Case Study: Real-Life Arc-Flash Mitigation Event on 380 Vac Switchgear

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For the complete history of this paper, refer to the next page.

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Abstract—This paper describes the implementation of always-on arc-flash detection using a combination of overcurrent and optical light sensors, along with the authors' extensive experience in planning, implementation, testing, and real-life events in a 380 Vac switchgear system. The rapid detection and interruption of arc-flash events is crucial in controlling the risk associated with potentially life-threatening incidents and turning them into valuable lessons without the high cost to life and equipment. Mitigation occurs within milliseconds, significantly reducing the total arc-flash energy between phase conductors or from phase to ground. High-speed mitigation is achieved by automatically tripping the molded case circuit breaker (MCCB) of the motor control center (MCC) or feeder where the arc flash occurs, thereby quickly lowering the calories per centimeter squared. The oscillography event report and accompanying photographs presented in this paper clearly demonstrate how this always-on technology can save lives.

Index Terms—arc-flash detection, motor control center

I. INTRODUCTION

A refinery in Bolivia, operational since 1978, is the largest oil refining plant in the country and relies heavily on electricity generated primarily by gas and steam turbines installed at the facility. Safety is the top priority at the refinery, as it is for most industrial and electrical plants worldwide.

To ensure the safety of both personnel and equipment, the refinery adheres to the National Fire Protection Association (NFPA) 70E: *Standard for Electrical Safety in the Workplace* [1]. This includes conducting comprehensive arc-flash studies and implementing arc-flash hazard warning plans. These measures are crucial for identifying potential hazards and mitigating risks associated with arc-flash incidents.

The refinery safety program is robust and multifaceted, encompassing regular safety training sessions for all employees, routine equipment inspections, and the use of personal protective equipment (PPE). Additionally, the refinery has established emergency response protocols and conducts periodic drills to ensure preparedness in the event of an incident.

The potential damage to personnel from an arc-flash event includes fatal heat, ultraviolet radiation, blast pressure, flying shrapnel, deafening sound waves, and psychological harm. While avoidance is sometimes impossible, the risk of exposure to an arc-flash event in the cable and breaker compartments, as well as in the bus sections of motor control centers (MCCs), can be mitigated in several ways. The NFPA 70E outlines the hierarchy of risk-control methods as follows [1]:

1. Elimination
2. Substitution
3. Engineering controls
4. Awareness
5. Administrative controls
6. PPE

An integral part of designing equipment and power systems for safety is conducting coordination and arc-flash studies. These studies help determine the cost-benefit ratio for the safety of valuable personnel and equipment. To ensure they remain current, these studies should be scheduled every five years and whenever significant modifications are made to the electrical system that warrant a reassessment.

Pairing arc-flash studies with protection coordination studies is essential for a comprehensive safety strategy. Protection coordination studies ensure that protective devices, such as circuit breakers and relays, operate in a coordinated manner to isolate faults and minimize the impact on the electrical system. When combined with arc-flash studies, these coordination studies help to optimize the settings of protective devices, ensuring they respond appropriately to arc-flash events. This pairing enhances the overall safety and reliability of the electrical system by reducing the likelihood of equipment damage and minimizing downtime.

In industrial plants, the system owner's primary goal is to ensure the industrial process runs smoothly without interruptions by employing several key strategies. These include having dual redundant MCCs and dual motors for the same process, maintaining a high level of equipment reliability through regular maintenance and inspections, investing in advanced technologies for real-time monitoring and predictive maintenance, and ensuring a well-trained workforce capable of quickly addressing any issues that arise.

Ensuring uninterrupted processes in the refinery is vital. Arc-flash energy, which is proportional to voltage, current, and time, can disrupt operations. The energy released depends on how long the event lasts. So reducing the duration to just a few milliseconds (ms), as discussed in this paper, is crucial for maintaining continuous operations and safety. By prioritizing safety and adhering to stringent standards, the refinery not only protects its workforce but also ensures the continuous and efficient operation of its facilities.

ARC-FLASH HISTORY AT THE REFINERY

Figure 1 presents a simplified diagram of the refinery power system. It shows the refinery's 115 kV utility connection and generators connected to the 10.5 kV and 3.3 kV buses. These generator connections contribute to elevated short-circuit levels within the system buses. This figure also shows the locations of the two arc-flash events discussed in this paper.
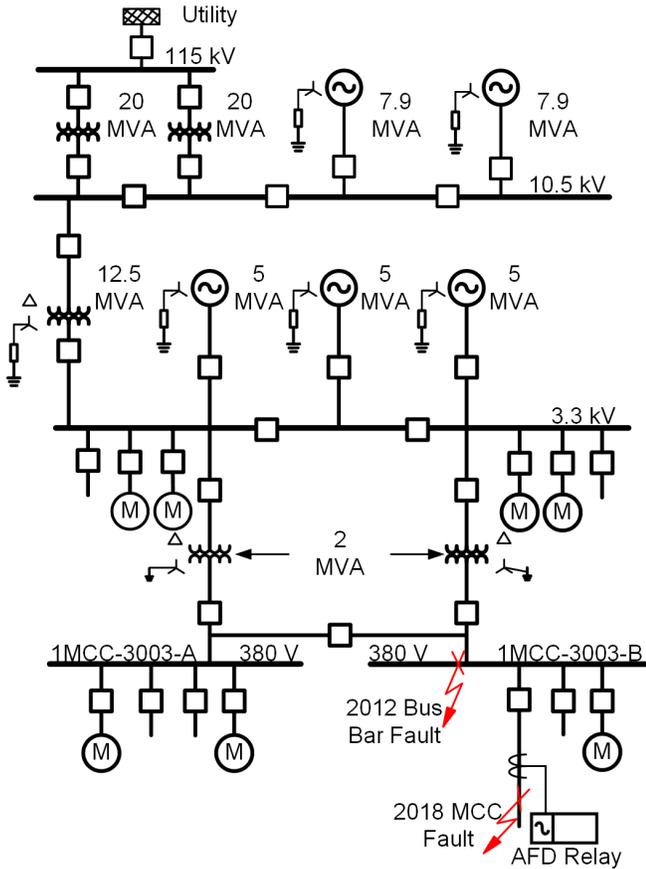

Figure 1   Simplified Diagram of the Refinery Power System

Figure 2   MCC Damaged in the 2012 Arc-Flash Event

Figure 3   Horizontal Busbar of the MCC

Figure 4   Busbar Side Cover

In 2012, an electric arc flash occurred in the 1MCC-3003-B, causing significant damage to the main bars. This incident was triggered by the contact of a strand from a newly installed copper cable during the energizing of the MCC. At that time, the only protection in place was an electromechanical relay from the 1980s. Fortunately, the precaution of withdrawing personnel from the area before energizing the MCC prevented any human injuries. Figure 2, Figure 3, and Figure 4 show the real impact to the equipment.

The lessons learned from the 2012 incident underscored the importance of modernizing protection systems and implementing arc-flash detection (AFD) and mitigation. In response, the technical team decided to identify and rank safeguards to protect workers from hazards, using the risk-control pyramid as a guide.

In 2015, an arc-flash study at the refinery classified its risk as Category 3. According to Annex H of the NFPA 70E, the required PPE for Category 3 includes a clothing system with a minimum arc rating of 25 calories per cm² (cal/cm^2) [1]. This system consists of arc-rated shirts and pants, coveralls, coats, and additional PPE, such as face shields, hoods, hardhat liners, safety glasses, hearing protection, heavy-duty leather gloves, voltage-rated gloves, and tools.

From 2015 to 2018, the refinery undertook modernization and automation projects, retrofitting approximately 250 outdated bimetallic overload relays with advanced microprocessor-based relays featuring built-in AFD for the MCC buckets.

II. ARC-FLASH MODERNIZATION

The arc-flash mitigation system was selected by the refinery technical team based on reporting, self-diagnostics, and always-on AFD features. Arc-flash events often happen when maintenance personnel accidentally drop tools, but they can also be caused by the buildup of corrosion or conductive dust on conductors. Additionally, animals like snakes or rats may come into contact with energized conductors, leading to these dangerous events. These incidents can happen at any time, often without warning. By having an always-on detection system, the refinery can quickly identify and mitigate arc-flash events, reducing the risk of severe damage and ensuring the safety of personnel and equipment. This continuous monitoring helps prevent disruptions and maintains the smooth operation of the refinery.

Figure 5 illustrates the always-on AFD logic, which uses comparators based on raw currents processed every 1 ms. This logic triggers the breaker trip via the binary output contact OUT02 if the instantaneous and unfiltered current samples exceed the threshold of the dedicated arc-flash overcurrent elements and the light threshold for two consecutive samples.
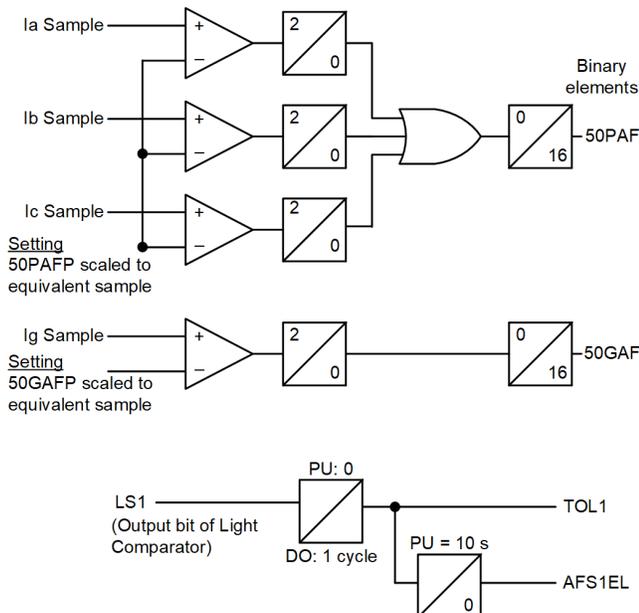

Figure 5   Arc-Flash Instantaneous Current and Light Logic

The protective relay features multiple protection functions with varying setting thresholds, and the arc-flash overcurrent elements 50PAF and 50GAF operate independently of other overcurrent protection functions. Always-on AFD occurs when both the **dedicated** overcurrent elements and the built-in light sensor identify an arc-flash event. This enables high-speed tripping while preventing overtripping due to external faults. The light sensor ensures protection against false trips caused by external faults. The dedicated light and current sensors of always-on AFD are not compared in this paper to the maintenance mode in circuit breakers, which are quite popular in the industrial space. Enabling a relay-based approach to reduce arc-flash energy by using the instantaneous overcurrent element during maintenance mode essentially provides a faster overcurrent pickup but has security issues, as mentioned in [2].

Overtripping, or undesired tripping, can cause significant operational disruptions in industrial refineries. Unplanned shutdowns halt production processes, leading to downtime and financial losses. This interruption affects the refinery's ability to meet production targets and fulfill contractual obligations. Frequent or unnecessary tripping can also damage equipment, reducing its lifespan and increasing maintenance costs. In some cases, it may lead to equipment failure, requiring costly repairs or replacements. Additionally, overtripping can create unsafe conditions for personnel, such as pressure build-ups or the release of hazardous materials, posing immediate dangers to workers.

The arc-flash settings for the protective relay used in AFD and mitigation are as follows:

- Phase Overcurrent Arc-Flash Pickup (50PAFP): This should be set to at least twice the expected maximum load in amperes.
- Residual Overcurrent Arc-Flash Pickup (50GAFP): This setting detects ground faults.
- TRIP: This setting is a logical equation with binary values that trigger a breaker trip (TR1).
- Controlled Binary Output: This setting is hardwired to the breaker. The logic is defined as OUT02 := (50PAF OR 50GAF) AND TOL1, where TOL1 is the arc-flash light detection input sensor element pickup.

The optical light sensor within the protective relay chassis includes a periodic self-diagnostic feature (monitored by the binary status of AFS1DIAG), which provides the health status of the arc-flash sensor without requiring any user settings.

The refinery technical team designed, planned, implemented, and tested each MCC protective relay. This thorough approach was crucial for the successful modernization of the refinery protection systems. The team rigorously tested the microprocessor-based relay by injecting overcurrent and light simultaneously. During testing, the performance of the AFD system was measured by analyzing the COMTRADE reports of the MCC relay, demonstrating a detection time of 3 ms and a mitigation time of 12.5 ms, which includes the 8–10 ms typically required for MCCB operation. To ensure the tested time remains constant and to avoid delays in the protection tripping of the MCCB, the technical team decided not to use repeater relays between the relay output and the trip coil, while considering the current capacity of the digital output.

The relay records the operation of the AFD and the breaker in a COMTRADE report and a Sequential Events Recorder time-stamped report. These reports validate the successful operation of AFD and mitigation. For training purposes, the combination of these reports, recorded video footage, personnel testimony, and postevent pictures are valuable tools for teaching how safety practices and procedures can be continuously improved for all personnel and visitors.

III. ARC-FLASH EVENT

In the refinery, a group of three electrical technicians from a contracting company entered the electrical building and proceeded to open a door of 1MCC-3003-B, which houses an electric-drive 30 horsepower pump. The AFD and mitigation relay for this MCC bucket had been installed and commissioned for several months, ensuring enhanced safety measures were in place. At approximately 10:30 a.m. on January 18, 2018, an incident occurred when one of the technicians accidentally touched the main contact of the MCC with a measurement stick. This inadvertent contact triggered an arc-flash event.

Figure 6 shows the light input sensor and the missing termination on the middle phase. The light sensor is circled in red and diagonally below it is the copper wire for Phase B current that short-circuited to the bottom of the MCC enclosure.
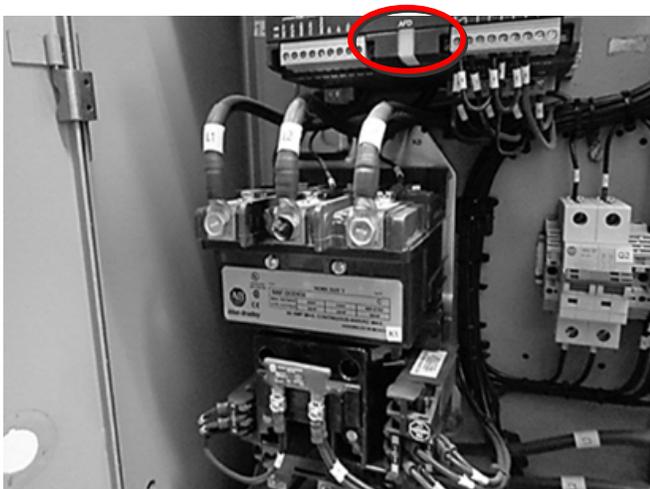
Figure 6   Minor Internal Damage Inside the MCC Bucket After the Arc-Flash Event

Figure 7 clearly shows the zoomed-in behavior of Phase B current (IB, depicted as a dotted line) involved in the arc-flash event. This COMTRADE report, recorded at a rate of 4,000 samples per second by the AFD relay, indicated that the AFD was initiated when the IB changed magnitude at 10:30:52.934. Approximately 3 ms later, the binary status of light detection Sensor 1 (TOL 1) changed from False to True. The combination of overcurrent and optical light sensors triggered the binary output OUT02 at 10:30:52.937. The AFD system mitigated the fault within 12.5 ms and prevented further damage to both the technicians and the equipment.
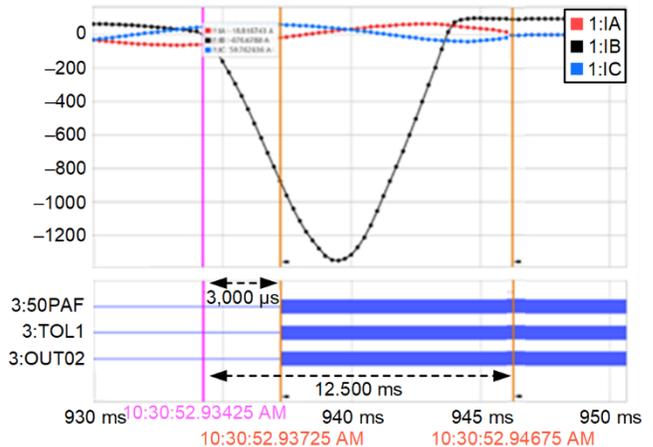
Figure 7   COMTRADE Report Shows 50PAF, TOL 1, and TR 1 Operated

Figure 8 and Figure 9, captured by security cameras, show the moment when the three technicians experienced the visual flash and sparks while in front of the MCC door. Although the technicians were startled and frightened by the event, they walked away unharmed.

Figure 8   Technicians in Front of Switchgear Before the Arc-Flash Event

Figure 9   Technicians in Front of Switchgear During the Arc-Flash Event

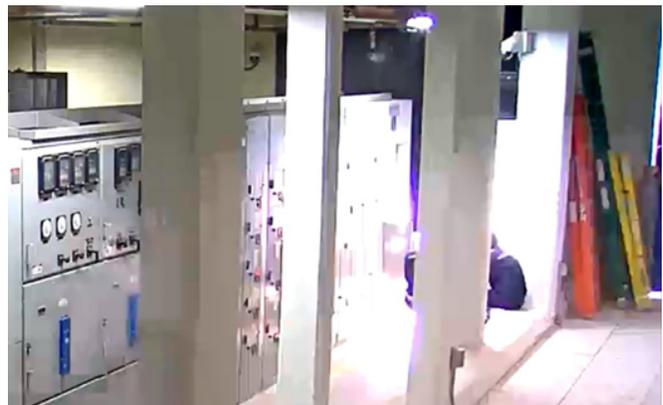The three technicians thoroughly reviewed the reports of the arc-flash event, which has since become a valuable learning experience for all refinery personnel. This incident underscores the real consequences of an electric arc and serves as an important reminder of the critical role of safety measures in preventing such occurrences.

The impact of AFD and mitigation on refinery availability is significant. In 2012, an arc-flash event protected by an electromechanical relay required about six hours of repair. In contrast, a similar event in 2018, protected by a microprocessor-based AFD relay, allowed for immediate restoration of electrical service. This highlights the importance of advanced technology in reducing downtime and improving operational efficiency.

V.   FURTHER MODERNIZATION PLANS

The discussed implementation of AFD and mitigation at the MCC was a significant enhancement for the MCC buckets. Following the lessons learned from the 2018 event, a step to improve safety for maintenance technicians was adding a cover to the phase terminations to prevent physical contact, as shown in Figure 10.

Figure 10   MCC Bucket With Installed Contact Cover

Future modernization plans include the use of the built-in Ethernet communications ports of the AFD microprocessor-based relays to expand the arc-flash protected zones by implementing IEC 61850 GOOSE communications. These Ethernet ports offer several advantages, including enablement of multiple protocols for simultaneous communications of high-speed data, SCADA data, and event reports. The IEC 61850 GOOSE messaging enables high-speed data transfer between publisher and subscribers and interoperability between devices from different manufacturers. Additionally, Ethernet ports facilitate easy network expansion for scalability and reconfiguration, enhancing overall system efficiency and reliability.

The modernization plan involves connecting the two Ethernet ports of neighboring MCC protection relays to a switched operational technology network. These relays can publish IEC 61850 GOOSE messages within approximately 4 ms to each other and to an upstream GOOSE subscriber or backup protective relay. The GOOSE messages from the MCC bucket relay transmit local statuses, enabling other protection relays in the communications-assisted protection scheme to use these received statuses for tripping as backup protection.

Traditionally, this transfer trip scheme is implemented through hardwired signals between relays. However, publishing GOOSE messages that act as a virtual wire through Ethernet provides additional benefits, such as security, high availability, and high speed of the scheme. To support security of the scheme, the quality bit of each GOOSE message can be monitored by the subscriber relay. Additionally, the subscriber relay should confirm with warning messages or automatically displayed alarms when GOOSE communications fail between devices. To support high availability of the scheme, if the Ethernet network fails, the publisher or subscriber relay can automatically use its failover Ethernet port, which resumes availability within 4 to 5 ms. Lastly, to support the high-speed requirement of the scheme, which is crucial for effective AFD and mitigation, the network design and settings include the implementation of path redundancy, VLAN segregation, and priority settings for GOOSE traffic.

Further plans include adding a system to manage the implementation of all the MCC relays with a centralized smart motor control system, as described in [3].

VI.   ARC-FLASH EVENT CALCULATIONS

As mentioned in Section II, an arc-flash study conducted in 2015 classified the risk for this MCC as Category 3, according to Annex H of the NFPA 70E [1]. This study was based on the 2002 IEEE 1584 standard. In the report, the bolted fault current (Ibf) for three-phase faults was 44.3 kA, with an arc duration of 150 ms. The study calculations resulted in an arcing current of 18.5 kA and an incident energy of 9.57 cal/cm^2.

Following the arc-flash event, the authors decided to recalculate the incident energy for 1MCC-3003-B using the updated IEEE-1584 standard, released in 2018 [4]. Appendix C in [4] recommends the vertical conductors/electrodes terminated in an insulating barrier within a metal box/enclosure (VCBB) configuration for determining incident energy in an MCC installation due to the risk of faults arcing to the line-side lugs. Appendix A of this paper provides detailed calculations for this configuration and the refinery system conditions.

The recalculated incident energy, as referenced in Appendix A of this paper, is 9.176 cal/cm² (A-14) and the final arc-flash boundary (AFB) is 1,404 mm (A-16). These results confirm the findings of the 2015 arc-flash study for the need for Category 3 PPE according to Annex H of NFPA 70E [1]. This calculation excludes the AFD and mitigation measures implemented at the refinery since 2018.

Furthermore, using the 2018 IEEE 1584 guide for arc-flash hazard calculations, the authors decided to calculate the incident energy for the January 18, 2018, arc-flash event, which had a total fault duration of approximately 12.5 ms. The result was an

incident energy of 0.997 cal/cm², with an AFB of 411.83 mm. Although the step-by-step calculations for the January 18 event are not included in this paper, the calculation results can be derived using the IEEE 1584-2018 guide [4].

When comparing the incident energy and AFB from the January 18th event to the recalculated values from the updated IEEE-1584-2018 arc-flash study for 1MCC-3003-B, there is an 89 percent reduction in incident energy and a 71 percent reduction in the AFB distance. This significant decrease could potentially lower the PPE requirement from Category 3 to Category 1, assuming the AFD and mitigation measures are operational.

VII.   CONCLUSION

In conclusion, this paper details the implementation of always-on AFD using a combination of a dedicated arc-flash overcurrent element and optical light sensors, supported by real-life events in a 380 Vac switchgear system. High-speed mitigation by the AFD protective relay is achieved by automatically tripping the breaker of the MCC, thereby quickly reducing the cal/cm².

After retrofitting around 250 outdated bimetallic overload relays with advanced microprocessor-based relays featuring built-in AFD for the MCC buckets, the January 18th, 2018 arc-flash event highlights the critical need for advanced AFD and mitigation systems. The oscillography event report and accompanying photographs in this paper clearly show how this always-on technology can save lives. Arc-flash hazard protection minimizes equipment damage during an arc-flash event, allowing for quicker and more cost-effective repairs. This approach also improves power system reliability and ensures maximum availability.

The calculations presented in this paper use the IEEE 1584-2018 standard to show a comparison and highlight the impact of AFD and mitigation to the incident energy and AFB. The combination of these technologies with continuous training and adherence to safety protocols offers a robust framework for improving electrical safety in industrial settings.

VIII.   REFERENCES

[1]   NFPA 70E, *Standard for Electrical Safety in the Workplace*, 2004 Edition.

[2]   J. Buff and K. Zimmerman, "Application of Existing Technologies to Reduce Arc-Flash Hazards," proceedings of the 33rd Annual Western Protective Relay Conference, Spokane, WA, October 2006.

[3]   A. D'Aversa, B. Hughes, and S. Patel, "Challenges and Solutions of Protecting Variable Speed Drive Motors," proceedings of the 66th Annual Conference for Protective Relay Engineers, College Station, TX, April 2013.

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IX.   VITAE

Eduardo S. Palma received his Bachelor of Science in electrical engineering from the University of South Florida in Tampa, Florida, in 2003, and his Master of Business Administration with a concentration in Globalization & International Business in 2012. In 2021, Eduardo earned the CISSP (Certified Information Systems Security Professional) certification from ISC2, establishing his expertise in cybersecurity. Eduardo is the technical manager for Latin America at Schweitzer Engineering Laboratories, Inc. (SEL), where he leads business development and technical support of products and solutions for industrial control systems (ICS) in the Caribbean, Central America, and South America. Eduardo is a published author and serves the utility, oil and gas, mining, and transportation sectors to provide innovative and high-quality solutions to enhance the performance and protection of their critical infrastructures.

Alvaro Gabriel Santi Flores received an electrical engineering degree from the Universidad Mayor de San Simón, Cochabamba, Bolivia, in 2007, and has been a member of the Bolivian Engineering Society (SIB) since that year. Alvaro has experience in high-voltage testing of substation equipment, implementation of turbomachinery, and specification of electrical equipment and critical motors for potentially hazardous areas. Alvaro joined YPFB in 2010, and he currently develops his activities as an electrical reliability professional at the Gualberto Villarroel Refinery, where he has managed various modernization and implementation projects of more than 400 electrical protection relays in high, medium, and low voltages from different vendors.

Mario Gutiérrez received his Bachelor of Science in electrical engineering from the Universidad de la Salle in Bogotá, Colombia, in 2007, and his Master of Science in electrical engineering with an emphasis on power systems from the Universidad de los Andes, in 2018. Mario has experience in engineering, assembly, testing, and commissioning of protection and control systems of medium-, high-, and extra-high-voltage substations, automation of distribution networks, and electrical studies and failure analysis of power systems. He joined Schweitzer Engineering Laboratories, Inc., (SEL), in 2019 as a protection application engineer, to provide technical support and training for Latin America and the Caribbean region.

Appendix A

Calculations for the refinery arc-flash study using the 2018 IEEE 1584 Guide

The steps used in this calculation are provided in the IEEE Std 1584-2018 [4] to determine the incident energy and AFB calculation for a low-voltage system. The applicable equipment electrode configuration is VCBB.

1. Determine the intermediate arcing currents (I_{arc_600}) in kA using the following equation:

$$I_{arc\_600} = 10^{(k_1 + k_2 \bullet \log(I_{bf}) + k_3 \bullet \log(G))} \bullet (k_4 \bullet I_{bf}^6 + k_5 \bullet I_{bf}^5 + k_6 \bullet I_{bf}^4 + k_7 \bullet I_{bf}^3 + k_8 \bullet I_{bf}^2 + k_9 \bullet I_{bf}^1 + k_{10}) = 35.8 \text{ kA} \qquad (A-1)$$

    where,
    Bolted fault current for three-phase faults (I_{bf}): 44.3 kA
    Gap between conductors (G): 25 mm+
    VCBB coefficients:
k1:	−0.017432
k2:	0.98
k3:	−0.05
k4:	0
k5:	0
k6:	−5.767•10⁻⁹
k7:	2.524•10⁻⁶
k8:	−0.00034
k9:	0.01187
k10:	1.013

2. Determine the final value of the arcing current (I_{arc}) in kA using the following equation:

$$I_{arc} = 1 \Big/ \sqrt{\left(\frac{0.6}{V_{oc}}\right)^2 \bullet \left[\left(\frac{1}{I_{arc\_600}^2}\right) - \left[\frac{(0.6^2 - V_{oc}^2)}{0.6^2 \bullet I_{bf}^2}\right]\right]} = 29.185 \text{ kA} \qquad (A-2)$$

    Where the system open-circuit voltage (V_{oc}): 0.380 kV rms.

3. Determine the arc duration or fault clearing time.

    The 1MCC-3003-B phase instantaneous overcurrent element pickup setting is 430 primary amperes with a delay of 100 ms for coordination purposes. The time T used in these calculations is 115 ms. This time is derived by summing the overcurrent element delay of 100 ms, the breaker operating time of 10 ms, and 5 ms for digital relay processing of this element.

4. Determine the incident energy

    Determine the enclosure size correction factor using the following enclosure dimensions:
    Width (W): 755 mm
    Height (H): 385 mm
    Depth: 185 mm

    Using the guidelines to determine the equivalent height and width, and considering that the width exceeds 660.4 mm, use the following formula:

$$Width_1 = \left[660.4 + (Width - 660.4) \bullet \left(\frac{V_{OC} + A}{B}\right)\right] \bullet 25.4^{-1} = 27.611 \text{ mm} \qquad (A-3)$$

    where,
    A is a constant equal to 10 for VCBB
    B is a constant equal to 24 for VCBB
    $Width_1$ represents the modified width utilized to determine the corresponding box dimensions.

Considering that the height is shallow, since the $V_{oc} < 600$ Vac and the enclosure depth ≤ 203.2 mm, use the following equation:

$$\text{Height}_1 = 0.03937 \bullet H = 15.157 \text{ mm} \tag{A-4}$$

Height$_1$ refers to the modified height applied to calculate the corresponding box dimensions.

The equivalent enclosure size (EES) is:

$$\text{EES} = \frac{\text{Height}_1 + \text{Width}_1}{2} = 21.384 \text{ mm} \tag{A-5}$$

Apply the correction factor (CF) for a "Shallow Enclosure" as follows:

$$\text{CF} = \frac{1}{b1 \bullet EES^2 + b2 \bullet EES + b3} = \frac{1}{-0.002778 \bullet EES^2 + 0.1194 \bullet EES - 0.2778} = 0.995 \tag{A-6}$$

where,
b1:	−0.002778
b2:	0.1194
b3:	−0.2778

5. Calculate the intermediate incident energy value (E_{600}) in joules (J)/cm².

$$E_{\leq600} = \left(\frac{12.552}{50}\right) \bullet T \bullet 10^{\left[k1+k2\bullet\log(G)+\left[\frac{(k3 \bullet I_{arc\_600})}{k4\bullet I_{bf}^7+k5\bullet I_{bf}^6+k6\bullet I_{bf}^5+k7\bullet I_{bf}^4+k8\bullet I_{bf}^3+k9\bullet I_{bf}^2+k10\bullet I_{bf}^1}\right]+k11\bullet\log I_{bf}+k12\bullet\log(D)+k13\bullet\log(I_{arc})+\log(1/CF)\right]}$$
$$= 44.962 \text{ J/cm}^2 \tag{A-7}$$

Where the coefficients are:
k1:	3.068459		k8:	−0.00034
k2:	0.26		k9:	0.01187
k3:	−0.098107		k10:	1.013
k4	0		k11:	−0.06
k5:	0		k12:	−1.809
k6:	−5.767•10⁻⁹		k13:	1.19
k7:	0.000002524			

6. Convert the intermediate incident energy value (E_{600}) to cal/cm²:

$$E_{600} = E_{\leq600} \bullet 1.2/5 = 10.791 \text{ cal/cm}^2 \tag{A-8}$$

7. Determine the intermediate AFB value (AFB$_{\leq600}$) in mm.

$$\text{AFB}_{\leq600} = 10^{\frac{\left[k1+k2\bullet\log(G)+\left[\frac{(k3\bullet I_{arc\_600})}{k4\bullet I_{bf}^7+k5\bullet I_{bf}^6+k6\bullet I_{bf}^5+k7\bullet I_{bf}^4+k8\bullet I_{bf}^3+k9\bullet I_{bf}^2+k10\bullet I_{bf}^1}\right]+k11\bullet\log(I_{bf})+k13\bullet\log(I_{arc})+\log\left(\frac{1}{CF}\right)-\log\left(\frac{20}{T}\right)\right]}{-k12}}$$
$$= 1.536 \bullet 10^3 \text{ mm} \tag{A-9}$$

Use the coefficients from Step 5.

8. The final AFB in mm is:

$$\text{AFB} = \text{AFB}_{\leq600} = 1.536 \bullet 10^3 \text{ mm} \tag{A-10}$$

9. The arcing current variation CF (VarC_f) is:

$$VarC_f = k1 \bullet V_{oc}{}^6 + k2 \bullet V_{oc}{}^5 + k3 \bullet V_{oc}{}^4 + k4 \bullet V_{oc}{}^3 + k5 \bullet V_{oc}{}^2 + k6 \bullet V_{oc} + k7 = 0.255 \tag{A-11}$$

where,
   k1: $1.138 \bullet 10^{-6}$
   k2: $-6.0287 \bullet 10^{-5}$
   k3: 0.0012758
   k4: -0.013778
   k5: 0.080217
   k6: -0.24066
   k7: 0.33524

10. Determine a lower bound of the average rms arcing current. I_{arc_min} is a second rms arcing current reduced based on the variation CF (kA).

$$I_{arc\_min} = I_{arc} \bullet (1 - 0.5 \bullet Var_{arCf}) = 25.47 \text{ kA} \tag{A-12}$$

11. Repeat Step 5 using the lower bound of the average rms arcing current to determine the incident energy for $Voc \leq 600$ V (J/cm^2). T = 115 ms from Step 3.

$$E_{\leq 600} = \left(\frac{12.552}{50}\right) \bullet T \bullet$$

$$10^{\left[k1 + k2 \bullet \log(G) + \left[\frac{(k3 \bullet I_{arc\_600})}{k4 \bullet I_{bf}^7 + k5 \bullet I_{bf}^6 + k6 \bullet I_{bf}^5 + k7 \bullet I_{bf}^4 + k8 \bullet I_{bf}^3 + k9 \bullet I_{bf}^2 + k10 \bullet I_{bf}^1}\right] + k11 \bullet \log(I_{bf}) + k12 \bullet \log(D) + k13 \bullet \log(I_{arc\_min}) + \log\left(\frac{1}{CF}\right)\right]}$$

$$= 38.235 \text{ J/cm}^2 \tag{A-13}$$

Use the coefficients from Step 5.

12. The final incident energy (E) in cal/cm² is:

$$E = E_{\leq 600} \bullet 1.2/5 = 9.176 \text{ cal/cm}^2 \tag{A-14}$$

13. The final AFB is:

$$AFB = 10^{\frac{\left[k1 + k2 \bullet \log(G) + \left[\frac{(k3 \bullet I_{arc\_600})}{k4 \bullet I_{bf}^7 + k5 \bullet I_{bf}^6 + k6 \bullet I_{bf}^5 + k7 \bullet I_{bf}^4 + k8 \bullet I_{bf}^3 + k9 \bullet I_{bf}^2 + k10 \bullet I_{bf}^1}\right] + k11 \bullet \log(I_{bf}) + k13 \bullet \log(I_{arc\_min}) + \log\left(\frac{1}{CF}\right) - \log\left(\frac{20}{T}\right)\right]}{-k12}}$$

$$= 1.404 \bullet 10^3 \text{ mm} \tag{A-15}$$

Use the coefficients from Step 5.

14. The final value of the AFB in mm is:

$$AFB = 1.404 \bullet 10^3 \text{ mm} \tag{A-16}$$

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