Improved Electrical Safety Through High Resistance Grounding

John P. Nelson, *Life Fellow, IEEE*

***Abstract*—High resistance grounding (HRG) is a well-proven technology for improving electric reliability for many industrial and utility facilities such as used in petrochemical, automotive, and generating plants. Many such facilities require the increased reliability for production and operational reasons. This paper will discuss the improved personnel safety aspects of using HRG on low-voltage systems. In particular, this paper will discuss the AQ1 following: 1) the probability of the three common faults occurring within an industrial plant, namely, three-phase, phase-to-phase, and ground faults; 2) how the probability of a ground fault can be used to improve electrical safety with HRG; 3) the impact of a ground fault on a system and the speed at which the ground fault on a solidly grounded system may propagate into a multiphase fault; 4) the risk reduction of a ground fault on an HRG system propagating into a multiphase fault; 5) the potential reduction in serious and fatal arc blast injuries through the use of an HRG system; and 6) potential single-pole breaker clearing issues when a second ground fault occurs on a second phase. This paper will include comments from recent testing, which was conducted at the KEMA Laboratories and presented in a recent Industry Applications Society Petrochemical Industry Committee paper in September 2014.**

***Index Terms*—Arc voltage, arcing faults, grounding conductors, high resistance grounding (HRG), impedance grounding, safety by design, solidly grounded, symmetrical components, zigzag transformer.**

I. Introduction

HIGH resistance grounding (HRG) has a long history of being successfully used within industrial power systems as a means of providing high reliability. The IEEE Green Book references the uses and applications for HRG systems for industrial and commercial power systems. [2] For those readers who are unfamiliar or need a brush up on HRG system, refer to the paper "High Resistance Grounding for Low Voltage Systems" for the Petroleum and Chemical Industry [3] or the book "Power System Grounding Design Handbook" [4]. There AQ2 is anecdotal evidence from one industrial customer that, on average, 95% of industrial faults originate as a line-to-ground fault. Less than 3% of the faults originate as a phase-to-phase fault, and less than 1% originate as a three-phase fault.[1] Experience has shown that most faults that originate as a three-phase fault are the result of maintenance grounding conductors not being properly removed prior to reenergizing the power system.

Utilizing HRG limits the fault current typically between 1 and 5 A. With a solidly grounded system, the ground fault current for a typical large industrial plant may be in the tens of thousands of amperes, which is sufficient to ionize the air surrounding the arc with a large plasma cloud. This high-temperature highly conductive plasma cloud will quickly allow the fault to propagate into a three-phase fault. Testing has shown that an arcing ground fault on a solidly grounded system will typically propagate into a three-phase fault in the subcycle range, whereas a ground fault on an HRG system will not. [1]

In technical terms, the ground fault current is limited by the amount of resistance in the zero-sequence circuit. (Under most conditions, the resistance is proportional to the size of the resistor connected between the ground and the neutral of the transformer. The zero-sequence resistance may be connected in other locations such as in a zigzag grounding transformer, a generator neutral, or some other artificially derived ground source.) The use of symmetrical component calculations is a convenient means to perform HRG system calculations. The calculations for a typical HRG system will show that there is minimal ground fault current flowing and there is practically no energy at the point of the ground fault. With proper alarming for a ground fault and with timely location and isolation of the ground fault, the incident energy level for the fault is 0 cal/cm^2. In contrast, a ground fault on a solidly grounded system will typically initiate a large cloud of plasma with quick propagation into a three-phase arcing fault, thus creating potentially high incident energy levels. In the latter case, the incident energy level is limited by only the system impedance and fault clearing time.

II. Electrical Injury Statistics

To put into perspective the importance of an HRG system in reducing the potential for and the number of arc blast injuries, a review of electrical injury statistics is necessary. During the period of 1992 through 2002, there were 3378 fatal electrical injuries listed in the Census of Fatal Occupational Injuries [6]. Of those 3378 electrical fatalities, all but 30 were attributed to electrocution through electrical contact. Less than 1% of the electrical fatalities were attributed to injuries resulting from electrical burns. During the same period, 47 406 nonfatal electrical injuries were categorized by the type of injury, which resulted in the following types of injuries:

- 18 360 or 38.7% were electrical burns;
- 29 046 or 61.3% were electrical shocks.

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[1] Procter and Gamble statistical data.

The above statistics are based on ten years of data and provide the following average annual statistics:

- 338 electrical related fatalities per year;
  - 335 fatalities due to electrocution;
  - 3 fatalities due to electrical burns;
- 4741 electrical injuries;
  - 1836 electrical burn injuries;
  - 2945 electrical shock injuries.

It should be noted that the use of HRG will assist in reducing the number of arc blast injuries and death, but will do little or nothing in preventing contact injuries. Other safety practices must be used to prevent the contact injuries and fatalities. However, in consideration of the 1836 electrical burn injuries, the potential of an HRG system in reducing the number of injuries to less than 20 is significant. Knowing that HRG cannot replace all of the solidly grounded system, it is still worth noting the potential reduction of an arc blast injury to those electricians and technicians working on an HRG system in comparison with those working on a solidly grounded system.

III. Degree of Risk in the Workplace

In recent years, there has been considerable concern with electrical safety. NFPA 70E (*Electrical Safety in the Workplace*), ANSI C2 (*National Electrical Safety Code*), IEEE 1584 (*IEEE Guide for Performing Arc Flash Calculations*), and NFPA 70 (*National Electric Code*) all have relatively new requirements concerning arc blast safety. It should be noted that the electric safety record within the United States is quite good considering the extensive usage of electricity and electrical components. Thus, a perspective into risk of an electrical accident in comparison with other hazards was undertaken by the author.

All activities in life have a certain amount of inherent risk. For example, the risk of average American dying in a motor vehicle is 1 in 6500.[2] If somehow we could invent a device to reduce the risk of being injured in an automobile accident, the risk would be then reduced to 1 : 65 000. That would reduce the number of motor vehicle accidents from 42 000 annually to approximately 420. This is an example of how effective reducing the risk of an electrical accident by two orders of magnitude is. Using 1992–2002 statistics, the average number of serious injuries can be reduced from 1836 to less than 19 and the number of fatalities from three to approximately one every 33 years [3].

In reviewing workplace risks, consider the following examples. According to the U.S. Department of Labor, the category of slips, trips and falls accounts for the largest category of work-related injuries, for a total 15% of all accidental work-related deaths and 17% of all disabling work-related injuries. In general, "a worker is five times more likely to suffer serious injuries due to a slip, trip or fall over being seriously injured in a work related vehicular accident."[3] In 2003, there were 696 fatalities and 257 100 employees injured from the category of slips, trips and falls.[4] With regard to workplace fatal injuries, during the period of 1992 through 2002, transportation was listed as the leader in fatal occupational injuries, with 23 272 fatalities over that period of time for a total of approximately 35% of all occupational fatalities. Therefore, while slips, trips, and falls were the statistical leader in workplace injuries, transportation was the statistical leader in occupational fatalities.[5] The average number of fatal occupational injuries from transportation is approximately 2327 or a little over three times of that for slips, trips, and falls. Therefore, it is important to analyze safety from two perspectives:

1) fatal injuries;
2) serious nonfatal injuries.

Electrical-related occupational fatalities accounted for approximately 5% of occupational incidents. Based on these statistics, an electrician is much more likely to be injured by a cause other than from electricity.

In performing work tasks, the employer and the employee must take into consideration the degree of risk involved in such a task and minimize that risk. In planning and executing a work plan, there is no way to eliminate all risks, except for avoiding that work task. However, after an accident has taken place, it is only in rare cases that someone can say that the accident could not have been prevented. This is a paradox in our safety culture where people are prepared to lay blame postaccident.

A good electric safety program involves controlling the degree of risk in performing each task, and thus, our objective in electric safety is to minimize the degree of risk to which an electrical technician[6] may be exposed. Therefore, the safety program should consider the degree of risk from injuries caused by all non-electrical risk hazards, including but not limited to the following:

1) slips, trips, and falls;
2) vehicular accidents;
3) pinch points;
4) cuts and abrasions.

Statistics have shown that electrical technicians are more likely to be injured by these hazards than from electrical shocks and burns.

Once consideration has been taken into the higher degree of risk tasks, the electrical technician should assess the electrical specific risks that are present. This assessment should include such things as follows:

1) *condition of the equipment*;
2) *familiarity with equipment*;
3) *experience of worker*;
4) *system grounding*;
5) *insulated bus and terminations*;
6) *task being performed*;
7) *magnitude of bolted three-phase fault current*;
8) *distance from arcing fault*.

A good common practice for other than routine electrical work is to complete a job safety analysis (JSA). The JSA should list the known hazards that exist, including such things as

[2] www.reason.com/archieves/2006/08/11dont-be-terrorized

[3] RISK∗TEX, p. 1.

[4] www.compliance.gov, p. 1.

[5] Trends in Electrical Injury, 1992–2002, p. 325.

[6] Electrical technician in this context means a qualified person working around electrical equipment, such as electricians, electrical apprentices, engineers, and operators.

those listed above, such as "slips, trips, and falls." In addition, consideration should be given to including a section as to the risk exposure.

Risk exposure may be listed as to the degree of risk involved. The risk may be listed as follows:

1) unlikely;
2) low;
3) moderate;
4) high.

Since slips, trips, and falls are one of the most common occupational hazards, the lowest risk level may be considered moderate, and such tasks as using a ladder to change a "light" fixture may be considered "high." Taking this to our current subject, the degree of exposure to an arc flash on a solidly grounded system may be moderate to high, whereas working on an HRG system may be deemed "unlikely."

IV. Test Results

A series of tests were conducted at the KEMA Test Facility on three vertical sections of low voltage motor control center with a 3200-A horizontal bus and a 600-A vertical bus. The test laboratory was set up to provide 85-kA peak of fault current, and the planned duration was for 0.5 s. The nominal test voltage was set to be 480 V; however, voltages in the range of 540 V were required to produce the required fault current profile. Due to various conditions in the laboratory, the expected maximum bolted fault current was limited to 65-kA peak, with many of the faults being further limited due to the arc voltage and arc resistance. However, fault currents in the range of 30- 50-kA peak were recorded [1].

Some of those test results are pertinent to this paper. In particular, the following are found.

1) A series of ground fault tests were conducted using an HRG system. As expected, there was no arc blast.
2) A series of phase-to-phase faults were conducted using an HRG system. A hypothesis had been formed that the incident energy level of an arcing fault not involving three phases on an HRG system would result in less incident energy than an arcing three-phase fault. During the testing of the phase-to-phase fault, it was noted that the fault quickly propagated into a three-phase fault within 1/4 of a cycle and that the speed of propagation was so fast that there was no significant decrease with the incident energy.
3) A series of phase-to-ground faults were conducted using a solidly grounded system. The same hypothesis was that a fault originating as a phase-to-ground or phase-to-phase fault on a solidly grounded system would have a lower incident energy level than one originating as a three-phase fault. Again, the fault quickly propagated into a three-phase fault in approximately 1/4 of a cycle, and the speed of propagation was so fast that there was no significant decrease with the incident energy.
4) The conclusion drawn from 2) and 3) above is that the practice of testing and calculating incident energy levels based on the inception of an arcing three-phase fault is reasonable and accurate.

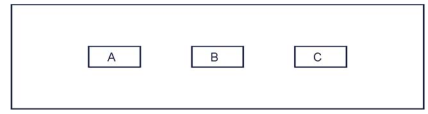

Fig. 1. Electrical buses in an enclosure.

V. Incident Energy Calculations

IEEE Standard 1584 is the IEEE Guide for Performing Arc-Flash Hazard Calculation and was first published in 2002. Throughout the standard, reference was made to the fact that the calculations are based on a three-phase fault for which the author concurs as being a good practice. As pointed out in [1], ground faults, phase-to-phase fault on solidly grounded systems, and phase-to-phase faults on HRG and ungrounded systems have a propensity to quickly propagate into three-phase faults.

However, IEEE 1584, in the opinion of the author, has an error in its basis for calculating incident energy levels on ungrounded and HRG systems. Equation 35 [7] has two constants, i.e., K_1 and K_2. K_2 is a grounding constant and is zero (0) for HRG and ungrounded systems and -0.113 for solidly grounded systems. For reference, IEEE-1584 equation 35 is as follows:

$$\log_{10} E_n = K_1 + K_2 + 1.081 \log_{10} I_a + .00110G \quad (1)$$

where

E_n	incident energy normalized;
K_1	constant for the box configuration -0.792 for open configuration, -0.555 for box configuration;
K_2	grounding constant;
$\log_{10} I_a$	$\log_{10}$ of arc current;
G	distance between arcing buses (mm).

There should be no difference in the constant K_2, whether the system is solidly grounded, impedance grounded, or ungrounded. Once a fault becomes a three-phase fault, the physics of the circuit is such that ground is no longer a factor. Therefore, the constant K_2 should be the same regardless of the method of grounding. Since it was determined to be -0.113 for a grounded system, that number should be used regardless of the method of grounding. To simplify the equation, K_2 could be combined with K_1. The KEMA testing results showed that no current flows in the ground other than the current that flowed through the enclosure (bus supports) to sustain the three-phase fault (see Figs. 1 and 2). Fig. 1 shows a typical bus arrangement where it would appear that a three-phase fault is not possible. However, it was found that the plasma from the arc was sufficient to encompass all three phases with the current path from phase A to phase C being through the structure, as is evidenced in Fig. 2. This was also noted in the KEMA oscillographs showing no ground current.

A comparison of incident energy level for solidly grounded and HRG systems requires some technical calculations For ease of calculations, an approximation of the levels will be made using a formula developed by the author. The basis for the approximation of incident energy levels was developed in a paper by Ammerman *et al.* [8], where estimates were provided for incident energy levels at voltages of 480, 600, and 1000

Fig. 2. Arc damage from outside phases to enclosure supports for a three-phase fault.

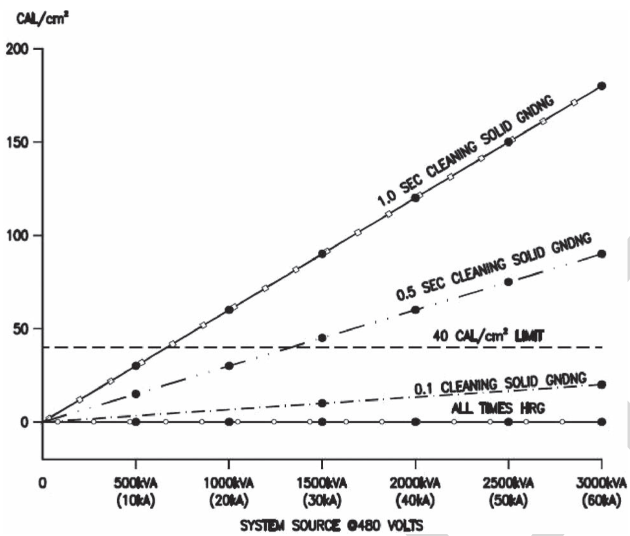

Fig. 3. Incident energy levels for solid versus high resistance grounding.

and above. The constants used in those approximations were rounded and provide a quick estimate of incident energy. The equation is identified as *the 3–4–5 Incident Energy Approximation*, i.e.,

$$E_n = K^* I^*_{\mathrm{arc}} t \quad (\mathrm{cal/cm}^2) \tag{2}$$

where

E_n	incident energy level in cal/cm^2;
K	constant of 3, 4, or 5
$K = 3$	for 480-V systems
$K = 4$	for 600-V systems
$K = 5$	for systems 1000 V and above;
t	time in seconds.

Using (2) for a 480-V system, incident energy levels were calculated for single-phase faults of varying magnitudes and times of 0.1–1.0 s for a single-phase fault on a solidly grounded system and for an HRG system. The results of the incident energy levels are provided in Fig. 3.

For convenience of the reader, the fault levels are provided in kiloamperes and standard transformer kilovoltampere sizes at 480 V. An important assumption to this graph is the fact that, for a solidly grounded system, the fault will quickly propagate into a three-phase fault for which the incident energy is calculated at the three-phase fault level. The other important note is that the ground fault on the HRG system will not cause an arc blast and will not propagate into a three-phase fault. That is the basis for the 0-cal/cm^2 incident energy level.

VI. Single-Pole Tripping Issue

Once a ground fault occurs on an HRG or even an ungrounded system, timely detection and removal of the ground fault is essential. A person with a basic understanding of HRG and ungrounded systems knows that the voltage on the grounded phase will be at or near 0 V, whereas the voltage on the two ungrounded phases will increase by as much as 1.73 times the normal phase voltage. For an example, a ground fault “A” phase on a 480-V system, the voltage on “A” phase will decrease from 277 to 0, and the voltages on the other two phases will go from 277 to 480 V. Another issue has been raised concerning single-pole tripping of molded-case circuit breakers on a high resistance or an ungrounded system and is worthy of discussion [9].

Gregory raised an interrupting rating issue concerning single-pole tripping on an HRG or an ungrounded system. The issue involves the fact that many two-pole and three-pole molded-case circuit breakers are designed and tested for operation on a solidly grounded system. When the molded case circuit breakers are used on an HRG or an ungrounded system, the breaker may be required to open using a single pole when second ground fault occurs on a different phase elsewhere in the system. The normal voltage on the opening of the pole under such a condition is no longer 58% of the line-to-line voltage for which the breaker is designed and tested; the voltage on the single pole can increase to 100%. It is this increase in the voltage across the contacts that reduces the interrupting capability of the breaker. For example, Gregory pointed out that a commonly used 65-kA breaker may be only tested at 8.7 kA interrupting for line-to-line voltage.

There are several issues that need to be addressed with regard to trouble shooting the first fault, which is an abnormal condition.

1) Special care needs to be taken when trying to locate the first ground fault on an HRG system. The normal procedure involves recognition of a ground fault on the HRG system. The alarm may be an indicating light, an audible alarm, or an ant alarm through a distributed control system. Good trouble shooting practices would suggest that the time of the alarm be recorded and that action be initiated to locate the fault. Best design practices for new projects would be to include sufficient metering to locate the feeder on which the fault is located. When trouble shooting, care should be taken to avoid contact with the unfaulted phase conductors since they will be operating at an elevated voltage typically 73% above normal voltage. In addition, care should be taken to avoid an arc blast.
2) The second issue involves the concern with inadequate single pole interrupting from a circuit breaker if a second ground fault occurs. While a second ground fault is a rare occurrence, Gregory pointed out that it can occur. From a

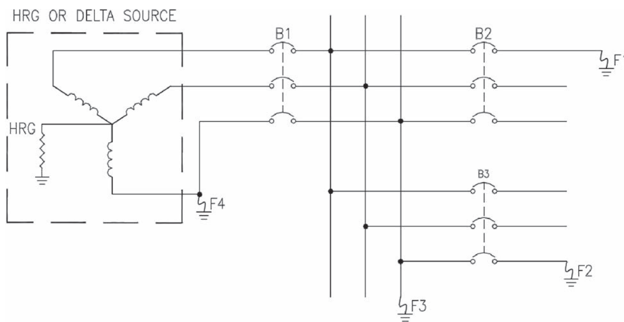

Fig. 4. Single-pole tripping.

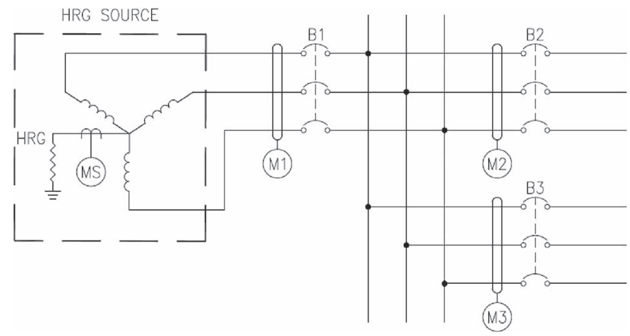

Fig. 5. Ground fault sensing.

protection point of view, the worst case location for one of the two ground faults will be between the HRG system and the main breaker (see Fig. 4). In Fig. 4, the drawing represents an HRG system serving a main breaker, i.e., B1, and two feeder breakers, i.e., B2 and B3. Several locations for faults should be considered with fault F1 being the first sustained ground fault.

a) Fault F2 represents a second ground fault located on an adjacent feeder and on a different phase than fault F1. While each of the two feeder breakers will be subjected to single-pole tripping, the fault current and recovery voltage will be interrupted by two separate poles in series.
b) Fault F3 represents a second ground fault located on the bus and on a different phase than fault F1. While each of the two breakers will be subjected to single-pole tripping, the fault current and the recovery voltage will be interrupted by two separate poles in series.
c) Fault F4 represents a second ground fault ahead of the main breaker and on the HRG system source. In this case, the feeder breaker B2 will try to interrupt the fault as a single pole with a phase-to-phase recovery voltage, which may reduce the interrupting capability. However, breaker B1 will most likely trip at the fault levels of concern, which may aid the proper tripping of breaker B2. In addition, the single-pole interrupting rating of breaker B1 may be sufficient to clear the fault.

With regard to the single-pole tripping issue for this unusual operation, the same problem exists for an ungrounded or a "delta" system. There are still many ungrounded systems in operation, including practically all shipboard power systems, which are almost universally operated ungrounded. In addition, Gregory correctly pointed out that the NEC does not require consideration for double contingency faults so that there is no code violation. Therefore, other than in theory, the practical considerations for single-pole tripping issues on HRG are essentially a nonissue. However, awareness of such a contingency is worthy to note.

VII. HRG Fault Sensing

Most HRG systems provide alarm contacts through either a voltage or a current sensing relay. With the sensitive microprocessor-based sensors and relays along with zero-sequence current transformers, ground fault sensing can be used to locate the feeder on which the first ground fault occurs. Using this type of sensing, location and/or tripping schemes may be implemented (see Fig. 5).

VIII. Conclusion

This paper has shown the safety benefits of HRG in the area of minimizing personnel from the dangers of an arc blast. In summary, the following conclusions can be made.

1) Within an industrial plant, using HRG and other enhanced engineering techniques such as bus insulation, the probability of an arcing fault can be reduced by two orders of magnitude. The HRG plays the most significant role by potentially reducing the number of arc blast incidences within an industrial setting by over 95%.
2) HRG does not improve electrical safety for "contact" or "touch" dangers, which are still the predominant cause of serious injuries and death. Contact-type injuries can still cause burns along with electric shock and electrocution.
3) The incident energy level calculations should not be higher on an HRG system in comparison with a solidly grounded system.
4) Tests on an HRG system consistently show that a single phase-to-ground fault will not propagate into an arcing multiphase fault and that the incident energy at the point of the fault is zero. However, higher than normal voltages will appear on the two unfaulted phases, which can lead to a second ground fault on one of the two unfaulted phases. If this occurs, an arc blast may be the result.
5) Testing conducted on ground faults on a solidly grounded system and phase-to-phase faults on an HRG will quickly propagate into a three-phase fault, and the incident energy levels are not significantly reduced due to the subcycle propagation into a three-phase fault.
6) A concern has been raised concerning the single-pole clearing of three-phase breakers on an HRG system when two ground faults occur on separate phases. Although this does not a appear to be a major issue as discussed in this paper, further research into this issue may be warranted.
7) With the high-temperature plasma, the fault easily propagated from a B to a C phase fault on the high resistance grounded system, and C phase to ground on the solidly grounded system, to encompass all three phases. Any

thought that the incident energy level will be significantly reduced on an arcing fault for a non-three-phase fault does not appear to be valid.

8) The modern molded-case circuit breaker, working well at a 1000-A setting, easily cleared the fault in 3–5 ms for faults occurring on the load side of the breaker.

Acknowledgment

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References

[1] J. P. Nelson, J. Billman, J. Bowen, and D. Martindale, "The effects of system grounding, bus insulation and probability on arc flash hazard reduction—Part 2 testing," in *Conf. Rec. IEEE PCIC*, 2014, pp. 29–43.

[2] *IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems (IEEE Green Book)*, IEEE Std. 142-2007, 2007.

[3] J. P. Nelson and P. K. Sen, "High resistance grounding of low voltage systems—A standard for the petroleum and chemical industry," *IEEE Trans. Ind. Appl.*, vol. 35, no. 4, pp. 941–948, Jul./Aug. 1999.

[4] J. R. Dunki-Jacobs, F. J. Shields, and C. St. Pierre, *Industrial Power System Grounding Design Handbook*. Dexter, MI, USA: Thomson-Shore, 2007.

[5] J. P. Nelson, J. D. Billman, and J. E. Bowen, "The effects of system grounding, bus insulation and probability on arc flash hazard reduction—The missing links," in *Conf. Rec. IEEE PCIC*, 2012, pp. 27–39.

[6] J. C. Cawley and G. T. Homce, "Trends in electrical injury, 1992–2002," in *Conf. Rec. IEEE PCIC*, pp. 325–338, Paper 2006-38.

[7] *IEEE Guide for Performing Arc Flash Calculations*, IEEE-1584-2002, Sep. 2002.

[8] R. F. Ammerman, P. K. Sen, and J. P. Nelson, "Arc flash hazard incident energy calculations—A historical perspective and comparative study of the standards: IEEE 1584 and NFPA 70E," in *Proc. 54th Annu. Petrol. Chem. Ind. Conf.*, 2007, pp. 1–13, PCIC-2007-02.

[9] G. D. Gregory, "Single pole short circuit interruption of molded-case circuit breakers," *IEEE Trans. Ind. Appl.*, vol. 35, no. 6, pp. 1265–1270, Nov./Dec. 1999, IEEE.

[10] J. R. Dunki-Jacobs, "The escalating arcing ground-fault phenomenon," *IEEE Trans. Ind. Appl.*, vol. IA-22, no. 6, pp. 1156–1161, Nov./Dec. 1986.

[11] R. H. Lee, "The other electrical hazard: Electric arc blast burns," *IEEE Trans. Ind. Appl.*, vol. IA-18, no. 3, pp. 246–251, May 1982.

[12] R. H. Kaufmann and J. C. Page, "Arcing fault protection for low-voltage power distribution systems—Nature of the problem," *Trans. Amer. Inst. Elect. Eng. Power App. Syst. III*, vol. 79, no. 3, pp. 160–165, Apr. 1960.

[13] NFPA, *National Electric Code*, Quincy, MA, USA, NFPA 70, Apr. 2015.

[14] H. B. Land and T. Gammon, "Addressing arc flash problems in low voltage switchboards industrial and commercial power systems technical conference record," in *Proc. 50th IEEE/IAS I&CPS*, May 2014, pp. 1–12.

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AUTHOR QUERIES

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AQ1 = As per journal style, abstract should be only a single paragraph. Thus, the displayed list was changed into a run in list. Please check.

AQ2 = The phrase “in excess of 95%” was changed to “on average, 95% of...” Please check if appropriate. Otherwise, please make the necessary changes.

AQ3 = LVMCC was expanded as “low voltage motor control center.” Please check if appropriate. Otherwise, please provide the corresponding expanded form.

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I. Introduction

HIGH resistance grounding (HRG) has a long history of being successfully used within industrial power systems as a means of providing high reliability. The IEEE Green Book references the uses and applications for HRG systems for industrial and commercial power systems. [2] For those readers who are unfamiliar or need a brush up on HRG system, refer to the paper "High Resistance Grounding for Low Voltage Systems" for the Petroleum and Chemical Industry [3] or the book "Power System Grounding Design Handbook" [4]. There is anecdotal evidence from one industrial customer that, on average, 95% of industrial faults originate as a line-to-ground fault. Less than 3% of the faults originate as a phase-to-phase fault, and less than 1% originate as a three-phase fault.[1] Experience has shown that most faults that originate as a three-phase fault are the result of maintenance grounding conductors not being properly removed prior to reenergizing the power system.

Utilizing HRG limits the fault current typically between 1 and 5 A. With a solidly grounded system, the ground fault current for a typical large industrial plant may be in the tens of thousands of amperes, which is sufficient to ionize the air surrounding the arc with a large plasma cloud. This high-temperature highly conductive plasma cloud will quickly allow the fault to propagate into a three-phase fault. Testing has shown that an arcing ground fault on a solidly grounded system will typically propagate into a three-phase fault in the subcycle range, whereas a ground fault on an HRG system will not. [1]

In technical terms, the ground fault current is limited by the amount of resistance in the zero-sequence circuit. (Under most conditions, the resistance is proportional to the size of the resistor connected between the ground and the neutral of the transformer. The zero-sequence resistance may be connected in other locations such as in a zigzag grounding transformer, a generator neutral, or some other artificially derived ground source.) The use of symmetrical component calculations is a convenient means to perform HRG system calculations. The calculations for a typical HRG system will show that there is minimal ground fault current flowing and there is practically no energy at the point of the ground fault. With proper alarming for a ground fault and with timely location and isolation of the ground fault, the incident energy level for the fault is 0 cal/cm^2. In contrast, a ground fault on a solidly grounded system will typically initiate a large cloud of plasma with quick propagation into a three-phase arcing fault, thus creating potentially high incident energy levels. In the latter case, the incident energy level is limited by only the system impedance and fault clearing time.

II. Electrical Injury Statistics

To put into perspective the importance of an HRG system in reducing the potential for and the number of arc blast injuries, a review of electrical injury statistics is necessary. During the period of 1992 through 2002, there were 3378 fatal electrical injuries listed in the Census of Fatal Occupational Injuries [6]. Of those 3378 electrical fatalities, all but 30 were attributed to electrocution through electrical contact. Less than 1% of the electrical fatalities were attributed to injuries resulting from electrical burns. During the same period, 47 406 nonfatal electrical injuries were categorized by the type of injury, which resulted in the following types of injuries:

- 18 360 or 38.7% were electrical burns;
- 29 046 or 61.3% were electrical shocks.

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[1]Procter and Gamble statistical data.

The above statistics are based on ten years of data and provide the following average annual statistics:

- 338 electrical related fatalities per year;
  - 335 fatalities due to electrocution;
  - 3 fatalities due to electrical burns;
- 4741 electrical injuries;
  - 1836 electrical burn injuries;
  - 2945 electrical shock injuries.

It should be noted that the use of HRG will assist in reducing the number of arc blast injuries and death, but will do little or nothing in preventing contact injuries. Other safety practices must be used to prevent the contact injuries and fatalities. However, in consideration of the 1836 electrical burn injuries, the potential of an HRG system in reducing the number of injuries to less than 20 is significant. Knowing that HRG cannot replace all of the solidly grounded system, it is still worth noting the potential reduction of an arc blast injury to those electricians and technicians working on an HRG system in comparison with those working on a solidly grounded system.

III. Degree of Risk in the Workplace

In recent years, there has been considerable concern with electrical safety. NFPA 70E (*Electrical Safety in the Workplace*), ANSI C2 (*National Electrical Safety Code*), IEEE 1584 (*IEEE Guide for Performing Arc Flash Calculations*), and NFPA 70 (*National Electric Code*) all have relatively new requirements concerning arc blast safety. It should be noted that the electric safety record within the United States is quite good considering the extensive usage of electricity and electrical components. Thus, a perspective into risk of an electrical accident in comparison with other hazards was undertaken by the author.

All activities in life have a certain amount of inherent risk. For example, the risk of average American dying in a motor vehicle is 1 in 6500.[2] If somehow we could invent a device to reduce the risk of being injured in an automobile accident, the risk would be then reduced to 1 : 65 000. That would reduce the number of motor vehicle accidents from 42 000 annually to approximately 420. This is an example of how effective reducing the risk of an electrical accident by two orders of magnitude is. Using 1992–2002 statistics, the average number of serious injuries can be reduced from 1836 to less than 19 and the number of fatalities from three to approximately one every 33 years [3].

In reviewing workplace risks, consider the following examples. According to the U.S. Department of Labor, the category of slips, trips and falls accounts for the largest category of work-related injuries, for a total 15% of all accidental work-related deaths and 17% of all disabling work-related injuries. In general, "a worker is five times more likely to suffer serious injuries due to a slip, trip or fall over being seriously injured in a work related vehicular accident."[3] In 2003, there were 696 fatalities and 257 100 employees injured from the category of slips, trips and falls.[4] With regard to workplace fatal injuries, during the period of 1992 through 2002, transportation was listed as the leader in fatal occupational injuries, with 23 272 fatalities over that period of time for a total of approximately 35% of all occupational fatalities. Therefore, while slips, trips, and falls were the statistical leader in workplace injuries, transportation was the statistical leader in occupational fatalities.[5] The average number of fatal occupational injuries from transportation is approximately 2327 or a little over three times of that for slips, trips, and falls. Therefore, it is important to analyze safety from two perspectives:

1) fatal injuries;
2) serious nonfatal injuries.

Electrical-related occupational fatalities accounted for approximately 5% of occupational incidents. Based on these statistics, an electrician is much more likely to be injured by a cause other than from electricity.

In performing work tasks, the employer and the employee must take into consideration the degree of risk involved in such a task and minimize that risk. In planning and executing a work plan, there is no way to eliminate all risks, except for avoiding that work task. However, after an accident has taken place, it is only in rare cases that someone can say that the accident could not have been prevented. This is a paradox in our safety culture where people are prepared to lay blame postaccident.

A good electric safety program involves controlling the degree of risk in performing each task, and thus, our objective in electric safety is to minimize the degree of risk to which an electrical technician[6] may be exposed. Therefore, the safety program should consider the degree of risk from injuries caused by all non-electrical risk hazards, including but not limited to the following:

1) slips, trips, and falls;
2) vehicular accidents;
3) pinch points;
4) cuts and abrasions.

Statistics have shown that electrical technicians are more likely to be injured by these hazards than from electrical shocks and burns.

Once consideration has been taken into the higher degree of risk tasks, the electrical technician should assess the electrical specific risks that are present. This assessment should include such things as follows:

1) *condition of the equipment*;
2) *familiarity with equipment*;
3) *experience of worker*;
4) *system grounding*;
5) *insulated bus and terminations*;
6) *task being performed*;
7) *magnitude of bolted three-phase fault current*;
8) *distance from arcing fault*.

A good common practice for other than routine electrical work is to complete a job safety analysis (JSA). The JSA should list the known hazards that exist, including such things as

[2]www.reason.com/archieves/2006/08/11dont-be-terrorized
[3]RISK∗TEX, p. 1.
[4]www.compliance.gov, p. 1.

[5]Trends in Electrical Injury, 1992–2002, p. 325.
[6]Electrical technician in this context means a qualified person working around electrical equipment, such as electricians, electrical apprentices, engineers, and operators.

those listed above, such as "slips, trips, and falls." In addition, consideration should be given to including a section as to the risk exposure.

Risk exposure may be listed as to the degree of risk involved. The risk may be listed as follows:

1) unlikely;
2) low;
3) moderate;
4) high.

Since slips, trips, and falls are one of the most common occupational hazards, the lowest risk level may be considered moderate, and such tasks as using a ladder to change a "light" fixture may be considered "high." Taking this to our current subject, the degree of exposure to an arc flash on a solidly grounded system may be moderate to high, whereas working on an HRG system may be deemed "unlikely."

IV. Test Results

A series of tests were conducted at the KEMA Test Facility on three vertical sections of low voltage motor control center with a 3200-A horizontal bus and a 600-A vertical bus. The test laboratory was set up to provide 85-kA peak of fault current, and the planned duration was for 0.5 s. The nominal test voltage was set to be 480 V; however, voltages in the range of 540 V were required to produce the required fault current profile. Due to various conditions in the laboratory, the expected maximum bolted fault current was limited to 65-kA peak, with many of the faults being further limited due to the arc voltage and arc resistance. However, fault currents in the range of 30- 50-kA peak were recorded [1].

Some of those test results are pertinent to this paper. In particular, the following are found.

1) A series of ground fault tests were conducted using an HRG system. As expected, there was no arc blast.
2) A series of phase-to-phase faults were conducted using an HRG system. A hypothesis had been formed that the incident energy level of an arcing fault not involving three phases on an HRG system would result in less incident energy than an arcing three-phase fault. During the testing of the phase-to-phase fault, it was noted that the fault quickly propagated into a three-phase fault within 1/4 of a cycle and that the speed of propagation was so fast that there was no significant decrease with the incident energy.
3) A series of phase-to-ground faults were conducted using a solidly grounded system. The same hypothesis was that a fault originating as a phase-to-ground or phase-to-phase fault on a solidly grounded system would have a lower incident energy level than one originating as a three-phase fault. Again, the fault quickly propagated into a three-phase fault in approximately 1/4 of a cycle, and the speed of propagation was so fast that there was no significant decrease with the incident energy.
4) The conclusion drawn from 2) and 3) above is that the practice of testing and calculating incident energy levels based on the inception of an arcing three-phase fault is reasonable and accurate.

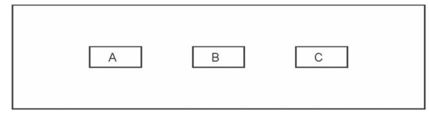

Fig. 1. Electrical buses in an enclosure.

V. Incident Energy Calculations

IEEE Standard 1584 is the IEEE Guide for Performing Arc-Flash Hazard Calculation and was first published in 2002. Throughout the standard, reference was made to the fact that the calculations are based on a three-phase fault for which the author concurs as being a good practice. As pointed out in [1], ground faults, phase-to-phase fault on solidly grounded systems, and phase-to-phase faults on HRG and ungrounded systems have a propensity to quickly propagate into three-phase faults.

However, IEEE 1584, in the opinion of the author, has an error in its basis for calculating incident energy levels on ungrounded and HRG systems. Equation 35 [7] has two constants, i.e., K_1 and K_2. K_2 is a grounding constant and is zero (0) for HRG and ungrounded systems and -0.113 for solidly grounded systems. For reference, IEEE-1584 equation 35 is as follows:

$$\log_{10} E_n = K_1 + K_2 + 1.081 \log_{10} I_a + .00110G \quad (1)$$

where

E_n	incident energy normalized;
K_1	constant for the box configuration -0.792 for open configuration, -0.555 for box configuration;
K_2	grounding constant;
$\log_{10} I_a$	$\log_{10}$ of arc current;
G	distance between arcing buses (mm).

There should be no difference in the constant K_2, whether the system is solidly grounded, impedance grounded, or ungrounded. Once a fault becomes a three-phase fault, the physics of the circuit is such that ground is no longer a factor. Therefore, the constant K_2 should be the same regardless of the method of grounding. Since it was determined to be -0.113 for a grounded system, that number should be used regardless of the method of grounding. To simplify the equation, K_2 could be combined with K_1. The KEMA testing results showed that no current flows in the ground other than the current that flowed through the enclosure (bus supports) to sustain the three-phase fault (see Figs. 1 and 2). Fig. 1 shows a typical bus arrangement where it would appear that a three-phase fault is not possible. However, it was found that the plasma from the arc was sufficient to encompass all three phases with the current path from phase A to phase C being through the structure, as is evidenced in Fig. 2. This was also noted in the KEMA oscillographs showing no ground current.

A comparison of incident energy level for solidly grounded and HRG systems requires some technical calculations For ease of calculations, an approximation of the levels will be made using a formula developed by the author. The basis for the approximation of incident energy levels was developed in a paper by Ammerman *et al.* [8], where estimates were provided for incident energy levels at voltages of 480, 600, and 1000

Fig. 2. Arc damage from outside phases to enclosure supports for a three-phase fault.

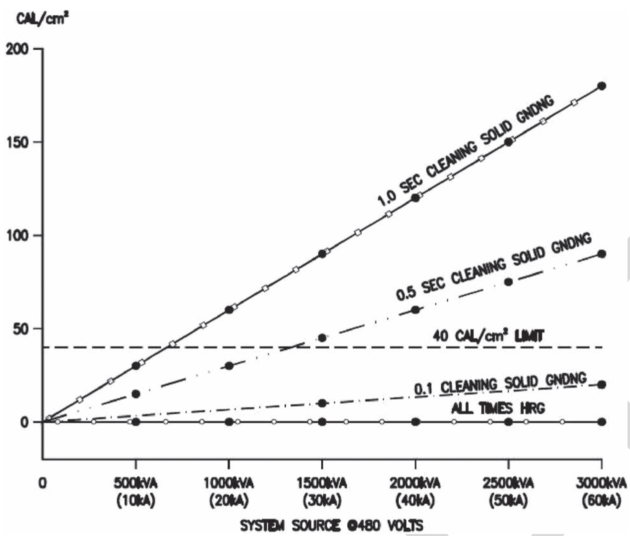

Fig. 3. Incident energy levels for solid versus high resistance grounding.

and above. The constants used in those approximations were rounded and provide a quick estimate of incident energy. The equation is identified as *the 3–4–5 Incident Energy Approximation*, i.e.,

$$E_n = K^* I^*_{\text{arc}} t \quad (\text{cal/cm}^2) \tag{2}$$

where

E_n	incident energy level in cal/cm^2;
K	constant of 3, 4, or 5
$K = 3$	for 480-V systems
$K = 4$	for 600-V systems
$K = 5$	for systems 1000 V and above;
t	time in seconds.

Using (2) for a 480-V system, incident energy levels were calculated for single-phase faults of varying magnitudes and times of 0.1–1.0 s for a single-phase fault on a solidly grounded system and for an HRG system. The results of the incident energy levels are provided in Fig. 3.

For convenience of the reader, the fault levels are provided in kiloamperes and standard transformer kilovoltampere sizes at 480 V. An important assumption to this graph is the fact that, for a solidly grounded system, the fault will quickly propagate into a three-phase fault for which the incident energy is calculated at the three-phase fault level. The other important note is that the ground fault on the HRG system will not cause an arc blast and will not propagate into a three-phase fault. That is the basis for the 0-cal/cm^2 incident energy level.

VI. Single-Pole Tripping Issue

Once a ground fault occurs on an HRG or even an ungrounded system, timely detection and removal of the ground fault is essential. A person with a basic understanding of HRG and ungrounded systems knows that the voltage on the grounded phase will be at or near 0 V, whereas the voltage on the two ungrounded phases will increase by as much as 1.73 times the normal phase voltage. For an example, a ground fault “A” phase on a 480-V system, the voltage on “A” phase will decrease from 277 to 0, and the voltages on the other two phases will go from 277 to 480 V. Another issue has been raised concerning single-pole tripping of molded-case circuit breakers on a high resistance or an ungrounded system and is worthy of discussion [9].

Gregory raised an interrupting rating issue concerning single-pole tripping on an HRG or an ungrounded system. The issue involves the fact that many two-pole and three-pole molded-case circuit breakers are designed and tested for operation on a solidly grounded system. When the molded case circuit breakers are used on an HRG or an ungrounded system, the breaker may be required to open using a single pole when second ground fault occurs on a different phase elsewhere in the system. The normal voltage on the opening of the pole under such a condition is no longer 58% of the line-to-line voltage for which the breaker is designed and tested; the voltage on the single pole can increase to 100%. It is this increase in the voltage across the contacts that reduces the interrupting capability of the breaker. For example, Gregory pointed out that a commonly used 65-kA breaker may be only tested at 8.7 kA interrupting for line-to-line voltage.

There are several issues that need to be addressed with regard to trouble shooting the first fault, which is an abnormal condition.

1) Special care needs to be taken when trying to locate the first ground fault on an HRG system. The normal procedure involves recognition of a ground fault on the HRG system. The alarm may be an indicating light, an audible alarm, or an ant alarm through a distributed control system. Good trouble shooting practices would suggest that the time of the alarm be recorded and that action be initiated to locate the fault. Best design practices for new projects would be to include sufficient metering to locate the feeder on which the fault is located. When trouble shooting, care should be taken to avoid contact with the unfaulted phase conductors since they will be operating at an elevated voltage typically 73% above normal voltage. In addition, care should be taken to avoid an arc blast.
2) The second issue involves the concern with inadequate single pole interrupting from a circuit breaker if a second ground fault occurs. While a second ground fault is a rare occurrence, Gregory pointed out that it can occur. From a

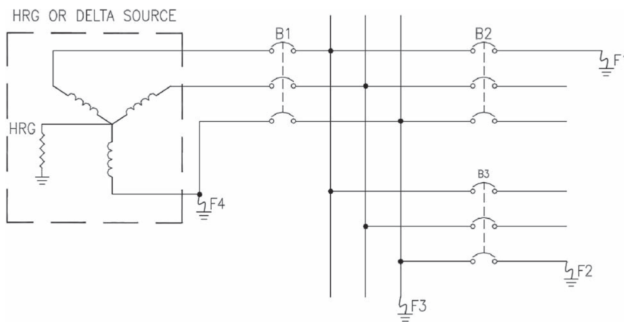

Fig. 4. Single-pole tripping.

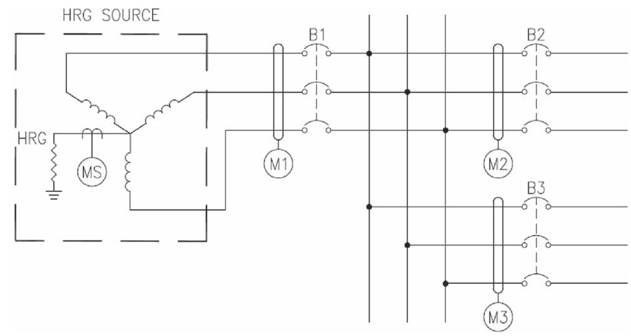

Fig. 5. Ground fault sensing.

protection point of view, the worst case location for one of the two ground faults will be between the HRG system and the main breaker (see Fig. 4). In Fig. 4, the drawing represents an HRG system serving a main breaker, i.e., B1, and two feeder breakers, i.e., B2 and B3. Several locations for faults should be considered with fault F1 being the first sustained ground fault.

a) Fault F2 represents a second ground fault located on an adjacent feeder and on a different phase than fault F1. While each of the two feeder breakers will be subjected to single-pole tripping, the fault current and recovery voltage will be interrupted by two separate poles in series.
b) Fault F3 represents a second ground fault located on the bus and on a different phase than fault F1. While each of the two breakers will be subjected to single-pole tripping, the fault current and the recovery voltage will be interrupted by two separate poles in series.
c) Fault F4 represents a second ground fault ahead of the main breaker and on the HRG system source. In this case, the feeder breaker B2 will try to interrupt the fault as a single pole with a phase-to-phase recovery voltage, which may reduce the interrupting capability. However, breaker B1 will most likely trip at the fault levels of concern, which may aid the proper tripping of breaker B2. In addition, the single-pole interrupting rating of breaker B1 may be sufficient to clear the fault.

With regard to the single-pole tripping issue for this unusual operation, the same problem exists for an ungrounded or a "delta" system. There are still many ungrounded systems in operation, including practically all shipboard power systems, which are almost universally operated ungrounded. In addition, Gregory correctly pointed out that the NEC does not require consideration for double contingency faults so that there is no code violation. Therefore, other than in theory, the practical considerations for single-pole tripping issues on HRG are essentially a nonissue. However, awareness of such a contingency is worthy to note.

VII. HRG Fault Sensing

Most HRG systems provide alarm contacts through either a voltage or a current sensing relay. With the sensitive microprocessor-based sensors and relays along with zero-sequence current transformers, ground fault sensing can be used to locate the feeder on which the first ground fault occurs. Using this type of sensing, location and/or tripping schemes may be implemented (see Fig. 5).

VIII. Conclusion

This paper has shown the safety benefits of HRG in the area of minimizing personnel from the dangers of an arc blast. In summary, the following conclusions can be made.

1) Within an industrial plant, using HRG and other enhanced engineering techniques such as bus insulation, the probability of an arcing fault can be reduced by two orders of magnitude. The HRG plays the most significant role by potentially reducing the number of arc blast incidences within an industrial setting by over 95%.
2) HRG does not improve electrical safety for "contact" or "touch" dangers, which are still the predominant cause of serious injuries and death. Contact-type injuries can still cause burns along with electric shock and electrocution.
3) The incident energy level calculations should not be higher on an HRG system in comparison with a solidly grounded system.
4) Tests on an HRG system consistently show that a single phase-to-ground fault will not propagate into an arcing multiphase fault and that the incident energy at the point of the fault is zero. However, higher than normal voltages will appear on the two unfaulted phases, which can lead to a second ground fault on one of the two unfaulted phases. If this occurs, an arc blast may be the result.
5) Testing conducted on ground faults on a solidly grounded system and phase-to-phase faults on an HRG will quickly propagate into a three-phase fault, and the incident energy levels are not significantly reduced due to the subcycle propagation into a three-phase fault.
6) A concern has been raised concerning the single-pole clearing of three-phase breakers on an HRG system when two ground faults occur on separate phases. Although this does not a appear to be a major issue as discussed in this paper, further research into this issue may be warranted.
7) With the high-temperature plasma, the fault easily propagated from a B to a C phase fault on the high resistance grounded system, and C phase to ground on the solidly grounded system, to encompass all three phases. Any

thought that the incident energy level will be significantly reduced on an arcing fault for a non-three-phase fault does not appear to be valid.

8) The modern molded-case circuit breaker, working well at a 1000-A setting, easily cleared the fault in 3–5 ms for faults occurring on the load side of the breaker.

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REFERENCES

[1] J. P. Nelson, J. Billman, J. Bowen, and D. Martindale, "The effects of system grounding, bus insulation and probability on arc flash hazard reduction—Part 2 testing," in *Conf. Rec. IEEE PCIC*, 2014, pp. 29–43.

[2] *IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems (IEEE Green Book)*, IEEE Std. 142-2007, 2007.

[3] J. P. Nelson and P. K. Sen, "High resistance grounding of low voltage systems—A standard for the petroleum and chemical industry," *IEEE Trans. Ind. Appl.*, vol. 35, no. 4, pp. 941–948, Jul./Aug. 1999.

[4] J. R. Dunki-Jacobs, F. J. Shields, and C. St. Pierre, *Industrial Power System Grounding Design Handbook*. Dexter, MI, USA: Thomson-Shore, 2007.

[5] J. P. Nelson, J. D. Billman, and J. E. Bowen, "The effects of system grounding, bus insulation and probability on arc flash hazard reduction—The missing links," in *Conf. Rec. IEEE PCIC*, 2012, pp. 27–39.

[6] J. C. Cawley and G. T. Homce, "Trends in electrical injury, 1992–2002," in *Conf. Rec. IEEE PCIC*, pp. 325–338, Paper 2006-38.

[7] *IEEE Guide for Performing Arc Flash Calculations*, IEEE-1584-2002, Sep. 2002.

[8] R. F. Ammerman, P. K. Sen, and J. P. Nelson, "Arc flash hazard incident energy calculations—A historical perspective and comparative study of the standards: IEEE 1584 and NFPA 70E," in *Proc. 54th Annu. Petrol. Chem. Ind. Conf.*, 2007, pp. 1–13, PCIC-2007-02.

[9] G. D. Gregory, "Single pole short circuit interruption of molded-case circuit breakers," *IEEE Trans. Ind. Appl.*, vol. 35, no. 6, pp. 1265–1270, Nov./Dec. 1999, IEEE.

[10] J. R. Dunki-Jacobs, "The escalating arcing ground-fault phenomenon," *IEEE Trans. Ind. Appl.*, vol. IA-22, no. 6, pp. 1156–1161, Nov./Dec. 1986.

[11] R. H. Lee, "The other electrical hazard: Electric arc blast burns," *IEEE Trans. Ind. Appl.*, vol. IA-18, no. 3, pp. 246–251, May 1982.

[12] R. H. Kaufmann and J. C. Page, "Arcing fault protection for low-voltage power distribution systems—Nature of the problem," *Trans. Amer. Inst. Elect. Eng. Power App. Syst. III*, vol. 79, no. 3, pp. 160–165, Apr. 1960.

[13] NFPA, *National Electric Code*, Quincy, MA, USA, NFPA 70, Apr. 2015.

[14] H. B. Land and T. Gammon, "Addressing arc flash problems in low voltage switchboards industrial and commercial power systems technical conference record," in *Proc. 50th IEEE/IAS I&CPS*, May 2014, pp. 1–12.

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AQ1 = As per journal style, abstract should be only a single paragraph. Thus, the displayed list was changed into a run in list. Please check.

AQ2 = The phrase "in excess of 95%" was changed to "on average, 95% of..." Please check if appropriate. Otherwise, please make the necessary changes.

AQ3 = LVMCC was expanded as "low voltage motor control center." Please check if appropriate. Otherwise, please provide the corresponding expanded form.

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