A Journey Toward Electrical Workplace Safety and Production Reliability

David B. Durocher
Senior Member, IEEE
Eaton Corporation
26850 SW Kinsman Road
Wilsonville, OR 97070
DavidBDurocher@eaton.com

Lawrence A. Kay
Member, IEEE
Lehigh Cement
12640 Inland Way
Edmonton, Alberta T5V 1K2
Lawrence.Kay@lehighcement.com

***Abstract* -- This paper outlines the experience of one global cement producer that embarked on site surveys and studies to achieve arc flash safety compliance at 13 cement plants in the U.S. and Canada. The enterprise wide electrical workplace safety initiative resulted in compliance by all plant sites to the latest standards, with new labels affixed to each openable electrical panel that quantified the hazard. Labels designated the proper personal protective equipment (PPE) required to ensure electricians performing energized work would be safe from potential arc events. The experience of one plant in deploying select new technologies to mitigate arc flash in areas where hazards were very high will be reviewed in detail. Site electrical upgrades resulted in enhanced safety along with an unexpected benefit; a significant improvement in production reliability. A follow-up project to increase the plant grinding capacity at the site outlines how new additions to the electrical infrastructure employed a "safety by design" approach to ensure arc flash safety.**

***Index Terms*-- Arc flash hazards, cement industry, health and safety, power system reliability, project management, protective clothing.**

I. INTRODUCTION

An cement plant in Western Canada is one of thirteen cement-producing facilities in North America owned by a global cement producer with headquarters in Europe. The plant is a dry process coal fired plant with a four-stage preheater-precalciner. It was constructed during the late 1970s with an original design capacity of 650,000 tonnes of cement per year. Since that time, the facility has been expanded and optimized to its current production capacity of approximately 1,200,000 tonnes of cement for a market that includes the Canadian provinces of Alberta, Saskatchewan and Manitoba. Limestone, the primary raw material, is shipped daily by train from the plant's quarry located in a city about 350 kilometers west of the plant. Clay is quarried onto the property while sand, iron ore and bottom ash from a coal power plant are trucked in daily for use in the pyro-process. Gypsum used in the cement grinding process is shipped by rail from the plant's gypsum quarry located at a mine in the neighboring Province of Manitoba. The facility includes a hammer mill crusher, vertical roller mill for the preparation of the kiln feed stock, and smaller vertical mill to produce pulverized fuel coal. There are three finish mills that have a combined grinding capacity of approximately 4,500 tonnes per day.

One of the core values of the global cement producing owner is maintaining a culture of adopting industry-leading safety standards designed to ensure employees are out of harm's way. In 2010, the company's North American Cement Technical Group teamed with plant operations to implement an arc flash compliance program for all facilities across the U.S. and Canada. Because its primary business is producing cement, not performing arc flash studies, the company solicited assistance from a global services and solutions provider to complete arc flash studies for all 13 plants. The initiative was completed in 2012 and a technical paper outlining this experience [1] was published shortly thereafter.

Completion of the arc flash study and report by a qualified engineering services provider was delivered to each site based on calculations of arc flash incident energy measured in calories/centimeter-squared (cal/cm^2) and required personal protective equipment (PPE) recommended for use as defined by consensus industry standards [2,3]. The report included calculated incident energy and required PPE at each electrical panel in the plant system. The report also included recommended electrical system updates where new technology could be deployed to assist in reducing or mitigating arc flash hazards in areas where the incident energy across the electrical system was unusually high. Using this list of recommendations, the plant developed an Authorization for Expenditure (AFE) document issued to internal leadership seeking capital support to remediate arc flash hazards and it was issued based on project upgrades implemented in two phases. The first phase included five high priority medium-voltage equipment upgrades and five high priority low-voltage equipment upgrades. This paper will describe the project in detail including the proposed electrical system upgrades; soliciting bids from suppliers to propose turnkey installation including engineering, procurement, installation and commissioning; and the project results including the effect on arc flash remediation and ultimately on process reliability.

II. An Overview of Arc Flash Hazards and Industry Standards

For many decades, the danger of shock hazards or electrocution has been well understood. An electrical shock occurs when the human body comes in contact with an energized conductor. During a shock event, current travels through the body toward ground, and it takes only mill amperes of current to cause serious injury or death. Perhaps the even greater electrical hazard that is somewhat less understood is arc flash. Unlike a shock incident, arc flash is the result of a rapid release of energy due to an arcing fault between phase bus bars, neutral or system ground. An arc flash event – typically the result of human error while electricians are working on or near energized electrical equipment – is usually caused by a dropped tool or accidental contact of a test probe between an energized conductor and ground.

The energy discharge from an arc flash is massive, resulting in an energy release at temperatures exceeding that of the sun's surface, as well as explosive pressure waves, shrapnel, and toxic gases. The destructive power of an arc flash can be immense, as an enormous amount of concentrated radiant energy explodes outward from electrical equipment in an arc flash event. Solid copper conductors are vaporized, expanding to 67,000 times their original mass, creating a superheated ball of plasma gas that can severely burn a worker's body. If the arc releases sufficient energy, a worker's non-flame-resistant clothing will ignite. Workers wearing flame-resistant clothing can also sustain burns if the arc releases energy above the thermal rating of the fabric. The pressure waves can often send loose material flying through the air including pieces of damaged components, tools, and other objects as shown in Fig. 1.

According to industry medical research statistics focusing on preventing workplace injuries and deaths [3], an average of over 1000 electrical burn injuries occur in electrical equipment every year across the U.S. These statistics are likely underreported, because the numbers don't include cases when victims are sent to a hospital or clinic for medical treatment. Instead, these recorded incidents typically involve severe injuries where the incident victim requires treatment from a specialized burn center. Adding unreported cases and "near misses" would result in total injuries many times this number.

Fig. 1. An electrical arc flash delivers an extreme heat and pressure wave with deadly force.

The arc flash hazard analysis completed at the plant required that data be collected across the facility power distribution system. The data was derived beginning with the existing electrical one-line drawing reviewed by a field based power systems engineer who then surveyed the site, verifying each electrical device in the system along with conductor lengths and protective settings. Once the data was collected, a short circuit analysis and a coordination study were performed. The resulting data was then fed into the equations described by IEEE Standard 1584·2002 [2]. These equations produce the necessary flash protection boundary distances and incident energy at an assumed working distance, which are then used to determine the minimum PPE requirement. Once the data is prepared and a flash study has been performed, the calculated arc flash incident energy analysis yields a PPE requirement for people working on or near each energized electrical panel across the facility. After the hazard at each electrical panel was determined, the applicable safety standard which in Canada was CSA Z462-2016 [4] required that a label quantifying the hazard in cal/cm^2 be posted on each electrical panel along with the appropriate PPE required to perform work in the panel while the system is energized. The label is unique for each electrical panel across the system. The arc flash study identified electrical panels that required frequent energized access for maintenance and troubleshooting and also those with the highest PPE requirements. Phase 1 of the plant upgrade program was focused on implementing electrical system changes required to reduce the arc flash energy down to lower the PPE requirement. This involved either adjusting or replacing existing circuit protective devices with more modern counterparts. The goal is to reduce the worker PPE requirements, moving the worker from high level PPE requirements such as clothing rated at 40 cal/cm^2 to a lower level PPE requirement of 8 cal/cm^2 as shown in Fig. 2. Lower levels of PPE reduce the hazard and the risk to those performing energized work.

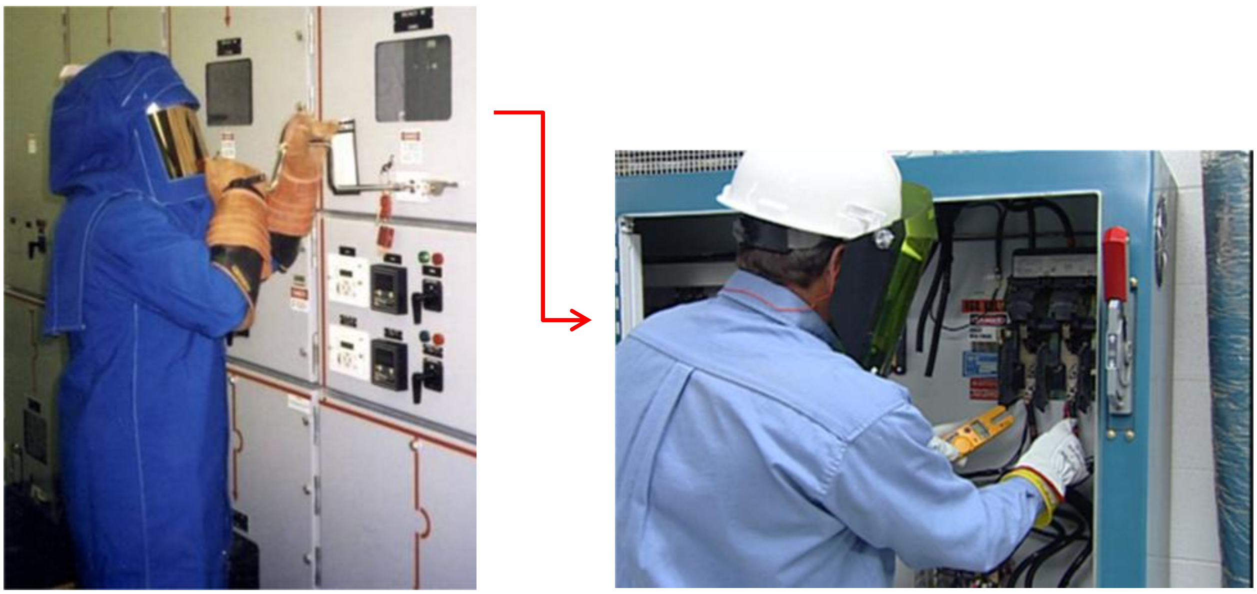

Fig. 2. After the arc flash study is complete, facility engineers review the results and identify areas of the electrical system where incident energy could be reduced, allowing workers to move from a higher level of PPE (40 cal/cm^2 shown at left), to a more manageable level of PPE (8 cal/cm^2 shown at right).

Typically, the higher levels of PPE are required at the main cubicle of a 600V unit substation and for some medium voltage circuits. Because an arc flash event is generally limited to systems where bus voltage exceeds 240V, the system model accounted for system busses only at 600V and above.

III. Continuing the Journey Toward Enhanced Safety

After the arc flash compliance program and site safety training were implemented at the plant, workplace safety for plant electricians made a giant leap forward. Electrical arc flash hazards previously unrecognized were now quantified and visible to operators before they began energized work. Proper PPE was issued to site electricians including 8 cal/cm^2 arc rated clothing as daily uniforms and a 40 cal/cm^2 suit used when performing energized work, where higher levels of PPE were determined to be required.

Following several months of safe operation, site electricians learned although the highest levels of PPE inherently offered the highest degree of protection from an arc flash event, the higher 40 cal/cm^2 level of protection was also cumbersome in terms of time required to perform energized work. It also introduced added risks like heat stress and loss of dexterity required to perform electrical tasks such as troubleshooting. Site operators also realized many of the electrical substations serving critical loads were determined to have calculated incident arc flash energy in excess of 40 cal/cm^2. The arc flash label affixed to those substation's 600V panels designated a "DANGER," arc flash label denoting there was no plant site issued PPE an electrician could wear and be considered safe while working on equipment while energized. In these instances, the only alternative was turning the power off, which created a new set of challenges, especially in the pyro-processing area of the plant where continuous operation was required.

A total of 10 critical 4160V to 600/347V substations were identified with "DANGER" labels where arc flash hazards were in excess of 40 cal/cm^2. The electrical panels for these were considered as candidates for system improvements, using various technology-based solutions to manage the arc flash hazard down to lower the PPE requirement. To achieve this, more modern counterparts generally replaced existing circuit protective devices.

In all 10 identified high hazard substations, a decision was made to pursue the recommended solution included in the original arc flash study. The primary medium-voltage fuse in a fused load-break switch assembly was retrofitted with a high performance vacuum breaker as shown in Fig. 3. This approach has been successfully implemented in other process industry applications [5] with proven success. Adding this functionality, along with updated electronic protective relays, offered enhanced protection and device clearing times that reduced the substation secondary bus arc flash energy from levels that topped out at over 100 cal/cm^2 to levels ranging between 5.8 and 35.7 cal/cm^2. The arc flash incident energy available for downstream low-voltage switchgear was further reduced by the addition of a primary and secondary bus overcurrent protective relay equipped with an “arc flash reduction maintenance switch”. This allowed electricians to set the feeder circuit breaker to a fast tripping maintenance setting prior to performing energized work in downstream electrical equipment. In select low-voltage switchgear of the same critical substations, existing 600V main circuit breakers were also equipped with the arc flash maintenance switch to reduce the arc flash energy for downstream low-voltage motor control centers.

Fig. 3. Above left is a photo of the existing primary fused load-break primary switch for each substation with the fuse holders still in place. Above right is modified assembly after modification, with fixed mounted mini-vacuum circuit

The local plant along with the North America Cement Technical Group issued an AFE Scope of Work – Arc Flash Compliance document that was sent to various suppliers with interest in proposing to do the work. The successful bidder was to be responsible for services to complete the arc flash compliance project. A scheduled site visit was included in the AFE, allowing bidders to walk the facility to gain understanding of all existing site conditions including distribution system layout and access to electrical rooms prior to submitting a proposal. The AFE advertised two scheduled shutdowns during 2014:

- January for inventory purposes: up to 3 weeks
- April for scheduled yearly shutdown: four weeks

Up to 5 of the 10 conversions were allowed to be completed during periods other than the advertised scheduled shutdowns. These additional shutdowns were stipulated for up to 24 hours scheduled in advance by the owner. After receiving multiple bids and completing a rigorous bid evaluation, a decision was made to turn to the global services and solutions provider that completed the original arc flash studies to assist in completing this work.

The project work commenced in mid-2014 and was completed on time and within the proposed budget. Photos in Fig. 4 show one of the 10 substations in the process of being upgraded during the scheduled outage. The image at the left shows the 4160V existing primary fused load-break switch structure with the existing dry type transformer. The fuse elements have been removed and the lower compartment in the structure was then up-fitted to accommodate the new fixed mounted vacuum circuit breaker. The center image shows the new circuit breaker mounted in the existing structure. Secondary control terminals above the breaker are shown along with a breaker open/close controls on the face of the breaker. The device can be mechanically charged via the lever at the left of the breaker controls but in this case the device was supplied as electrically operated so a charging motor was included. At the right is an image of the rear of the vacuum breaker showing new current transformers installed at the load terminals.

Fig. 4. Existing primary switch at left, retrofitted with new vacuum circuit breaker at center and current transformers at the rear of the breaker at right.

The image at the left in Fig. 5 shows the transformer secondary bus with new current transformers that were added for secondary bus protection. New primary and secondary current transformers were wired to the new protective relay cabinet shown at the right. Note the new relay cabinet includes a breaker control switch at the lower section. This is used to

Fig. 5. Transformer secondary bus with new current transformers at left, new protective relay cabinet at right.

control the new electrically operated primary vacuum circuit breaker. Above the switch are breaker position indicating lights including Open (green), Closed (red) and Tripped (yellow). Just above the lights are shorting block terminations for the new primary and secondary current transformers. At the top of the cabinet are two overcurrent protective relays, one connected at the primary vacuum circuit breaker for protection of the transformer primary circuit and the other connected at the transformer secondary bus for protection of the 600V low-voltage bus. Note also that the selector switch on the cabinet at the lower left is a switch to enable the maintenance mode. As mentioned previously, the overcurrent relays include “maintenance mode” settings, a feature that allows users to select an enhanced protection setting while testing or troubleshooting is being performed in downstream equipment. In the maintenance mode, the primary vacuum circuit breaker clears the fault even faster than with the instantaneous trip setting. A reduced clearing time significantly reduces arc flash incident energy should an arcing fault occur. The tradeoff using the maintenance setting is that for the time while the mode is engaged, selective coordination with downstream protective devices will be overridden to achieve this fast clearing time. This means in the maintenance setting, potential nuisance trips could occur during normal operation when, for instance, a large downstream motor with a high inrush current is called on to start. Protecting people when they are at risk of a potential arc flash event is considered a good tradeoff, so users are generally willing to accept possible circuit breaker nuisance tripping to keep themselves out of harm’s way. Fig. 6 shows an updated single-line diagram of one of the upgraded substations. Note the low-voltage switchgear also includes a tripping system with maintenance mode functionality. This protective setting is used when secondary feeder circuit breakers are being racked from the energized 600V bus, again lowering the arc flash incident energy to protect plant workers.

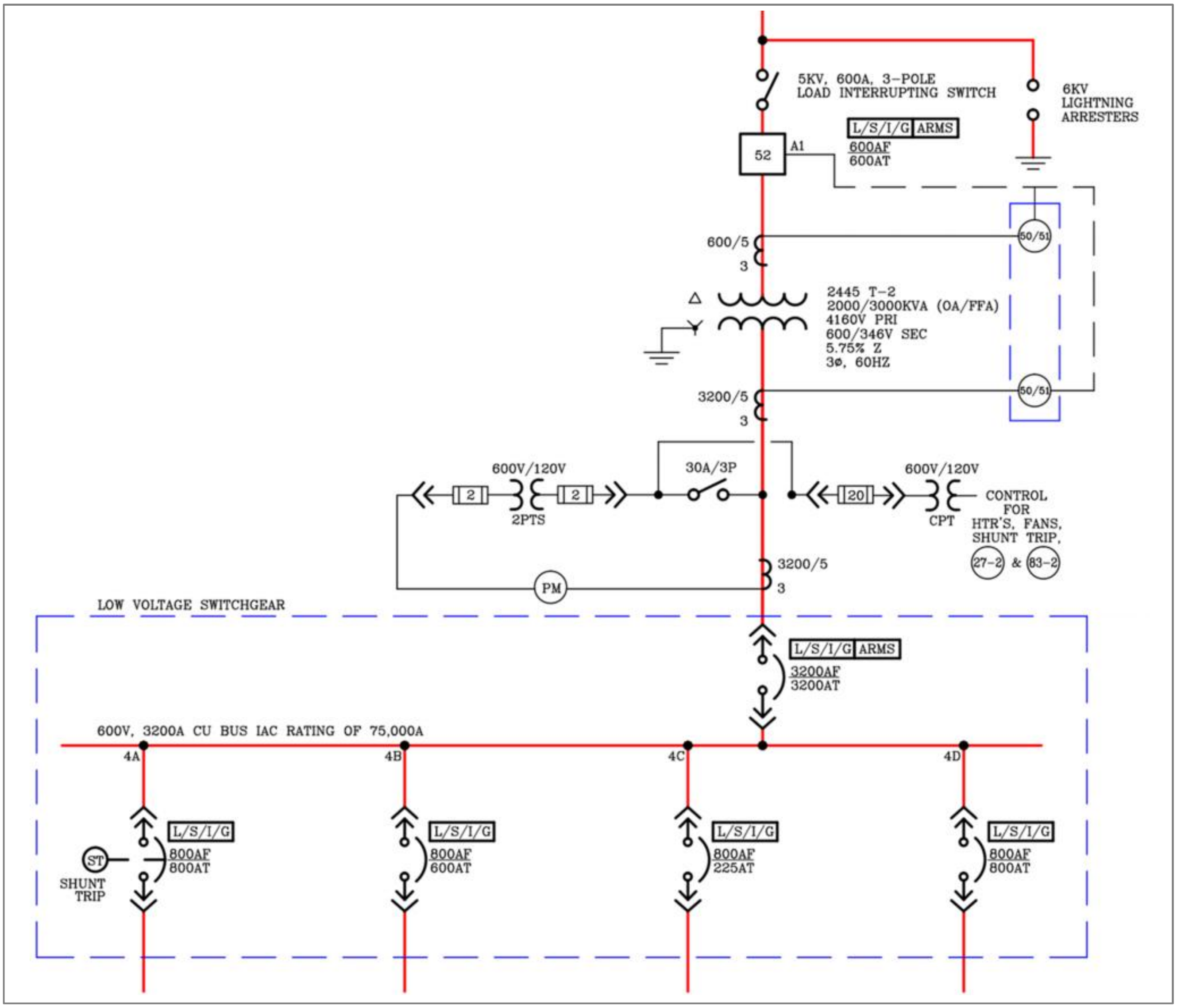

Fig. 6. One of 10 substations upgraded to include a 4160V primary vacuum circuit breaker with primary/secondary bus protection and new 600V secondary main circuit breakers with ARMS, reducing arc flash energy at the low voltage switchgear bus.

Following the installation to retrofit the 10 substations, the engineering services provider revisited the arc flash study, updating the calculated values and providing new arc flash labels to affix to each assembly. Table 1 shows the 10 existing bus locations and the resulting incident energy at each bus after the upgrade was complete. Note each of the bus locations includes a calculation for the selective coordination setting (Line) and arc flash reduction maintenance switch (ARMS) setting. The last two bus calculations include three operating conditions, as the electrical system for these substations includes a tie-breaker so scenarios with the tie open and closed were calculated.

TABLE 1: ARC FLASH ANALYSIS SUMMARY TABLE (UPDATED STUDY RESULTS AFTER UPGRADES)

Bus Name	Device Name	Bus kV	Bus Bolted Fault kA	Device Bolted Fault kA	Arcing Fault kA	Trip Time (s.)	Bkr. Opening (s.)	AF Boundary	Working Distance (in.)	Incident Energy (cal/cm^2)
MCC 2408E (Line)	RLY SUB2402E 02	0.6	28.25	22.33	16.17	0.2	0.083	7' 8"	18	17.2
MCC 2408E (ARMS)	RLY SUB2402E 02	0.6	28.25	22.33	16.17	0.017	0.083	7' 8"	18	6.9
MCC 2413E (Line)	RLY SUB2403E 02	0.6	28.39	22.82	16.52	0.2	0.083	7' 9"	18	17.4
MCC 2413E (ARMS)	RLY SUB2403E 02	0.6	28.39	22.82	16.52	0.017	0.083	4' 5"	18	7
MCC 2436E (Line)	RLY SUB2404E 02	0.6	28.58	22.78	16.48	0.3	0.083	9' 2"	18	23.1
MCC 2436E (ARMS)	RLY SUB2404E 02	0.6	28.58	22.78	16.48	0.017	0.083	4' 5"	18	7
MCC 2430E (Line)	RLY TX-A4 02	0.6	29.87	24.13	17.4	0.2	0.083	7' 12"	18	18.4
MCC 2430E (ARMS)	RLY TX-A4 02	0.6	29.87	24.13	17.4	0.017	0.083	4' 7"	18	7.3
BUS A2 2500A	RLY SUB2432E 02	0.6	35.05	23.01	15.32	0.9	0.083	19' 11"	24	35.1
BUS A2 2500A (ARMS)	RLY SUB2432E 02	0.6	35.05	23.01	15.32	0.017	0.083	5' 2"	24	4.8
MCC 2457E (Line)	RLY SUB2457E 02	0.6	22.99	22.02	16.21	0.4	0.083	10' 1"	18	26.9
MCC 2457E (ARMS)	RLY SUB2457E 02	0.6	22.99	22.02	16.21	0.4	0.083	3' 12"	18	5.8
MCC 2475E (Line)	RLY SUB1420 02	0.6	29.6	23.43	16.91	0.2	0.083	11' 7"	18	18
MCC 2475E (ARMS)	RLY SUB1420 02	0.6	29.6	23.43	16.91	0.017	0.083	7' 2"	18	7.2
SEC SUB 2490 (Line)	RLY SUB2490 02	0.6	34.65	28.53	20.33	0.4	0.083	11' 11"	18	35.7
SEC SUB 2490 (ARMS)	RLY SUB2490 02	0.6	34.65	28.53	20.33	0.017	0.083	4' 2"	18	8.5
Bus 2445 T1 SEC (Line)	RLY T1 01/02	0.6	43.42	33.17	21.61	0.3	0.083	13' 7"	24	20
Bus 2445 T1 SEC	RLY T1 02	0.6	43.42	33.17	21.61	0.218	0.083	9' 7"	24	12
Bus 2445 T1 SEC (ARMS)	RLY T1 01/02	0.6	43.42	33.17	21.61	0.017	0.083	6' 2"	24	6.2
Bus 2445 T2 SEC (Line)	RLY T2 01/02	0.6	43.42	33.17	21.61	0.3	0.083	13' 7"	24	20
Bus 2445 T2 SEC	RLY T2 02	0.6	43.42	33.17	21.61	0.218	0.083	9' 7"	24	12
Bus 2445 T2 SEC (ARMS)	RLY T2 01/02	0.6	43.42	33.17	21.61	0.017	0.083	6' 2"	24	6.2

IV. NEW GRINDING MILL ADDITION

In 2015 the plant embarked on a new grinding mill addition. Electrical equipment within the scope of this project included a new 2500kVA, 4160V substation with a dry type substation transformer close-coupled to a 3200 ampere (A), 600V secondary low-voltage metal-enclosed switchgear assembly. The switchgear included a 3200A main low-voltage power circuit breaker, two 1600A feeder circuit breakers and two 800A feeder circuit breakers. Although the company's corporate engineering group was responsible to develop project specifications and lead procurement, the organization was now well aware of the importance of specifying the assemblies that would perform in accordance with consensus electrical workplace safety standards [4]. The new electrical power distribution equipment was specified to include low-voltage circuit breakers with integral overcurrent protective relays including ARMS functionality. Adding the new equipment required an update of the arc flash study so new labels could be affixed to the new power distribution assembles, but forward thinking by the owner's engineering team ensured the incident energy for the newly installed equipment would as designed address the hazards of arc flash energy.

V. OTHER PLANT RELIABILITY ENHANCEMENTS

The successful arc flash compliance project served as an unexpected trigger of a quest by the plant's electrical engineer to survey the entire plant electrical system and identify areas that were comprised or in need of upgrades. Added power systems protection installed during the arc flash project included updated protective relays on the 5kV bus. These new relays began on occasion to shut the operation down due to ground fault and other spurious nuisance trip conditions. Further investigation to determine the cause of these unexplained trips revealed that the newly installed protective relays were functioning as designed. A combination of the seasonal climate change in the region coupled with the lack of a disciplined electrical preventive maintenance program resulted in the discovered need to implement several overdue system upgrades. Included in this section are a few of the key areas where additional upgrades were implemented:

A. GROUND GRID

As discussed in [6] and [7], the installation and maintenance of the ground grid is the single most important structure of any electrical installation. A faulty or non-existent ground grid can produce lethal step and touch voltages to personnel, cause destructive damage to equipment (electrical and mechanical) and contribute to costly down time. Low impedance is the key to electrical equipment protection. An operating plant should have a maximum ground impedance (resistance) of 1 to 2 ohms. Testing throughout the plant site revealed ground impedance at 100 to 120 ohms of resistance – extremely high levels with step potentials that could potentially cause serious personnel injury and equipment damage. Existing ground cable and ground rods at various locations throughout the plant site were unearthed, revealing that several 4/0 ground cable and rods were either severely damaged or heavily oxidized. Several incidents of premature motor failure, nuisance ground faults, instruments faulting on calibrations, etc. had been experienced. Repairs were implemented, including adding 1,800 feet of 4/0 bare ground cable and installing 200 ground rods to protect each low-voltage motor control center (MCC). After the upgrades, a TIME versus VOLTAGE chart dropped from a worst-case 127V to 10-12V. Plus, nuisance "ghost" trips of larger motors – which had resulted in the plant shutting down – almost immediately stopped. In addition, flash-overs to the PLC racks, instruments, and MCCs subsided; dangerous "sheath currents" on cables were dramatically reduced; and "ground fault" trips on larger motors were significantly reduced.

B. 5KV CABLE UPGRADES

Investigation of medium voltage cables installed at the plant revealed areas where cables were nearing imminent failure. Critical polyethylene insulation plant cables were showing signs of water tree aging [8]. Water trees grow from defects – contaminants (ions), protrusions or voids – when the insulation is subjected to electrical stress and moisture. These lower the dielectric strength of cable insulation and cause a large number of failures of cables in service, particularly in older vintage cables that have higher levels of defects than more recently installed cables. Electrical failure usually occurs when an electrical tree initiates from a water tree and bridges the insulation or by thermal runaway when a water tree that bridges the insulation reaches a sufficiently high conductivity. All the 5kV main feeder cables that supplied power to each of the 10 MCCs (approximately 14 kilometers in total length) showing signs of extensive water tree defects and insulation cracks were replaced with new conductors. Implementation of the 5kV cabling upgrade began during the arc flash compliance upgrade and continued after installation was complete. The installation of the 5kV cabling was accelerated due to the fact that newly installed protective relays on the 5kV systems were sensitive enough to detect insulation cracks, sheath currents and ground faults for the existing cables. In some cases, the newly installed protective relays settings did not allow plant operators to reenergize substations until the faulty cables were replaced. Fig. 7 shows examples of ground grid and cable systems issues.

Fig. 7. As found ground connections compromised or severed grid at left and center, 5kV existing replaced cable at right.

C. ANNUAL SYNCHRONOUS MOTOR TESTING (3000HP & 4500HP)

Annual testing of the most critical coal, rollermill, kiln and mill transformers and synchronous motors was put in place to ensure reliability and efficiency. At the beginning of the new test program, multiple inefficiencies were detected including capacitors bulged and leaking, cable stress cones deteriorated, exciter and stator dowel pins missing or loose, defective instruments and faulty wiring. Further testing was implemented with laser scans to check for alignment of the rotor to both the stator and excite. The plant found a rotor out of alignment with the stator on a 4500 horsepower (HP) mill synchronous motor. On another mill, an exciter field was found out of alignment on a 3000HP synchronous motor. With the air gap not symmetrical, the magnetic field symmetry was oblong due to an uneven field buildup at the stator coils. During operation, key components of large mill motors are subjected to severe mechanical stresses. Air gap eccentricity resulted in increased levels of vibration due to the uneven magnetic field created between the circumference of the rotor and stator. These elevated levels of vibration resulted in excessive movement of the stator winding, which led to increased friction and potentially a turn-to-turn or coil-to-coil failure, or a ground fault . Increased mechanical vibration accelerates bearing failure, which could seize the motor shaft, overheat the windings, or allow additional movement of the shaft, leading to a rotor-to-stator rub. Uneven magnetic stresses applied to the rotor, coupled with the increased vibration, also contribute to mechanical looseness developing in the rotor assembly. The risk of rotor pull-over increases exponentially with the amount of air gap eccentricity. Upon finding these alignment problems, and because of other concerns, a total upgrade to the protection and control of these critical motors was completed to enhance the plant reliability. Since this testing was initiated, the reliability of large rotating machines has markedly improved.

D. ANNUAL TRANSFORMER TESTING (5kV/600V/347V)

Many of the existing power transformers were operating at temperatures above manufacturer's recommendations. Increased heat would randomly transfer between the three phase coils, resulting in operating efficiencies below factory specifications, reduced transformer life and wasted energy. An aggressive testing procedure was completed on the affected transformers. Plant maintenance discovered that cracked and deteriorated arc arrestors on the 5kV primary feeders caused magnetic stresses and extreme heat. Heat buildup melted the insulators supporting the main transformer ground that separated the arc arrestors from the main frame of the transformer, effectively grounding the main transformer base. Extreme magnetic stresses and heat caused damage to the resin coating that encapsulates each coil. Eddy currents, which are generated when a conductor is placed in a changing magnetic field, also attributed to heat build-up. Voltage surges at the 5kV distribution system with steep rise times rapidly propagated eddy currents in the transformer primary conductors. Current waveform distortion in the form of harmonics affected the transformers and other electrical equipment. Inspections and immediate repairs were conducted on all 10 substation transformers.

Due to concerns of long-time elevated operating temperatures, an oil analysis was performed for plant liquid filled transformers as outlined in industry standards [9]. Evidence of contamination with potentially explosive gases in the oil was discovered. In these cases, mechanical repairs were completed on the damaged tap changers immersed in the oil and the transformer oil was replaced to bring the coolant back within factory specifications. Since new processes were put in place to routinely test transformer oil, equipment reliability for both liquid filled and dry-type substation transformers has markedly improved.

Following a disciplined process of new upgrades and testing, one of the main finishing mills continued to experience numerous erratic, unexplained nuisance shut downs. An in-depth investigation of the MCC determined that corona was the most probable cause of nuisance trips. Corona is a luminous, sometimes audible discharge that occurs when there is an excessive localized electric field gradient causing the ionization and ultimate electrical breakdown of insulation. Corona is characterized by a colored glow frequently visible in a darkened environment with an audible discharge that increases in intensity with increasing voltage potential. Ozone, an odorous, unstable form of oxygen can frequently be generated due to the effects of corona. Rubber is destroyed by ozone, and nitric acid can be created if sufficient moisture is present. These have detrimental effects on electrical insulators. Irregularities (such as nicks and scrapes on conductor surfaces or sharp edges on suspension hardware) concentrate the electric field at a pinpoint location, increasing the electric field gradient and the resulting corona. Although corona is a low energy phenomena, it can over time substantially degrade insulators causing system failure due to dielectric breakdown. To address insulation breakdown issues caused by corona, substation transformers were thoroughly cleaned, affected control wires were repaired and buss bars were rewrapped with a high-voltage insulating tape. Cleaning of all 10 substation transformers and re-insulating the main buss bars eliminated the erratic nuisance trip conditions.

E. ANNUAL MAIN SUBSTATION (138kV/5kV) TESTING

Following testing and calibration of the electromechanical relays and the 5kV air circuit breakers, tests results showed inconsistencies in set points and calibrations for the overcurrent protective relays. Because many protective relays were vintage induction disk devices, set points of the electromechanical relays constantly drifted from targets. An aggressive project was initiated to upgrade and replace substation switchgear protection with solid-state protective relays.

To address added arc flash safety concerns by plant electricians, a new remote switching station was manufactured and installed outside the substation building. This station includes switchgear circuit breaker controls along with indicating lights to demonstrate a zero energy state, signaling to workers that it is safe to enter the substation.

VI. CONCLUSIONS

After the critical electrical substations were upgraded, the plant electrical maintenance employees were very pleased. The company's focused commitment to employee safety was obvious given the visible investment to upgrade the plant electrical infrastructure. As a result, employees were better able to focus on operating the plant more efficiently and effectively. One unexpected benefit was a dramatic improvement in operating uptime. Unplanned outages dropped significantly following the Arc Flash Compliance upgrade project coupled with reliability initiatives itemized in the previous section. Today, the operational uptime and reliability of the plant has increased significantly, elevating the site as a new benchmark performer amongst its industry peers.

The dramatic safety and operational improvements can be attributed to the electrical/instrumentation projects supervisor at local plant with support from the plant manager. Interestingly, both of these gentlemen have an electrical engineering background so there was a clear understanding and appreciation for the value of a safe and reliable electrical distribution and control system. Typically, these assets are some of the most overlooked in the global cement industry, but that is not the case at the Western Canada Cement Plant.

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