MITIGATING ELECTRIC SHOCK AND ARC FLASH ENERGY – A TOTAL SYSTEM APPROACH FOR PERSONNEL AND EQUIPMENT PROTECTION

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Abstract — This paper provides a comprehensive discussion for the application and selection of various techniques and technologies available for the reduction and mitigation of arc fault hazards to personnel and equipment. It also presents a broad approach that considers the total electrical system configuration and design. No one technology can address all safety concerns. Current available technologies for reducing arc flash hazard such as optical light detection, pressure detection, temperature detection, and current signatures are discussed and advantages and disadvantages of each technique are outlined. An analysis is presented of how a total system approach can optimize benefits of various technologies by utilizing complementary technologies, such as impedance grounding, equipment construction, and operational techniques. The importance of the fundamental power system configuration selection, equipment design aspects, and maintenance is also discussed.

Index Terms—Arc Flash Mitigation, Electrical hazards, Light detection, Pressure detection, High resistance grounding

I. INTRODUCTION

Certain electrical hazards have been known since the advent of electricity's use in the late 19th century. The most familiar to most people is the shock and electrocution hazard. Experimentation has demonstrated that greater than 99.5% of the population can voluntarily let go for an electrical current flow through the body of 6 mA. As the magnitude of current flow is increased through the body, the person is more likely to become frozen to (i.e., cannot let go of) an energized conductor, respiratory paralysis can occur at approximately 18 mA of current flow, and the probability of heart ventricular fibrillation (VF) increases for a current flow exceeding 30 mA. There is a very low probability of VF at 30 mA current flow, which increases to greater than 50% probability of VF for long-term (in the order of seconds) exposure to an 80 mA current flow hand-to-foot. Once heart VF occurs, a person's heart rhythm must be re-established by use of a defibrillator, or death by cardiac arrest will occur. A good reference that describes the effects of electrical current on humans is IEC TS 60479-1 [1]. Although a shock itself may not injure a person, as the shock current magnitude increases, the degree of involuntary muscular contractions also increases. These contractions can easily lead to a person falling from an elevated platform or ladder, resulting in a fall injury or death if a fall restraint is not used when working from heights.

The second hazard that has had extensive treatment in technical literature over the past 15 years is the arc-flash burn hazard. When an electric current passes through air between ungrounded conductors or between ungrounded conductors and grounded conductors, the temperatures can reach 35,000°F. Exposure to these extreme temperatures both burns the skin directly and causes ignition of clothing, which adds to the burn injury. The majority of hospital admissions due to electrical accidents are from arc-flash burns, not from shocks. Each year more than 2000 people are admitted to burn centers with severe arc-flash burns. Arc-flashes can and do kill at distances of 3 m (10 ft) [3],[4]. The NFPA 70E and CSA Z462 standards describe personal protective equipment requirements for arc-flash exposures exceeding incident energy levels of 5 J/cm^2 (1.2 cal/cm^2), which is the threshold of a second-degree skin burn[3].

The last and least quantifiable hazard is the arc-flash "blast" hazard. The tremendous temperatures of the arc cause the explosive expansion of both the surrounding air and the metal in the arc path. For example, copper expands by a factor of 67,000 times when it turns from a solid to a vapor. The danger associated with this expansion is one of high pressures, sound, and shrapnel. The high pressures can easily exceed hundreds or even thousands of pounds per square foot, knocking workers off ladders, rupturing eardrums, and collapsing lungs. The sounds associated with these pressures can exceed 160 dB. Finally, material and molten metal is expelled away from the arc at speeds exceeding 1120 km/hr (700 mph), fast enough for shrapnel to completely penetrate the human body [3]. At present, the consensus standards do not address the blast hazard, other than the complete avoidance of exposure. It is the most difficult to quantify, due to the variability of electrical equipment construction and the affect of the arc-initiating event [3].

II. SHOCK HAZARD AND MITIGATION TECHNIQUES

As described in the above section on Electrical Hazards, a shock can have several physiological effects, depending on the magnitude of the current and the time of exposure. A good representation of the effects of ac current is given in Fig. 20 of [1], included below as Fig. 1. Direct current generally has less severe effects than alternating current for the same

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current magnitude, by a factor of approximately 4, and the reader is referred to [1] 3, and the corresponding text for further information. Our discussion is generally related to ac shock hazards, but could be extended to dc with appropriate adjustments. One significant difference is that unlike ac, the threshold of immobilization or "let-go" is not well defined for dc. Cramp-like muscular contractions and pain only occur when making and breaking direct current [1].

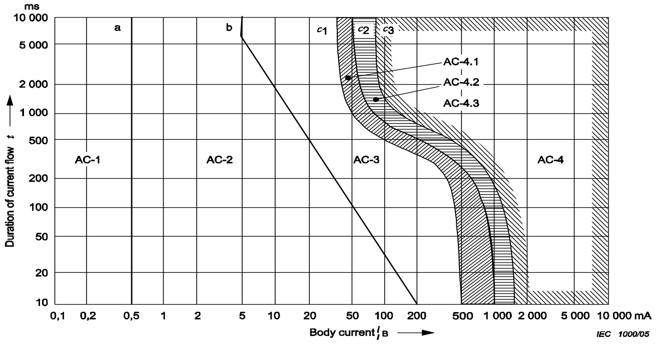


Fig. 1 Conventional time/current zones of effects of ac currents (15 Hz to 100 Hz) on persons for a current path corresponding to left hand to feet [1]

The zones AC-1, AC-2, AC-3, and AC-4 (including AC-4.1, 2, and 3) are described in Table 11 from [1], and are included below as Table 1.

TABLE 1
TIME/CURRENT ZONES FOR AC 15 HZ TO 100 HZ FOR HAND TO FEET PATHWAY – SUMMARY OF ZONES OF FIG. 1 [1]

Zones	Boundaries	Physiological Effects
AC-1	Up to 0.5 mA curve a	Perception possible but usually no "startled" reaction.
AC-2	0.5 mA up to curve b	Perception and involuntary muscular contractions likely but usually no harmful electrical physiological effects.
AC-3	Curve b and above	Strong involuntary muscular contractions. Difficulty in breathing. Reversible disturbances of heart function. Immobilization may occur. Effects increasing with current magnitude. Usually no organic damage to be expected.
AC-4$^{1)}$	Above curve c_1	Patho-physiological effects may occur such as cardiac arrest, breathing arrest, and burns or other cellular damage. Probability of ventricular fibrillation increasing with current magnitude and time.
	c_1 - c_2	AC-4.1 Probability of ventricular fibrillation increasing up to about 5%.
	c_2 – c_3	AC-4.2 Probability of ventricular fibrillation up to about 50%.
	Beyond curve c_3	AC-4.3 Probability of ventricular fibrillation increasing above 50%.

1) For durations of current flow below 200 ms, ventricular fibrillation is only initiated within the vulnerable period if the relevant thresholds are surpassed. As regards ventricular fibrillation, this figure relates to the effects of current which flows in the path left hand to feet. For other current paths, the heart current factor has to be considered.

The most immediate hazard from a low-level shock is the "startle" reaction, which may result in a fall or a more severe contact with an energized part. In the range of approximately 6 mA to 22 mA, almost all people will lose the ability to let go of a grasped conductor [1].

The hand-to-hand body impedance for 125 volts ac is between 850 and 2675 ohms [1], and grasping a conductor or faulty electrical device rated 120 volts can result in a current flow between 45 mA and 140 mA. This range of current is clearly in the area where cardiac arrest can result from a shock that goes undetected by a circuit protective device. A person's hand-to-hand internal impedance for exposure voltages in excess of 220 volts ac, where the skin is ruptured by current flow, is in the range of 575 to 1050 ohms [1], and the current flow through the body can be correspondingly higher for shock exposures in excess of 220 volts. It should be noted that the total body hand-to-foot impedance of a person can be significantly lower than the hand-to-hand impedance by a factor of 10% to 30% [1].

How does one avoid a shock? The first and most strongly recommended approach is to de-energize any electrical equipment prior to working on it. Additionally, adopt a "test before touch" mentality and habit whenever working on electrical equipment to assure that a defect in the isolation equipment does not exist, or that a mistake in isolation has not been made. A secondary approach is to use shock protective equipment or devices.

Personal protective equipment for shock protection includes rubber insulating gloves, sleeves, and blankets [2][10]. Insulating gloves are recommended whenever a person's hands enter the Restricted Approach Boundary [3][4] , which is "an approach limit within which there is an increased risk of shock, due to electrical arc over combined with inadvertent movement, for personnel working in close proximity to an exposed energized electrical conductor or circuit part ."[3] This boundary distance is 304.8 mm (1 ft 0 in) for system phase-to-phase voltages 301 through 750 volts, and 660.4 mm (2 ft 2 in) for system phase-to-phase voltages 751 through 15 000 volts. Refer to [3] for shock protection boundary distances for other system voltage levels. This means that most voltage testing that is done by a worker, even if it is to prove that a system is de-energized, requires that insulating rubber gloves be used. Rubber insulating sleeves are required where there is a danger of arm or shoulder contact with an energized conductor and there is no positive assurance that the arms will not violate the approach distance for the voltage involved.

It is important that insulating rubber equipment be maintained and regularly tested [2][10]. Leather protector gloves [15] , worn over the insulating rubber gloves, are required for all but a few situations [2] in order to physically protect the rubber from physical damage.

The use of insulated and insulating hand tools [21] is another option for working on equipment applied at system voltages 1000 volts and below. Special training is required for the use of live-line tools [5][11], which are typically used for work on voltages 17 kV and above [5] in combination with insulating rubber gloves. For work on uninsulated or inadequately insulated overhead line construction, insulating line hose and covers [5][6] are additional means of shock protection that can be used.

A final component of personal protective equipment for shock protection of the head is the safety helmet, or “hard hat.” The American standard for safety helmets [16] requires that Class E rated head protection pass an insulation test voltage of 20 kV ac, while another common standard [7] only requires passing a test voltage of 1200 volts ac.

At system voltages 1000 volts and below, another approach is available using a power system protective approach [17] [18] called the ground-fault circuit-interrupter (GFCI) or residual current device (RCD). The GFCI or RCD approach is recommended for all cord-connected electric power tools and other cord-connected devices used outdoors, in damp environments, or on concrete slabs that originate at grade level. Note that it is important to inspect all portable electrical equipment and tools prior to each use, and not to use the equipment if it is defective or damaged. The presence of the GFCI or RCD for shock protection is not an excuse for neglecting the condition of electrical tools, equipment, or components. Test the GFCI or RCD for proper operation in accordance with the manufacturers' recommendations prior to each use to assure that it will work if needed.

The term GFCI is unique to North American devices tested to UL 943 [17]; the term RCD is used in the context of international (IEC) standards. Sensitivity ranges from 6 mA for the GFCI to 30 mA for the typical RCD. A sensitivity of 6 mA was selected by the North American codes and standards when the devices were introduced in the 1970's to permit a person to be able to “let go” if they grasped a live conductor. The principal operating characteristic, besides the pickup sensitivity, is the speed of operation for the GFCI or RCD – typically 0.04 second or faster. While a GFCI or RCD cannot limit the magnitude of the ground fault, which is determined by the power supply’s source impedance and the impedance of the fault between phase and ground, it can certainly detect very low fault-current magnitudes and initiate fast isolation of the fault. Examining Fig.1, it can be concluded that a current of approximately 400 mA through the body can be tolerated for up to 0.1 second with minimal possibility of cardiac arrest.

If a product search is made for the availability of portable residual current devices (PRCDs), per the international IEC Standard 61540[19][20] most are of 30 mA sensitivity. Some are available for 6 mA and 10 mA sensitivity. The use of a lower sensitivity RCD is recommended, but secure commercial availability should be verified. International standards permit the use of 30 mA RCDs for personnel protection and this sensitivity will prevent most electrocutions, since it is below the normal threshold of ventricular fibrillation (see Fig. 1).

One aspect that the user needs to be aware of: the inherent capacitance between the phase “hot” conductor and the equipment grounding conductor within a temporary extension cord itself, will be in the order of 5 mA per km length of cable at a voltage of 230 volts to ground. This is sensed by the GFCI or RCD and appears as a continuous leakage current to ground or earth. Construction applications may be limited to approximately 1 km total length of extension cords connected to a single GFCI or RCD that has a 6 mA pickup, in order to avoid false trips. To avoid nuisance trips, it is recommended that the total connected extension cord length not exceed approximately 500 meters at 230 volts for application with a single 6 mA GFCI or RCD device on a branch circuit. The allowable length doubles to about 1000 meters at 120 volts.

III. ARC FLASH HAZARDS EFFECTS AND MITIGATION TECHNIQUES

Until recently, the main line of defense in mitigating the hazards of an arc was to use appropriate personal protective equipment for the worker in close proximity to the potential arc. Even though this method only provides protection against arc flash thermal burns, it was widely accepted and became standard for the industry.

One method to calculate incident energy is by utilizing equations in IEEE 1584 [12]. These formulae take into consideration the type of system grounding, distance from the ac, fault-clearing time, and available bolted fault current. The equations are empirically derived based on actual testing.

There has been documentation over the years indicating that between 80% and 95% of all electrical faults initiate as ground faults. By limiting the ground fault current to a small magnitude, a great majority of all phase-to-phase arcing faults can be eliminated.

NFPA 70E [3] and Z462 [4], and other references refer to high-resistance grounding as a method for arc flash mitigation. The reason for this is that the probability of developing an arc flash from a single phase to ground fault is less on a high-resistance grounded system than on a solidly grounded system, due to the extremely low energy of an arcing ground fault with a maximum of five amperes magnitude.

The schematic in Fig. 2 shows a typical high-resistance grounded system with a relay that can detect the presence of a ground fault, assist in the location of the fault, and, protect the system on the occurrence of a second arcing ground fault on a different phase and feeder by isolating the feeder with lower priority.

A high resistance grounded system does not eliminate all faults or arc flash hazards. Some faults may occur as phase to phase or three phase faults. In order to mitigate the hazard of these types of faults, further protection is necessary and will be discussed in the following sections.

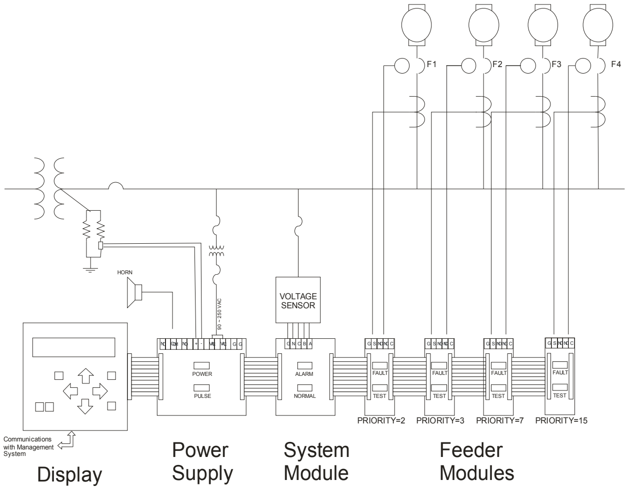


Fig. 2, High resistance Grounded System

High resistance grounding for arc flash mitigation is only effective if the first ground fault can be cleared before the second ground fault causes phase to phase fault. A second incipient fault can be removed by commercially available high resistance ground detection technology [22]. An example of this technology is described in Appendix B.

A) Time

Incident Energy is directly proportional to the amount of time the fault is present on the system. Dr. Land [13] suggests that if an arcing fault is extinguished in less than 100 ms, then there will not be enough energy produced to burn through the steel enclosure of metal-enclosed or metal-clad switchgear. In order to mitigate the energy, the fault must be detected in as short a time as possible without tripping erroneously. Fuses and low voltage molded case circuit breakers, especially the current-limiting type, offer fault-clearing times significantly faster than 100 ms, but fuses are not considered in this paper’s discussion.

B) Overcurrent Relays

In a properly coordinated electrical system the isolation device closest to the fault should clear the fault before any upstream circuit breaker or other device clears the fault. System engineers usually use time delays in upstream circuit breakers to properly coordinate the protection, consequently resulting in more incident energy as a fault occurs closer to the source.

To overcome this, relay manufacturers have developed zone selective interlocked type protection to coordinate an electrical system without introducing significant time delays. Differential type protection has also been applied to detect local faults within the protected zone, but that do not react to “through faults” outside the zone.

Arcing faults occur in two forms, parallel arcing faults and series arcing faults. A parallel arcing fault is a fault between phases or between phase and ground. This type of fault produces the greatest amount of fault current. A series arcing fault, for example, is an arcing fault that occurs within only one phase, as in a loose connection. It is virtually impossible to detect the series type of arcing fault using conventional overcurrent relays, as the current will be detected as the normal load of the circuit.

Some work has been conducted to try and capture the signature of an arc by using wavelet computational analysis, this method is still very much in its infancy, and requires great computational effort and extensive time for calculations.

C) Temperature

An early detection system utilizes monitors to detect the temperature within the electrical enclosure. The ability exists today to monitor the temperature and to provide an early warning of a pending situation. Land [13] suggests that most arcing faults are caused by faulty electrical connections in the bus or cables. Normal load currents cause the connection to melt, creating inline, or series type faults. By monitoring the temperature of the interior of the switchgear compartment the user can receive an early warning of an impending fault. An added benefit of the temperature monitoring is that it will be possible to have “Condition Based Maintenance” rather than routine scheduled maintenance. Users can now set thresholds on temperature and have the ability to trend. See Fig. 3 for an example of a typical temperature sensor.

Fig. 3 Temperature sensor

D) Light detection

Due to the speed of light, the light flash is the first direct energy emitted during an arc flash. Consequently, optical relays may be the best method to detect and mitigate the arc flash hazard. Optical relays are used to detect the presence of a light source. This detection is based on intensity of light and is less reliant on a specific wavelength produced by the arc. There are many manufacturers of this type of technology and many different forms of light detection are used. Some technologies use fiber optic strands to detect the presence of an arc, while some use photo electric cells to detect the light. These devices are very fast and can detect a fault between and send a trip initiation to a circuit-interrupting device at a time of approximately 1 ms to 7 ms after the arcing fault’s initiation.

The quantity and placement of the light detection sensors has to be thoroughly examined by an individual who has knowledge of the switchgear or motor control center. Care must be taken not to place the light detection sensors in direct exposure to devices that may emit an arc in normal operation. This may include, but is not limited to, load break switches, contactors, or air-magnetic type of circuit breakers.

E) Pressure detection

Pressure detectors can be placed inside the switchgear and can activate a trip signal from 8-18 ms since pressure waves will travel at the speed of sound. Lee [9] shows that arcing faults can produce anywhere from 20 psi to 1000 psi. The time to clear the fault could still be under the 100 ms duration with the use of an appropriate circuit interrupting device.

The installation of pressure detectors can be labor intensive and could require tubing to channel the pressure wave to the detector.

IV. DISTANCE

Personal protective equipment, such as arc-rated flame-resistant clothing and a face shield, can permit a person to work closer to an arc source than would otherwise be possible. However, due to the uncertainty of incident energy calculations, the probability of complete protection from burns is less than 100 percent. A better approach is to increase the distance between the person and the potential arc source.

There are many ways to increase the distance between a person and the point of an arc. For example, this may include remote operation and remote racking (insertion or removal) of circuit breakers.

V. BOLTED FAULT CURRENT

The last remaining input variable that has not been addressed is the bolted fault current (I_{BF}). There are some devices that will create a bolted fault to mitigate the energy from an arc. These devices will extinguish the arc in 1-5 ms. In doing so, the switchgear, transformers, generators and motors can be subject to mechanical forces at near maximum design capability. After a fault event, the components of the entire system should be thoroughly examined before being returned to service.

The method mentioned above will extinguish the arc by collapsing the voltage potential, thus eliminating the source of the arc. It is possible to reduce the arcing fault without creating a bolted short circuit. One method has been previously described [14]. The schematic shown in Fig. 4 shows a very fast device that will open on the detection of an arc fault. This will insert a resistor into the circuit and simultaneously open the main breaker.

The logic unit will issue an activation signal to the fast acting device (perhaps a solid state device) and the main circuit breaker simultaneously. The breaker will open in 3-5 cycles, 50 ms to 83 ms. If this proves to be too long, the fast acting device will open in perhaps 8.33ms (one-half cycle on a 60 Hz basis), thereby placing the resistor in the circuit and limiting the fault current from 50-65 kA to 300-600 A. If the resistor is 1 ohm on a 600 V system, this will limit the incident energy from 5.7 cal/cm^2 on a system with 50 kA fault current (cleared in 50 ms) to 0.9 cal/cm^2 with a fault current of 50 kA. for 8.33 ms, followed by a current of 347 A for the remainder of the 50 ms total fault-clearing time. The above incident energies are calculated using IEEE Std. 1584 for 600 V power switchgear on a solidly-grounded system at a working distance of 458 mm.

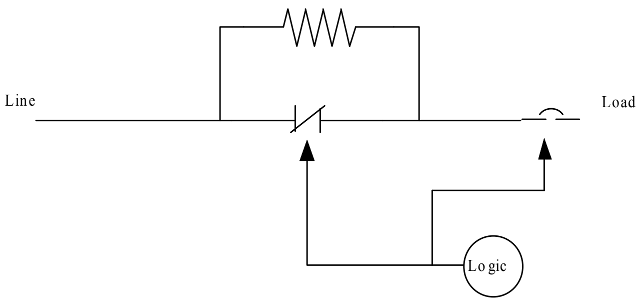


Fig. 4 Fault limiting device

VI. TOTAL SYSTEM APPROACH

The total system approach would include a high resistance grounded system to minimize the frequency of the faults, a temperature sensor to monitor the internal ambient temperature of the switchgear compartment, and an arc flash detection system based on either optical or pressure detection [22].

This approach will decrease any fault from propagating to three phase faults with the high resistance grounded system. It will also provide users with an early warning alarm should the temperature of any compartment increase above a predetermined set point.

The last portion of the approach is a detection system that will detect a fault after the fault occurs to limit the amount of time the system is subjected to the fault.

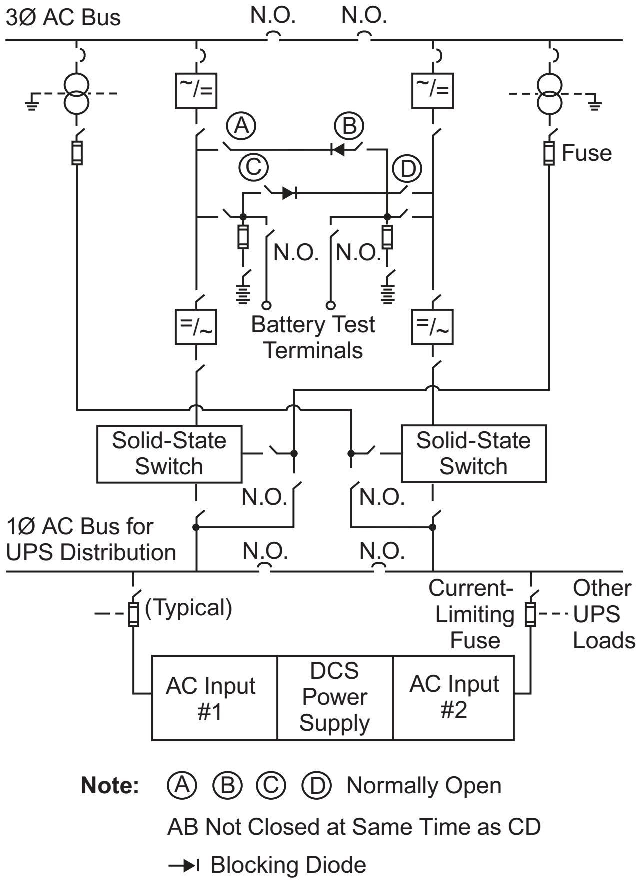
VII. POWER SYSTEM SELECTION, EQUIPMENT DESIGN ASPECTS

This section supplements the discussion included in the above section on the Total System Approach to Enhance Safety, which emphasized the design of specific equipment. During the conceptual design of a power system, the compatibility of the selected configuration to maintenance operation must be kept at the forefront.

Shock hazards can be reduced by the specification of “touch safe” terminals (designated “ingress protection” type IP20) within all equipment, the construction of which prevents a person from physically touching any low-voltage terminal with his or her finger. To access such terminals, a tool such as a screwdriver must be used. It is assumed that only a qualified electrical person using appropriate personal protective equipment and insulated tools would attempt to work on the terminal while energized.

One element that is common on equipment supplied to International Electrotechnical Commission (IEC) standards, but not so commonly available on North American equipment, is the integral earthing or grounding switch that is rated to withstand the short-circuit rating of the equipment. This can be used to advantage to minimize the need for intrusive grounding of circuits by personnel using live-line tools and grounding clusters. Be particularly mindful of the ability to positively lock the earthing switch using mechanical, rather than electrical, means to assure worker safety.

Be liberal with the use of isolation switches so a worker will be able to safely maintain equipment that is partially energized. For example, see the sample one-line diagram, Fig. 5, below for a critical uninterruptible power supply (UPS) system.



Note: Ⓐ Ⓑ Ⓒ Ⓓ Normally Open

AB Not Closed at Same Time as CD

→I Blocking Diode

Fig. 5 An AC Uninterruptible supply system configuration

The various components of the UPS – the rectifier, battery, inverter, bypass transformer, solid-state transfer switch, or even the power distribution panel itself – can all be safely isolated if proper attention is given to the layout and design to guard and segregate the various energized components within the equipment, in addition to the inclusion of isolation switches.

Another example of accommodating maintenance is the practice of designing a dual redundant substation with two tie circuit breakers in series, as shown in Fig. 6.

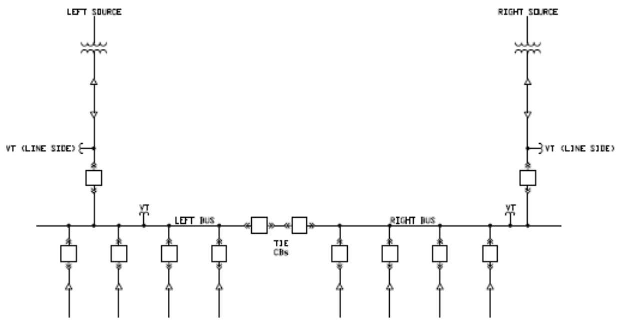


Fig. 6 A representative double-ended substation with two tie circuit breakers in series

The inclusion of two tie circuit breakers in series facilitates safe and positive isolation for personnel who need to work directly on either the left or right bus. The two circuit breakers can be opened and withdrawn from the cubicles to safely facilitate the maintenance operation on the buses and tie circuit breakers. Without the two circuit breakers in series (i.e., with only one tie circuit breaker), it is impossible to do maintenance on the tie cubicle bushings or stabs safely without taking both buses out of service. The outage of both buses may be infeasible in continuous process operations. Note the inclusion of voltage transformers (VTs) on both the line and bus sides of the main circuit breakers. See Appendix A for a method of phasing the two buses by use of secondary voltages of voltage transformers. This is an inherently safer work practice than conducting “hot stick” phasing at the primary voltage.

VIII. CONCLUSION

Optimum benefits are achieved when safety is considered during the design phase by evaluating the objectives and various options available. Proper utilization of finger protected terminals in the equipment can substantially reduce the shock hazard from low-voltage terminals. System configurations that are easily isolated and de-energized for maintenance activities should be selected. The use of ground-fault circuit-interrupters or residual current devices on all outdoor, low-voltage branch circuit receptacle outlets can eliminate many electrocutions. Utilizing high-resistance grounded systems with resistor monitoring and priority isolation of a second fault, and impedance grounding of higher voltage systems, can essentially eliminate arc flash hazard in a majority of cases. Utilizing optical protection and rapid isolation with selective use of arc resistance equipment can provide total protective schemes with optimum personnel protection and equipment protection. Finally, personal protective equipment has its place in contributing to electrical safety, but should be the last line of defense in case there are failures in any of the system design mitigations.

IX. ACKNOWLEDGEMENT

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APPENDIX A

PHASING THOUGH THE USE OF VOLTAGE TRANSFORMERS AND SECONDARY VOLTAGE VERSES "PHASING HOTSTICKS"

The Phasing Process

When a system is being commissioned, it is important to assure that the power system on either side of a main or tie circuit breaker or switch has the correct phase relationship or phase sequence. If the switching device is closed under an incorrect phasing condition, this will result in the equivalent of a short circuit on the system—with potentially damaging results to equipment or the interruption of a processing plant's operations. The traditional approach has been for a qualified electrical worker to use hotsticks to prove the phasing. The hotstick probes are placed on the primary (high voltage) stabs within a circuit breaker cubicle to measure that there is zero voltage between each of the phases before an attempt is made to close a circuit breaker. This hotstick process can expose the worker to high incident energy levels from an arc flash, if a fault were to occur by accident during the operation.

Recommended Approach Using Instrument Voltage Transformers

Following is an outline that could be adapted as a procedure on a double-ended substation (see Fig. 6) or other arrangement depending on the specifics of the installation:

- The use of the secondary, low voltage, side of voltage transformers (VTs) depends on the specification and supply of VTs on both the "line side" and "bus side" of the circuit breakers to be phased.
- Initially, open all circuit breakers. Insert only the circuit breakers necessary to perform the operation in each step described below. All other circuit breakers not involved in that step should be withdrawn from their cubicles to the "test position," where the primary voltage stabs are not engaged. One source VT will be used as the reference VT for each measurement. In this example, the left-side source VT is used as the reference.
- First, insert and close the left-side source circuit breaker onto the left-side bus and measure that proper line-to-line voltages are present. Then measure the voltages between the respective A, B, and C phase secondary terminals (A to A, B to B, and C to C) of the left-side source side VT and the left-side bus VT. All voltages should be zero.
- Insert and close the tie circuit breaker onto the "dead" right-side bus and assure that proper line-to-line voltages are present. Measure the voltages between the respective A, B, and C phase terminals of the left-side source VT and the right-side bus VT. All voltages should be zero.
- Open the tie and left-side source circuit breakers and withdraw the circuit breakers to the test positions.
- Measure the voltages between the respective A, B, and C phase terminals of the left-side source VT and the right-side source VT. All voltages should be zero.
- Insert and close the right-side source onto the right bus and measure that proper line-to-line voltages are present. Then measure the voltages between the respective A, B, and C phase terminals of the left-side source side VT and the right-side bus VT. All voltages should be zero.
- Insert and close the tie circuit breaker onto the "dead" left-side bus and assure that proper line to- line voltages are present. Measure the voltages between the respective A, B, and C phase terminals of the left-side source VT and the left-side bus VT. All voltages should be zero.
- The phase relationships of all the VTs have been proven if the above steps have been followed.
- Open the tie circuit breaker and withdraw it, then insert and close the left-side circuit breaker.
- As a final verification step, measure that proper line-to-line voltages are present on the bus VTs on both sides of the open tie circuit breaker. Then measure the voltages between the respective A, B, and C phase terminals of the left-side bus VT and the right-side bus VT. All voltages should be zero.
- If the voltages measured in the above step are zero, the phasing is correct and the tie circuit breaker can be inserted and safely closed, as during a closed-transition bus transfer or for a normally-closed tie configuration.

APPENDIX B

ISOLATING SECOND GROUND FAULTS ON INDUSTRIAL SYSTEMS

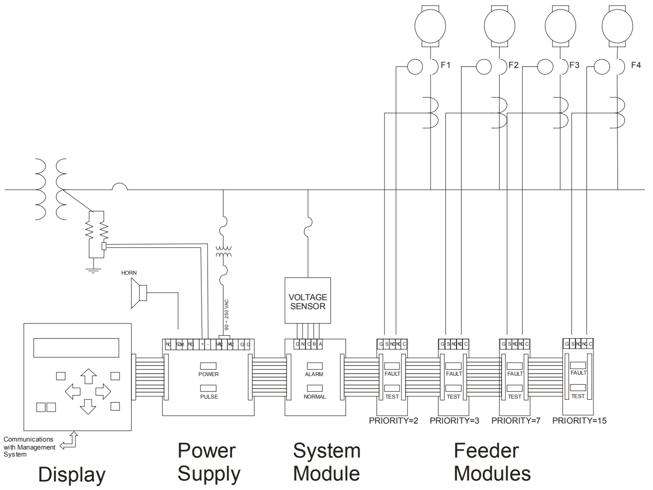

Fig. B-1 High Resistance Grounding with Second Fault Protection

This schematic illustrated in Fig. B-1 shows a small distribution system. This HRG system protection monitors both the voltage of the three phases and the zero sequence current in Feeders 1 through 4. Should a ground fault occur in feeder 2,on A phase, the system will alarm and indicate the faulted phase "A", and feeder (Feeder No. 2). This allows operators to trace the fault utilizing the pulsing resistor in the Neutral Grounding Resistor. Now should a fault occur on C Phase of feeder No. 3, the two feeder modules F2, and F3, communicate with each other to determine which feeder has been programmed with the lower priority. The feeder with the lower priority, in this case Feeder No. 2 will initiate a trip in less than 200ms. This will keep the high priority feeders on the system for as long as possible to protect critical loads.

This HRG system can be utilized in more complex double ended and redundant distribution systems with the same benefits. Up to 50 feeders can be monitored with up to 16 discrete priorities offering protection for even the most complicated of systems. These systems are widely in use in Petro Chemical Industries, Pulp and Paper Industries, Financial and Data centers, Hospitals, Airports, and many other critical Facilities.

XI. VITA

Daleep Mohla (S'72-M'73-SM'01, F'06) Principal Consultant DCM Electrical Consulting Services Inc. received a BSEE degree from West Virginia Institute of Technology, WV in 1973. He worked for 3 years with Pullman-Swindell Consulting Engineer before joining Union Carbide Corporation in 1976 and Dow Chemical in 2001 following merger of the two companies. He retired from Dow in January 2003 and currently the Principal Consultant and owner of DCM Electrical Consulting Services, Inc.

During his 27 years service with Union Carbide and Dow, he was involved with all phases of electrical design and technical support for large projects and support of personnel in operations and maintenance of chemical facilities. He is a long time member of National Electrical Code , Code panel 5 on Grounding and Bonding and is part of the technical committee responsible for NFPA 70E –Standard for Electrical Safety in the Workplace.

He is a champion of Electrical safety by design practices presenting multiple papers and tutorial on the subject of design He was a member of IEEE- Standards Association Standards Board (IEEE-SASB) from 1999-2006, secretary of P 1584 WG on guidelines for performing Arc flash hazard calculations, vice –chair of IEEE 142 (Green Book), member of IEEE 1349 (IEEE Guide for application of Electric motors in Class 1, Division 2 areas, and IEEE 141(Red Book). In 2007, Daleep was awarded the coveted David Azbill award *in recognition of extraordinary contributions to the Petroleum and Chemical Industry Committee sponsored standards.*

Daleep has co-authored and presented numerous technical papers in PCIC which includes three prize winning papers. He has presented various tutorials on Electrical Safety and National Electrical Code changes.

Tim Driscoll (BSc.'76) received his Bachelor of Science, Electrical Engineering degree in 1976 from the University of Calgary, Calgary, Alberta, Canada. Since graduation he has been employed at Shell Canada in various positions including control engineering, project management and electrical engineering. Current responsibilities include electrical engineering support for all Shell Canada's facilities in the areas of operations, maintenance, safety, energy, and capital projects. He has co-authored several papers and presentations at the IEEE PCIC Conference, the PCIC Europe Conference, the IEEE Electrical Safety, Technical & Mega Projects Workshop and the Electrical Safety Workshop. He is a member of the Association of Professional Engineers, Geologists and Geophysicists of Alberta.

He is also chairman of the Alberta Code for Electrical Installations at Oil & Gas Facilities and the Technical Content Subcommittee on the CSA Objective Based Industrial Electrical Code (OBIEC). He is a member of several other CSA Part II standards and Part I sections, and IEEE standards.

Paul S. Hamer (S'70–M'74–SM'89–F'97) received the B.S.E.E degree from Virginia Polytechnic Institute and State University, Blacksburg, and the M.S.E.E. degree from Oregon State University, Corvallis, in 1972 and 1979, respectively. In 1979, he joined Chevron Corporation, where he is currently a Senior Consulting Engineer, Electrical Machinery and Power Systems, with Chevron Energy Technology Company, Richmond, CA. His primary responsibilities include power system, motor, and generator application and consultation. He has worked on many refining, chemical, and oil production projects during his career with Chevron. In 2008, he was appointed a Chevron Fellow, Chevron's highest recognition for individual accomplishment. He has contributed to the American Petroleum Institute (API) standards for induction and synchronous machines and the API recommended practice on electrical area classification. He has represented the API on the National Electrical Code, Code-Making Panel 11, and on the Technical Committee for NFPA 70E, *Standard for Electrical Safety in the Workplace*. From 1972 through 1977, he was with the Westinghouse Electric Corporation, where he was a Service Performance Engineer with the Large Generator Department and an Industrial Power System Engineer and Resident Engineer with the Industry Services Division.

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