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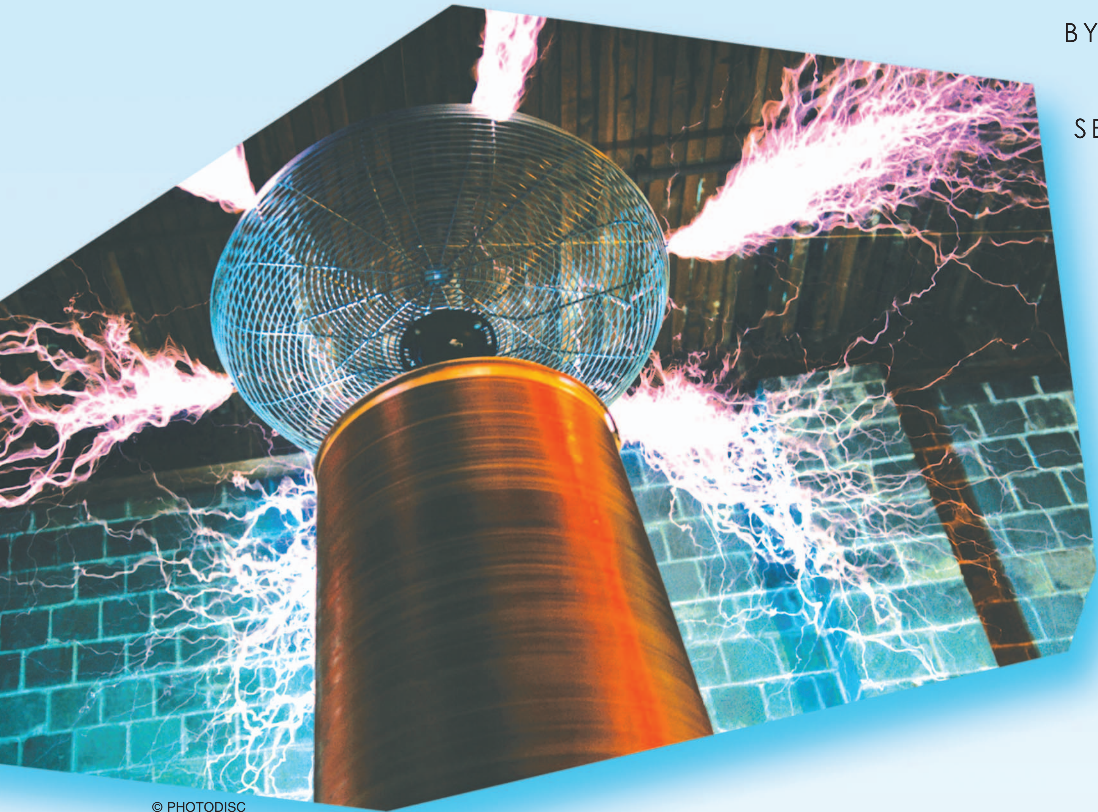

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A total system approach for personnel and equipment protection

MITIGATING ELECTRIC SHOCK AND ARC-FLASH ENERGY

THIS ARTICLE PROVIDES A COMPREHENSIVE DISCUSSION OF 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 technology can address all safety concerns. Current available technologies, such as optical light detection, pressure

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detection, temperature detection, and current signatures, for reducing arc-flash hazard are discussed, and the advantages and disadvantages of each technique are outlined. An analysis is presented about how a total system approach can optimize the benefits of various technologies by using 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.

EACH YEAR, MORE THAN 2,000 PEOPLE ARE ADMITTED TO BURN CENTERS WITH SEVERE ARC-FLASH BURNS.

Ventricular Fibrillation

Certain electrical hazards have been known since the advent of electricity in the late 19th century. The most familiar 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 of 6 mA through the body. 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, and 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 a long-term (in the order of seconds) exposure to an 80-mA current flow from hand to foot. Once heart VF occurs, a person's heart rhythm must be reestablished by the use of a defibrillator or death by cardiac arrest can occur. A good reference that describes the effects of electrical current on humans is International Electrotechnical Commission (IEC) Technical Specification (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 for 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 temperature can reach 35,000 °F. Exposure to these extreme temperatures 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 and not from shocks. Each year, more than 2,000 people are admitted to burn centers with severe arc-flash burns. Arc flashes can and do cause death at distances of 3 m (10 ft) [3], [4]. The National Fire Protection Association (NFPA) 70E and Canadian Standards Association (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 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 pressure, 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 sound associated with these pressures can exceed 160 dB. Finally, material and molten metal are expelled away from the arc at speeds exceeding 1,120 km/h (700 mi/h), fast enough for the 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 most difficult to quantify because of the variability of electrical equipment construction and the effect of the arc-initiating event [3].

Shock Hazard and Mitigation Techniques

As described in the earlier section, 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 alternating current (ac) is given in [1, Figure 20], which is included in this article as Figure 1. Direct current (dc) generally has less severe effects than ac for the same current magnitude, by a factor of approximately four, and the reader is referred to [1, Sec. 6] for further information. Our discussion is generally related to ac shock hazards but could also 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. Cramplike muscular contractions and pain only occur when making and breaking dc [1].

The zones AC-1, AC-2, AC-3, and AC-4 (including AC-4.1, AC-4.2, and AC-4.3) are described in [1, Table 11] and are included in this article as Table 1.

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 6–22 mA, almost all people will lose the ability to let go of a grasped conductor [1].

The hand-to-hand body impedance for 125-V ac is between 850 and 2,675 Ω [1], and grasping a conductor or faulty electrical device rated 120 V can result in a current flow between 45 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-V ac, where the skin is ruptured by current flow, is in the range of 575–1,050 Ω [1], and the current flow through the body can be correspondingly higher for shock exposures in excess of 220 V. 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 10–30% [1].

How does one avoid a shock? The first and most strongly recommended approach is to deenergize 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.

THERE HAS BEEN DOCUMENTATION OVER THE YEARS INDICATING THAT BETWEEN 80 AND 95% OF ALL ELECTRICAL FAULTS INITIATE AS GROUND FAULTS.

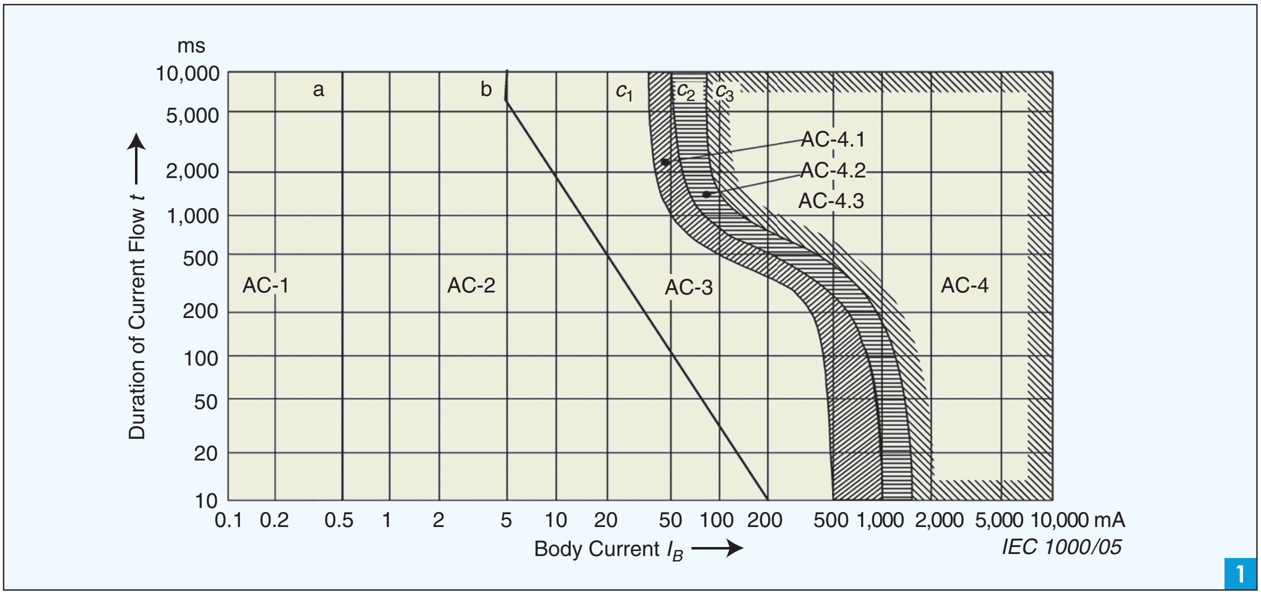
Personal protective equipment for shock protection includes rubber insulating gloves, sleeves, and blankets [2], [10]. Insulating gloves are recommended whenever a person’s hands enter the restricted approach boundary [3], [4], which is “an approach limit within which there is an increased risk of shock, because of electrical arc over combined with inadvertent movement, for personnel working in close proximity with 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 V and 660.4 mm (2 ft 2 in) for system phase-to-phase voltages 751 through 15,000 V. Refer to [3] for shock protection boundary distances for other system voltage levels. This means that most voltage testing done by a worker, even if it is to prove that a system is deenergized, 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] 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 1,000 V 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 1,200-V ac.

At system voltages 1,000 V 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 before each use and to not 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



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

GFCI or RCD for proper operation in accordance with the manufacturers' recommendations before each use to assure that it will work if needed.

The term GFCI is unique to North American devices tested to Underwriters Laboratories (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 1970s to permit a person to be able to let go if he 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 s 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 Figure 1, it can be concluded that a current of approximately 400 mA through the body can be tolerated for up to 0.1 s with a minimal possibility of cardiac arrest.

If a product search is made for the availability of portable RCDs (PRCDs), per the international IEC Standard 61540 [19], [20], most are of 30 mA sensitivity. Some are available for 6 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 VF (see Figure 1).

A SERIES ARCING FAULT IS AN ARCING FAULT THAT OCCURS WITHIN ONLY ONE PHASE, AS IN A LOOSE CONNECTION.

One aspect that the user needs to be aware of is 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/km length of cable at a voltage of 230 V 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, to avoid false trips. To avoid nuisance trips, it is recommended that the total connected extension cord length does not exceed approximately 500 m at 230 V for application with a single 6 mA GFCI or RCD device on a branch circuit. The allowable length doubles to about 1,000 m at 120 V.

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. Although this method only provides protection

TABLE 1. TIME/CURRENT ZONES FOR AC 15–100 HZ FOR HAND-TO-FEET PATHWAY—SUMMARY OF ZONES OF FIGURE 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	Pathophysiological effects may occur, such as cardiac arrest, breathing arrest, and burns or other cellular damage. Probability of VF increases with current magnitude and time
	c_1–c_2	AC-4.1 probability of VF increasing up to about 5%
	c_2–c_3	AC-4.2 probability of VF up to about 50%
	Beyond curve c_3	AC-4.3 probability of VF increasing above 50%

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

against arc-flash thermal burns, it was widely accepted and became a standard for the industry.

One method to calculate incident energy is by using the equations in IEEE 1584 [12]. These formulas 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 CSA 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 (HRG) system than on a solidly grounded system because of the extremely low energy of an arcing ground fault with a maximum magnitude of 5 A.

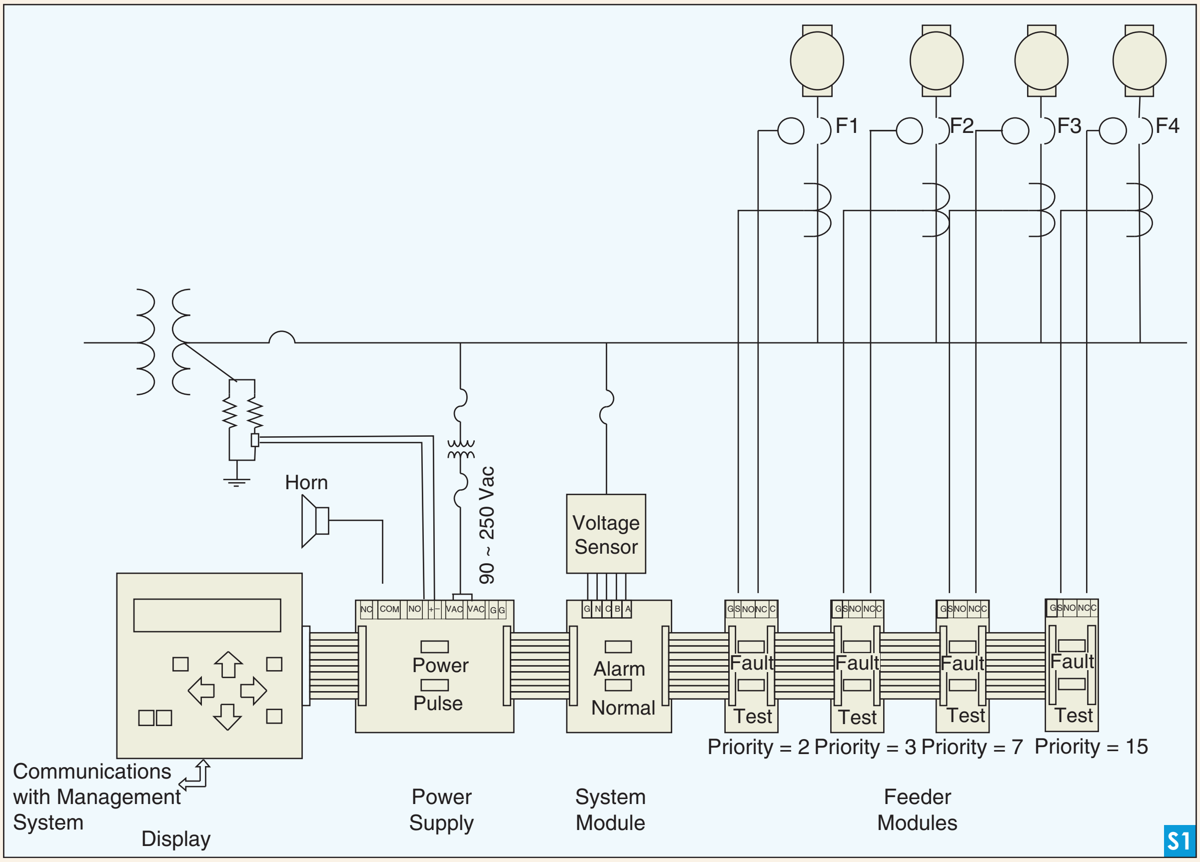
An HRG system does not eliminate all faults or arc-flash hazards. Some faults may occur as phase-to-phase or three-phase faults. To mitigate the hazard of these types of faults, further protection is necessary and is discussed in the following sections.

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.

ISOLATING SECOND GROUND FAULTS ON INDUSTRIAL SYSTEMS

The schematic illustrated in Figure S1 shows a small distribution system. This HRG system protection monitors both the voltage of the three phases and the zero-sequence current in Feeders 1–4. Should a ground fault occur in Feeder 2, on A phase, the system will alarm and indicate the faulted phase A and feeder (Feeder 2). This allows operators to trace the fault using the pulsing resistor in the neutral grounding resistor. Now should a fault occur on C Phase of Feeder 3, the two feeder modules, F2 and F3, communicate with each other to determine the feeder that has been programmed with a lower priority. The feeder with the lower priority, in this case Feeder 2, will initiate a trip in less than 200 ms. This will keep the high-priority feeders on the system for as long as possible to protect critical loads.

This HRG system can be used 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 petrochemical industries, pulp and paper industries, financial and data centers, hospitals, airports, and many other critical facilities.



An HRG system with second fault protection.

A second incipient fault can be removed by commercially available high-resistance ground detection technology [22]. An example of this technology is described in "Isolating Second Ground Faults on Industrial Systems."

Time

Incident energy is directly proportional to the amount of time the fault is present on the system. 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 -clad switchgear. 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 the discussion of this article.

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 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, and this method is still in its infancy and requires great computational effort and extensive time for calculations.

Temperature

An early detection system uses monitors to detect the temperature within the electrical enclosure. The ability exists today to monitor the temperature and 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. An example of a typical temperature sensor is shown in Figure 2.

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Temperature sensor. (Used with permission from Finmeccanica.)

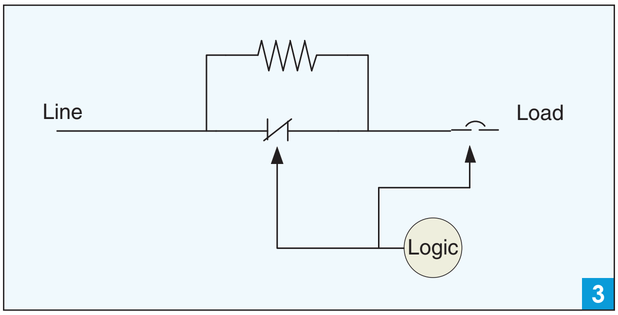
Light Detection

Because of 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 the 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 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 and send a trip initiation to a circuit-interrupting device at a time of approximately 1–7 ms after the initiation of an arcing fault.

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.

Pressure Detection

Pressure detectors can be placed inside the switchgear and can activate a trip signal from 8 to 18 ms since pressure waves will travel at the speed of sound. Lee [9] shows that arcing faults can produce pressure waves from 20 to 1,000 lb/in^2. 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



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Fault-limiting device.

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

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, because of the uncertainty of incident energy calculations, the probability of complete protection from burns is less than 100%. A better approach is to increase the distance between the person and potential arc source.

A PARALLEL ARCING FAULT IS A FAULT BETWEEN PHASES OR BETWEEN PHASE AND GROUND.

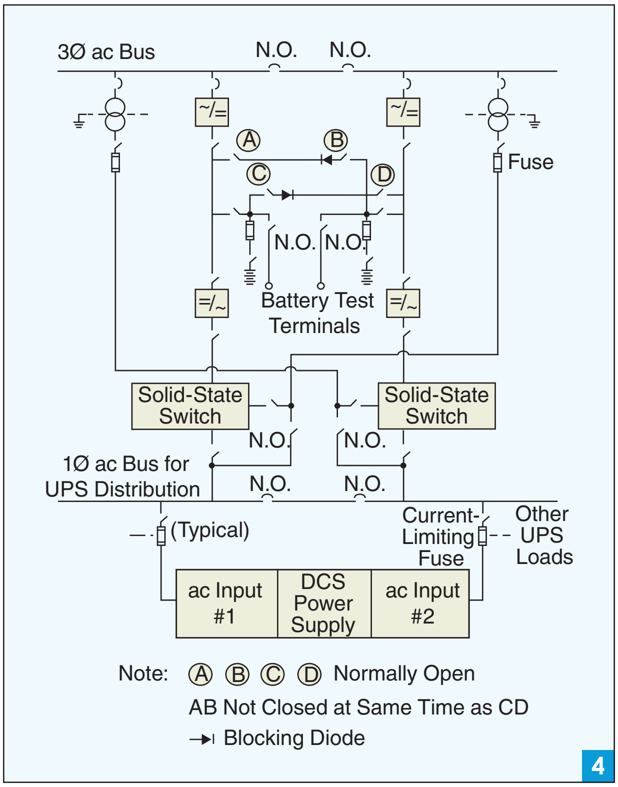
There are many ways to increase the distance between a person and the point of an arc. For example, this may include remote operation and remote racking (insertion or removal) of circuit breakers.

Bolted Fault Current

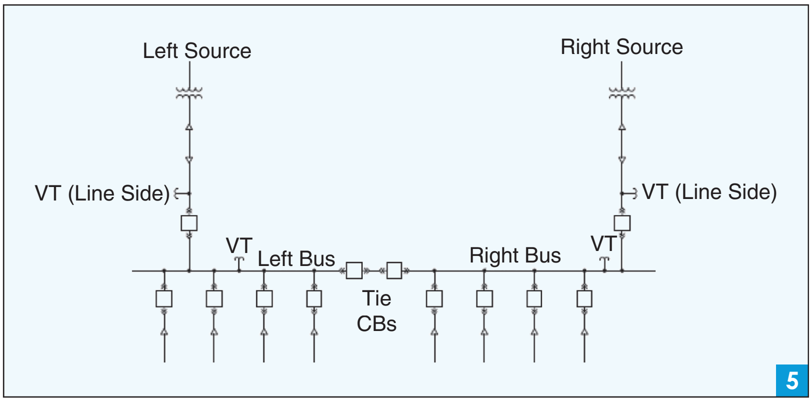
The last remaining input variable that has not been addressed is the bolted fault current (I_{BF}). There are some devices that will create a bolted fault to mitigate the energy from an arc. These devices will extinguish the arc in 1–5 ms. In doing so, the switchgear, transformers, generators, and motors 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. This method will extinguish the arc by collapsing the voltage, 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 Figure 3 shows a 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 three to five cycles, 50–83 ms. If this proves to be too long, the fast-acting device will open in perhaps 8.33 ms (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 Ω 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 Standard 1584 for 600-V power switchgear on a solidly grounded system at a working distance of 458 mm.



An ac uninterruptible supply system configuration.



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

Total System Approach

The total system approach would include a HRG system to minimize the frequency of 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 HRG 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.

Power System Selection and Equipment Design Aspects

This section supplements the discussion 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 common on equipment supplied to IEC standards, but not so commonly available on North American equipment, is the integral earthing or grounding switch rated to withstand the short-circuit rating of the equipment. It has the advantage of minimizing 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 (Figure 4) for a critical uninterruptible power supply (UPS) system.

The various components of the UPS—the rectifier, battery, inverter, bypass transformer, solid-state transfer

PHASING THROUGH THE USE OF VOLTAGE TRANSFORMERS AND SECONDARY VOLTAGES VERSUS PHASING HOTSTICKS

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 interruption operations of a processing plant. 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 was 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 Figure 5) or other arrangement depending on the specifics of installation.

- The use of the secondary, low voltage, side of VTs depends on the specification and supply of VTs on both the line and bus sides 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 deenergized 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 deenergized 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.

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 Figure 5. 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 buses or tie circuit breakers. 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 "Phasing Through the Use of Voltage Transformers and Secondary Voltages Versus Phasing Hotsticks" for a method of phasing the two buses by use of secondary voltages of VTs. This is an inherently safer work practice than conducting hotstick phasing at the primary voltage.

OPTICAL RELAYS ARE USED TO DETECT THE PRESENCE OF A LIGHT SOURCE DURING AN ARCING FAULT.

Conclusions

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 deenergized for maintenance activities should be selected. The use of GFCIs or RCDs on all outdoor, low-voltage branch circuit receptacle outlets can eliminate many electrocutions. Utilizing HRG systems with resistor monitoring and priority isolation of a second fault, and resistance grounding of higher voltage systems, can essentially eliminate arc-flash hazard in a majority of cases. Using 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.

Acknowledgments

The authors thank the IEC for permission to reproduce information from its International Standard IEC/TS 60479-1, Edition 4 (2005).

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