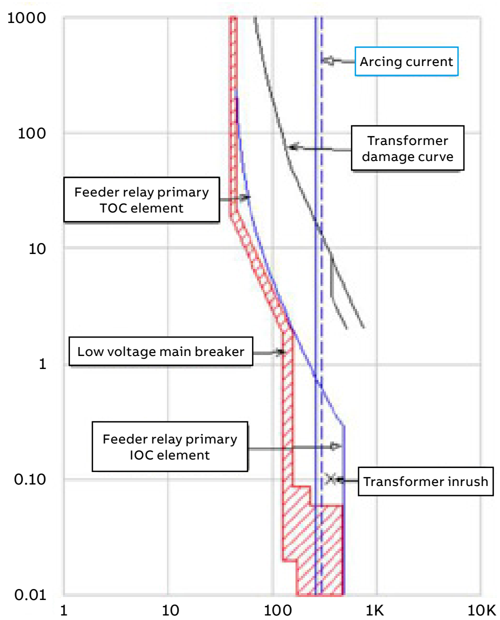
02 Arc flash results for basic protection scheme using LIS with vacuum breaker

This arrangement provides a significant arc flash reduction compared to primary fuse protection, but has some limitations. The overcurrent protection cannot distinguish different fault locations because only one set of CTs located on the primary side is connected to the relay. Figure 4 shows the time-current curves for the basic protection scheme. The primary time-overcurrent element (TOC) is set to the left of the transformer damage curve to protect the transformer. The relay's protection settings must be set above the inrush current of the transformer to allow energization, which limits the sensitivity of the scheme in general, and particularly limits the

— 03 Time-current curves for basic protection using a feeder relay (vertical axis is time in seconds, horizontal axis is 480 V current in amps x 100)

— 04 Arc flash results for improved protection scheme using LIS with vacuum breaker

degree of arc flash energy reduction that is achievable for arcing faults on the secondary side of the transformer. The primary instantaneous overcurrent (IOC) element is set above the 480 V available fault current to maintain coordination with low voltage protection devices.



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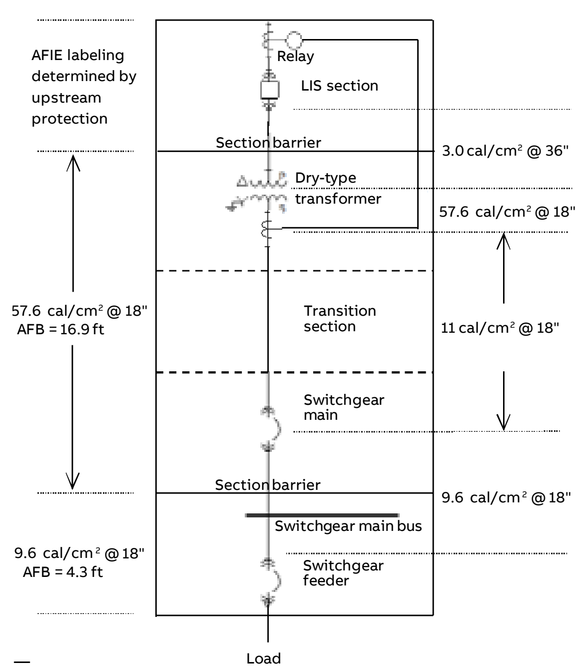
Using a relay that can accept multiple CT set inputs and adding a CT set on the transformer secondary can further improve the protection provided by the LIS with vacuum breaker. This is described next.

Improved protection using LIS with vacuum breaker

Adding a second set of CTs to the basic scheme described above overcomes the basic protection schemes' inability to distinguish fault location. A secondary set of CTs is installed on the low voltage side of the transformer, and both sets of CTs are wired as overcurrent inputs to a multi-input overcurrent protection relay. The primary CT set provides overcurrent protection for the transformer, while the secondary CT set provides overcurrent protection and improved arc flash mitigation on the low voltage sections. Due to space constraints inside the transformer enclosure, the secondary CT set can only be installed in the bus transition section or inside the main breaker section on the source side of the main breaker for a retrofit installation. For new installations, the transformer may be provided with secondary CTs inside the enclosure. In either retrofit or new installations, a portion of the low voltage bus will be upstream of the secondary CTs. Even a very small section of low voltage bus or a transformer secondary termination upstream of the secondary CTs results in an incomplete zone of protection. Faults upstream of the secondary CTs will be protected by the primary protection elements, resulting in much slower protection.

The results of the arc flash calculations for the improved scheme are shown in figure 4.[3] While use of the secondary CT set can greatly reduce the arc flash energy on a region of the low voltage bus upstream of the switchgear main breaker, the section labeling (shown on the left-hand side of the figure) will be the same as the basic protection scheme that uses only a primary CT set. Since no complete section barriers exist between the transformer and low voltage main, the transformer enclosure, transition section and low voltage switchgear main section must all be labeled at the worst-case 57.6 calories/cm² level.



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The LIS section does have an internal barrier between the high voltage switch and transformer, so it can be labeled at the calculated 3.0 calories/cm² on the load side of the vacuum breaker, or the incident energy that is line side of the vacuum breaker, whichever is higher.

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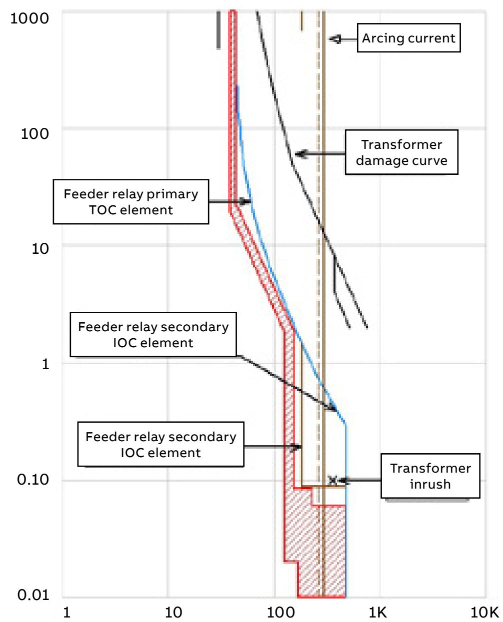
05 Time-current curves for improved protection scheme using a feeder relay with dual CT set inputs (vertical axis is time in seconds, horizontal axis is 480 V current in amps x 100)

Figure 5 shows the time-current curves as applied to the typical 2,500 kVA, dry-type secondary substation when using the improved protection scheme. The secondary CT set does not sense transformer inrush current, allowing for lower pick-ups that produce faster trip times. The secondary IOC element is set below the calculated 480 V arcing current. A delay has also been added to the secondary IOC to maintain coordination with low voltage protection devices.



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The performance of the improved scheme on the dry-type secondary substation is mediocre at best. A section of bus between the transformer secondary winding connections and the secondary set of current transformers remains well above 40 calories/cm^2.

Improved protection plus differential protection
The performance of the improved protection scheme can be enhanced further by using a transformer protection relay in lieu of a standard feeder overcurrent relay. The transformer protection relay provides primary and secondary overcurrent elements just like the feeder relay, but it also provides differential protection for the transformer.

Transformer differential measures the current into and out of the transformer. The transformer relay will then perform magnitude, phase and zero sequence compensation on these measured values. The vector sum of the compensated values is the differential current. Since the transformer differential has a well-defined zone of protection, there is no issue with this protection "over-reaching" and operating for a fault outside its protective zone. This allows transformer differential to operate with no intentional time delay.

The transformer differential function not only provides better protection for the transformer, but also reduces the arc flash incident energy from the transformer secondary to the low voltage main. Next, this paper will examine two cases that vary by the location of the secondary CTs.

1. Secondary CTs located on load side of low voltage main breaker
Figure 6 shows the results of the arc flash mitigation performance of a metal-enclosed LIS with a vacuum breaker using the improved protection scheme plus the differential protection applied to the typical 2,500 kVA dry-type secondary substation. In this case, the secondary CTs are installed on the load side of the low voltage main breaker.

With the application of the transformer protection relay, the arc flash incident energy has been reduced to a maximum of 6 calories/cm^2 in the transformer enclosure and transition section. An arcing fault occurring anywhere on the bus between the primary and secondary CT sets is inside the differential zone of the relay. Consequently, the fault clearing time for a fault in this zone, due to the differential protection, is now less than 4.5 cycles (3-cycle breaker opening time plus 1.4 cycles of relay operating time).

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06 Arc flash results using the improved protection scheme with differential protection (secondary CTs downstream of main breaker)

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07 Time-current curves for transformer protection relay with secondary CTs downstream of main breaker (vertical axis is time in seconds, horizontal axis is 480 V current in amps x 100)

The low voltage main breaker clears the arcing current faster than the transformer differential. However, the horizontal electrode orientation (HCB) associated with the main breaker cell increases the incident energy relative to the incident energy associated with the vertical conductor orientation (VCB) used between the low voltage main breaker line side and the transformer secondary. This difference in electrode orientation used in the analysis is the reason the low voltage main section has a higher incident energy than the transition section or transformer enclosure, despite being included in the transformer differential zone of protection. There is still value in placing the secondary CTs on the load side of the main breaker, because this location eliminates any gaps in the differential zone of protection on the low voltage bus on the line side of the main breaker.

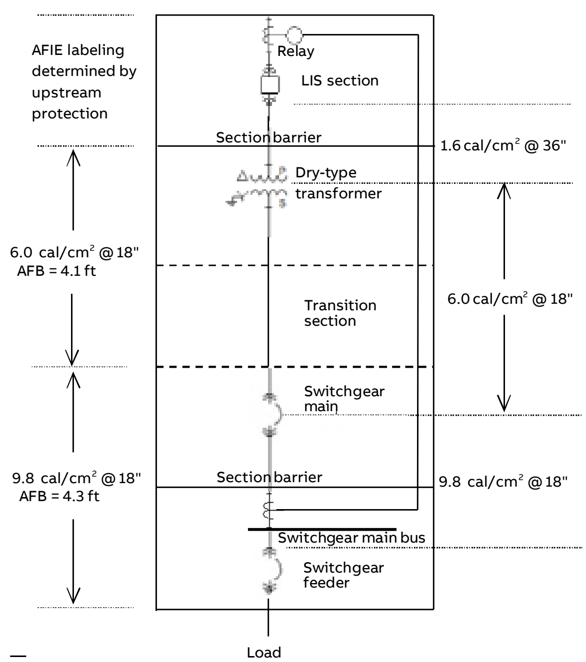

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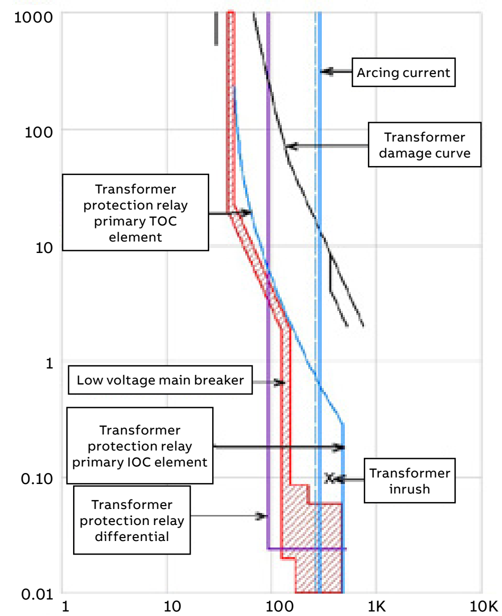
Figure 7 shows the time-current curve for the transformer protection relay. The differential element is now protecting the transformer against short-circuit damage, so the primary overcurrent element is used for transformer overload protection only.

The transformer protection relay should always be configured to trip the high voltage vacuum breaker and, in most applications, should trip the low voltage main breaker for a differential operation. This may require installing a shunt trip on the low voltage main breaker. If the substation is main lug only with no main breaker, the relay may need to be configured to trip the high voltage vacuum breaker and all the low voltage feeder breakers for a differential operation.

2. Secondary CTs located on line side of low voltage main breaker

Figure 8 shows the results of the arc flash mitigation performance of a metal-enclosed LIS with a vacuum breaker using the improved protection scheme plus the differential protection applied to the typical 2,500 kVA dry-type secondary substation. In this case, the secondary CTs are installed on the line side of the low voltage main breaker in the transformer enclosure.



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The differential zone of protection now covers less of the low voltage equipment bussing. Accordingly, the section of low voltage bus calculated at 6.0 calories/cm^2 is reduced to the area between the transformer secondary and the secondary CTs. Because of the combination of transformer differential protection and instantaneous overcurrent protection that is sensitive to the 480 V faults, the result of this scheme is much better than the improved protection scheme described previously.

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08 Arc flash results using the improved protection scheme with differential protection (secondary CTs upstream of main breaker)

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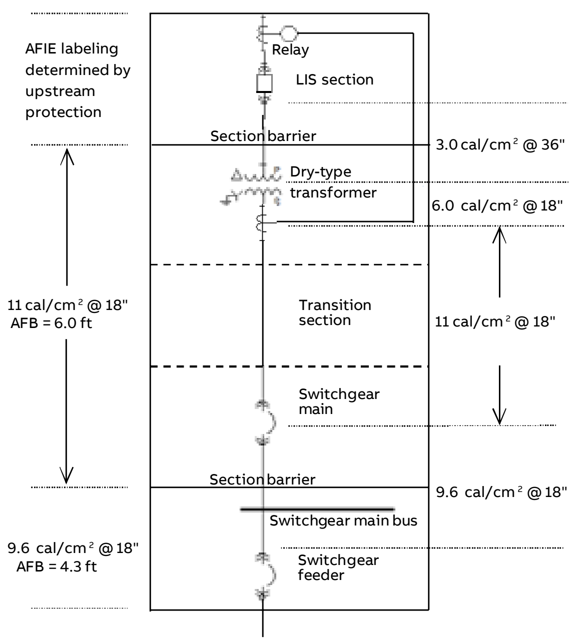
09 Time-current curves for transformer protection relay with secondary CTs upstream of main breaker (vertical axis is time in seconds, horizontal axis is 480 V current in amps x 100)

Figure 9 shows the time-current curves for this case. Between the secondary CTs and the switchgear main breaker, protection is provided by the primary instantaneous current element. This IOC element has been set to coordinate with the switchgear main breaker and is, therefore, not as fast as the bus differential clearing time, leading to the calculated 11.0 calories/cm².



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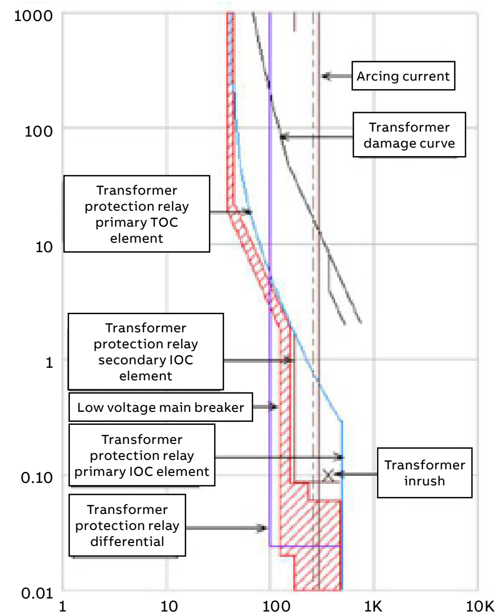

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Conclusions

The performance of the feeder protection relay is limited by the location of the secondary set of CTs. If the CTs cannot be installed at the transformer secondary terminals without having any live bus on the transformer side of the CTs, a section of low voltage bus will have an elevated incident energy level.

Replacing the feeder relay with a transformer protection relay will not only improve the arc flash performance of the LIS with vacuum breaker, but it will also increase the protection of the substation transformer. The closer the secondary CTs can be placed to the low voltage main breaker, the more complete the differential zone of protection becomes for reducing arc flash incident energy. The most complete zone of protection results from placing the secondary CTs on the load side of the low voltage main breaker.

Additional advantages of the transformer differential scheme

In addition to improved arc flash related to life safety, the transformer differential scheme provides a measure of economic asset protection beyond that of a standard feeder management relay.

Transformers are a critical and expensive component of a power distribution system. Replacement secondary substation-style transformers are engineered products with long lead times. Lead time for a standard 2500 kVA dry-type transformer is currently 20 weeks after drawing approval. Lead times for large and/or specialty substation transformers are even longer.

Transformer differential relays limit the duration of winding phase-to-phase faults, phase-to-ground faults, winding inter-turn faults, etc. Due to the reduced duration of these faults, a fault condition within the differential zone of protection may require only transformer repair rather than total transformer replacement. Adjacent equipment that is close coupled to the transformer is also less likely to be severely damaged.

References

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

[2] Catlett, R.; Lang, M.; Scala, S.; Novel Approach to Arc Flash Mitigation for Low Voltage Equipment; IEEE IAS Electrical Safety Workshop (ESW), 2016.

[3] Catlett, R.; Lang, M.; Scala, S.; Considerations for the Application of a MV High Speed Grounding Switch for Arc Flash Mitigation of LV Equipment, IEEE Pulp, Paper & Forest Industries Conference, 2016

[1] Assumptions used in system modeling: 12.47 kV primary voltage, 20 kA of available fault current at the primary device line side, 150E EJO fuse at the LIS, nominal 5.75% transformer impedance, 480 V secondary voltage, LV main circuit breaker with 60 millisecond opening/arc-clearing time. Arc flash energy results shown throughout this paper are based on the 2018 IEEE-1584 standard [1]. The HCB (horizontal conductors in a box (enclosure)) electrode configuration is used in the switchgear sections; VCB (vertical conductors in a box (enclosure)) is used everywhere else.

[2] Arc flash incident energy results shown are typical for an overcurrent protection relay. An ABB REF 615 relay was used in this example with a vacuum breaker having an opening time of 3 cycles (50 milliseconds). All other system assumptions stated in endnote 1 remain the same.

[3] Figure 4 and all subsequent figures showing arc flash incident energy values are based on the same system and modeling assumptions used in the previous cases. Only the relay type or relay configuration changes to support the scheme described.

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9AKK108467A3586 REV A OCTOBER 2022