A USERS GUIDE TO ARC RESISTANT LOW VOLTAGE SWITCHGEAR & MOTOR CONTROL – ANALYTICAL COMPARISON VS ARC FLASH TEST RESULTS

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ABSTRACT

This paper describes enhanced safety and maintenance features required within LV Motor Control Centers and Switchgear. Enhanced capabilities will include discussion of using NFPA 70E [1], ANSI C37.20.7 [2] and IEEE 1584 [3] in the development of low voltage arc resistance equipment. Highlights will include discussion of arc flash danger to personnel and the solutions used in the development of arc resistant low voltage switchgear and motor control centers. Arc flash software modeling shall be compared with actual testing of equipment per ANSI C37.20.7.

INTRODUCTION

An arc flash incident is defined as an enormous amount of concentrated radiant energy that explodes outward from electrical equipment, creating pressure waves that can damage a person's hearing; a high-intensity flash that can damage their eyesight; and a super-heated ball of gas that can severely burn a worker's body and melt metal. Before starting out attempting to identify the reduction of arc flash hazards, priorities must be set, such as:

- Has an arc-flash study been done?
- Has the equipment been tested properly?
- How can I model the equipment properly
- What feature sets are required to reduce arc-flash hazards?
- Can the hazard be completely removed? For example, removing all power prior to work.

IEEE Standard 1584 [3], IEEE Guide for Performing Arc Flash Hazard Calculations defines the practice for performing detailed arc flash calculations. This method has become the currently accepted industry practice used for calculating the prospective incident energy that could be available at a given location which can be used to determine the PPE requirements.

A software model can be developed in order to identify the calculated amount of energy released. These software programs quickly identify the grade of clothing required by operators and easily provide protective signs for electrical equipment stating the type of protective clothing required when working around energized equipment. In addition, these programs quickly and accurately calculate the effects of flowing faults in three-phase, single-phase AC and DC power distribution systems.

Multiple factors must be taken into account to evaluate the specific arc flash energy available, such as the site's available flash energy hazard, safety training, and safety program [6]. The equipment test procedure is well defined in ANSI C37.20.7 [2]. This standard establishes a method by which metal-enclosed switchgear, as defined by IEEE Std C37.20.2 [7], can be tested for resistance to the effects of arcing due to an internal fault. The test procedure and actual test results for equipment are described in this document.

Conclusions are drawn based on theoretical modeling compared to actual test results of low voltage motor control center arc flash testing.

IEEE 1584 9-STEP PROCESS FOR ARC FLASH ANALYSIS [8]

Published by the Institute of Electrical and Electronics Engineers and titled "Guide to Performing Arc Flash Calculations," IEEE 1584 provides empirical formulas for determining arcing fault current, flash protection boundaries, and incident energy. The formulas are valid for systems ranging from 208 V to 15 kV. Theoretical formulas are provided for conditions outside this range.

ARC FLASH ANALYSIS PROCESS

IEEE 1584 establishes a nine-step process for gathering information and calculating arc flash hazards. The steps are:

1. COLLECT ELECTRICAL SYSTEM DATA

Collecting system data is the most difficult and time-intensive
step in performing an arc flash hazard analysis, but accurate information is vital to correctly calculating flash boundaries. A relatively small error at this point can invalidate all further calculations.

Information collected should be recorded on a one-line diagram of the facility's electrical system. This diagram should be updated whenever modifications are made to the system, and a typical diagram is shown in Figure #1.

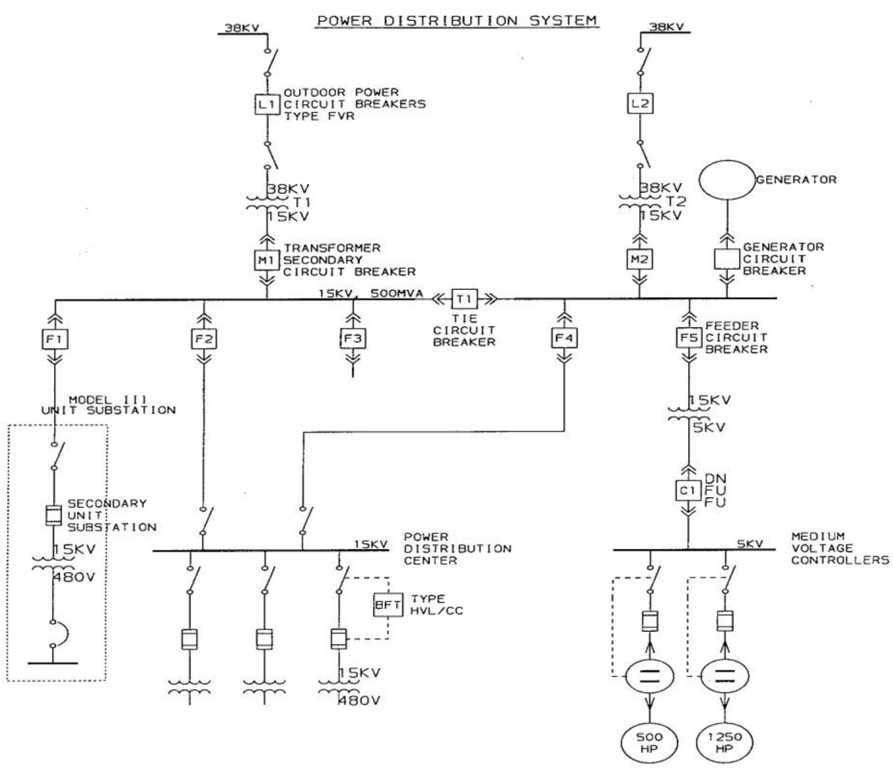

Figure 1: Typical One-Line Diagram

2. DETERMINE MODES OF OPERATION

Many electrical systems, especially in smaller facilities, have only a single mode of operation. In large facilities, however, it is common to find a number of operating modes, possibly including: emergency modes in which only backup generators provide power; multiple utility sources or generators that are switched in or out; and motors or portions of the system that may start or cease operation. All of these different modes cause changes in current at various points in the system, altering incident energy and flash boundaries.

3. DETERMINE BOLTED FAULT CURRENTS

The bolted fault current is the current that would flow through a short circuit consisting of two conductors bolted together. It is the maximum current available to flow through a short circuit. This information is used to calculate the arc fault currents. Bolted fault currents should be determined for each piece of equipment likely to require maintenance or inspection while energized.

4. DETERMINE ARC FAULT CURRENTS

The current that flows through an arcing fault is usually significantly less than the bolted fault current, due to greater resistance. Arc fault current calculations are based on voltage, bolted fault current, conductor gap distance, and other factors. IEEE 1584 presents two formulas for calculating arc fault currents, one for use with 0.208-1 kV systems, and the other for systems between 1 and 15 kV.

For systems between 0.208 and 1 kV:

$$\lg I_a = K + 0.662(\lg I_{bf}) + 0.0966(V) + 0.000526(G) + 0.5588(V)(\lg I_{bf}) - 0.00304(G)(\lg I_{bf})$$

For systems between 1 and 15 kV:

$$\lg I_a = 0.00402 + 0.983(\lg I_{bf})$$

Where I_a = arc fault current in kA; K = -0.153 for open-air arcs and -0.097 for enclosed arcs; I_{bf} = 3-phase bolted fault current in kA; V = voltage in kV; G = conductor gap in mm

5. DETERMINE PROTECTIVE DEVICE CHARACTERISTICS AND DURATION OF ARCS

The time-current curves of upstream protective devices are a major factor in determining how long an arc-fault will last. An effort should be made to determine the actual settings rather than relying on standard values, as these may cause incident energy to vary greatly.

Another consideration when analyzing protective devices is that incident energy depends on both fault current and time. Since protective devices are slower at lower currents, minimum fault currents often pose the worst-case arc flash scenario.

6. DOCUMENT VOLTAGES AND EQUIPMENT CLASSES

Voltage and equipment class determine what equation should be used to find the flash boundary, as well as the bus gap distances required by the equations. Systems operating at <1 kV use a different equation than those operating between 1 kV and 15 kV. In addition, IEEE 1584 recognizes six equipment classes, as shown in table #1. The bus distances used to help determine the arcing fault current.

Classes of equipment	Typical bus gaps, mm
Open Air	10 – 40
Low-voltage switchgear	32
15kV switchgear	152
5kV switchgear	104
Low-voltage MCCs and panelboards	25
Cable	13

Table 1: Classification of Equipment with typical bus gaps

7. ESTABLISH WORKING DISTANCES

The working distance is the distance from a potential arc source to a worker's face and chest. It is a critical quantity in determining the flash hazard boundary, as even an increase of a few inches in working distance can cause a significant drop in incident energy. 18 inches is the working distance most commonly assumed in calculations, but efforts should be made to determine actual working distances. Some usual working distances are shown in table 2.

Classes of equipment	Typical working distance, in
Low-voltage switchgear	24
15kV / 5kV switchgear	36
Low-voltage MCCs and panelboards	18
Cable	18

Table 2: Typical Working Distances

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8. DETERMINE INCIDENT ENERGIES

Incident energy is defined in NFPA 70E as "the amount of energy impressed on a surface, a certain distance from the source, generated during an electrical arc event." In an arc flash hazard study, the "surface" is the worker's body at the assumed working distance. Incident energy is expressed in cal/cm^2. IEEE 1584 uses the following formulas:

(1) $E = 4.184(C_f)(E_n)(t/0.2)(610^x/D^x)$

Where E = incident energy in joules/cm2; Cf is a calculation factor (1.0 for voltages above 1 kV, and 1.5 for voltages below 1 kV); En = normalized incident energy (from equation (2) below); t = arc duration in seconds; D = distance from arc in mm; x = distance exponent (see table 3 below)

Equipment Type	*D* (Distance Exponent)
Open air	2.0
Low-voltage (.208-1 kV) switchgear	1.473
High-voltage (1-15 kV) switchgear	0.973
Low-voltage MCCs and panels	1.641
Cables	2.0

Table 3: Distance Exponent

$$\textbf{(2)}\ \lg E_n = K_1 + K_2 + 1.081(\lg I_a) + 0.0011(G)$$

Where En = energy normalized for distance of 610 mm and arc duration of 0.2 seconds, in joules/cm2; K1 = -0.792 for open-air arcs and -0.555 for enclosed arcs; K2 = 0 for ungrounded/high-Z systems and -0.113 for grounded systems; G = arc gap in mm; Ia = predicted 3-phase arc fault current in kA

9. DETERMINE FLASH PROTECTION BOUNDARY (FPB)

The FPB is the distance at which incident energy is 1.2 cal/cm2, which is the amount of heat needed to cause second-degree burns. [8] The IEEE formula for calculating FPB is

$$D_B = [4.184(C_f)(E_n)(t/0.2)(610^x/E_B)]^{1/x}$$

Where EB is the desired incident energy at the boundary (usually 1.2 cal/cm^2, but occasionally set at a value matching proposed PPE rating), with other variables defined as for the incident energy equations above.

ARC FLASH SOFTWARE MODELING

There is very few credible arc flash software modeling tools available on the market. In order to be successful in modeling an arc flash event, three critical items are required. Precise information for every aspect of the power system with an extensive library of devices to easily add to the model, software compliance to national standards such as IEEE 1584, and expert service available to support any questions or enhancement requirements to the model.

An arc flash calculation study requires calculating the equivalent arcing short circuit current at each location under study. The arcing current is used to evaluate the time current characteristic of the upstream overcurrent device that would interrupt the arc flash.

Electrical network modeling software was used to model the simple circuit for testing the low voltage motor control center at the lab prior to actual testing. Generator parameters and breaker output characteristics were provided by the testing power lab, including the bus connection sizing and ampacity rating. This allowed a model to be created as shown in figure 2.

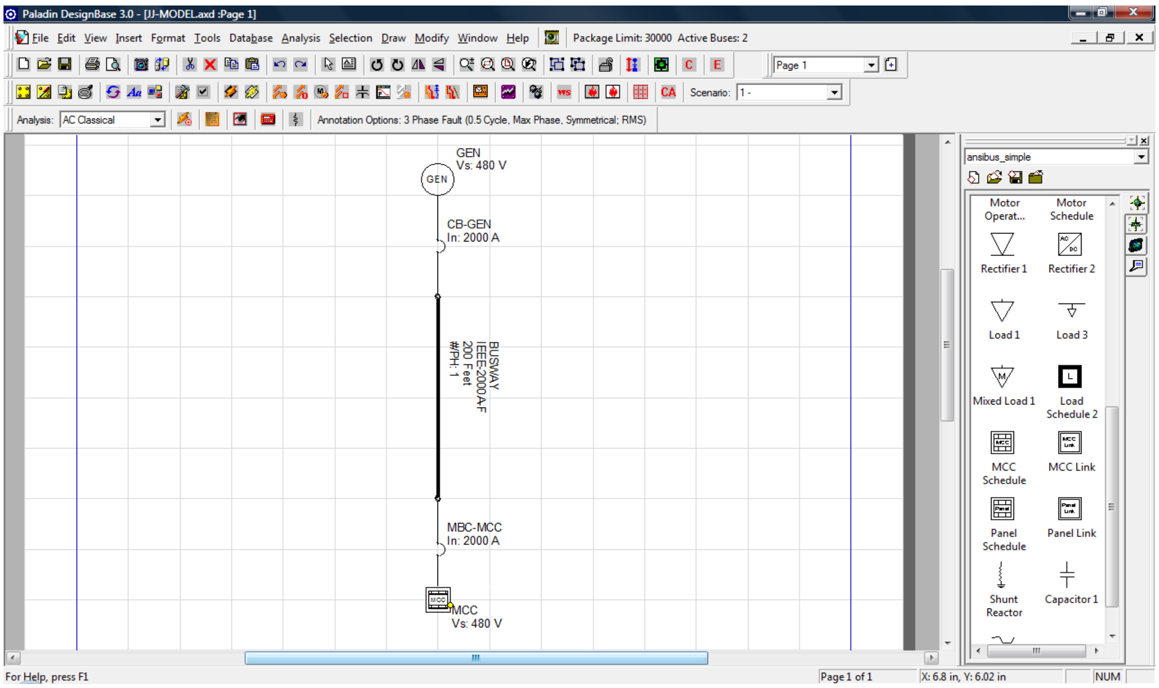

Figure 2: Software modeling for arc-flash testing

Based on the modeling from software, the electrical system model is graphed comparing incident energy (cal/cm^2) with arc flash duration (cycles) [9]. Various characteristics are entered into the model and can have dramatic changes on the incident energy released as shown in figure 3.

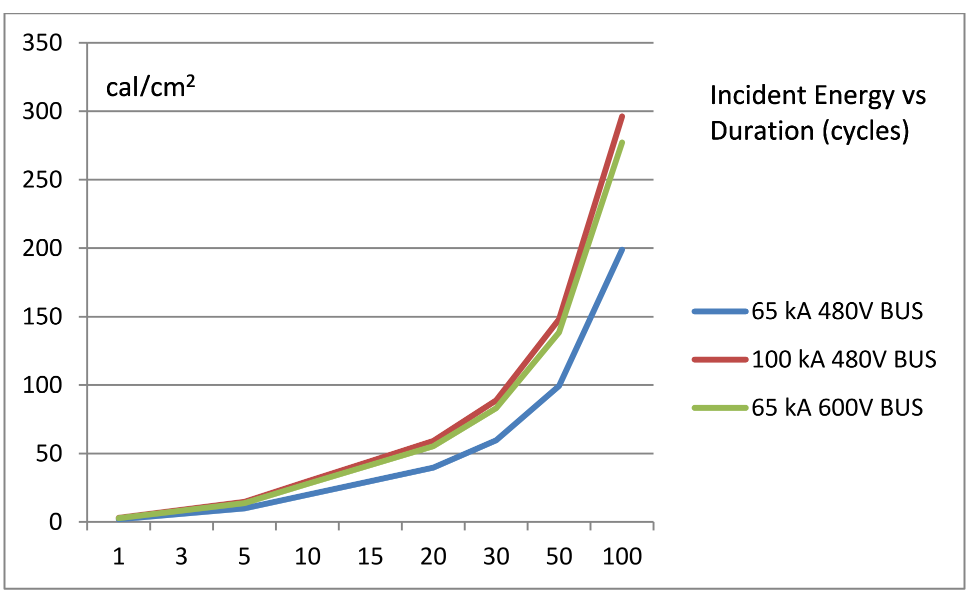

Figure 3: Software modeling analysis results for arc-flash testing

Once the arcing current and clearing time have been established, the IEEE 1584 formulas provide methods to calculate the incident energy in cal/cm^2 which can be used for the selection of personal protective equipment (PPE) as shown in table 4. The incident energy, flash protection boundary and category of PPE along with approach limits for shock protection can become part of the detailed arc flash label.

Min Incident Energy, cal/cm^2	Max Incident Energy, cal/cm^2	Risk Category	Required Min Rating of PPE, cal/cm^2
0	Eb*	0	
Eb* + 0.001	4	1	4
4.001	8	2	8
8.001	25	3	25
25.001	40	4	40
40.001	and above	Not Available	N/A

* *Eb* is Incident Energy to second degree burn for bare skin exposure.

Table 4: Hazard Risk Categories

Another important feature of the software shows a comparison of arc duration vs. PPE level required as shown in figure 4. It is clear to see that faster clearing times significantly reduce the PPE requirements.

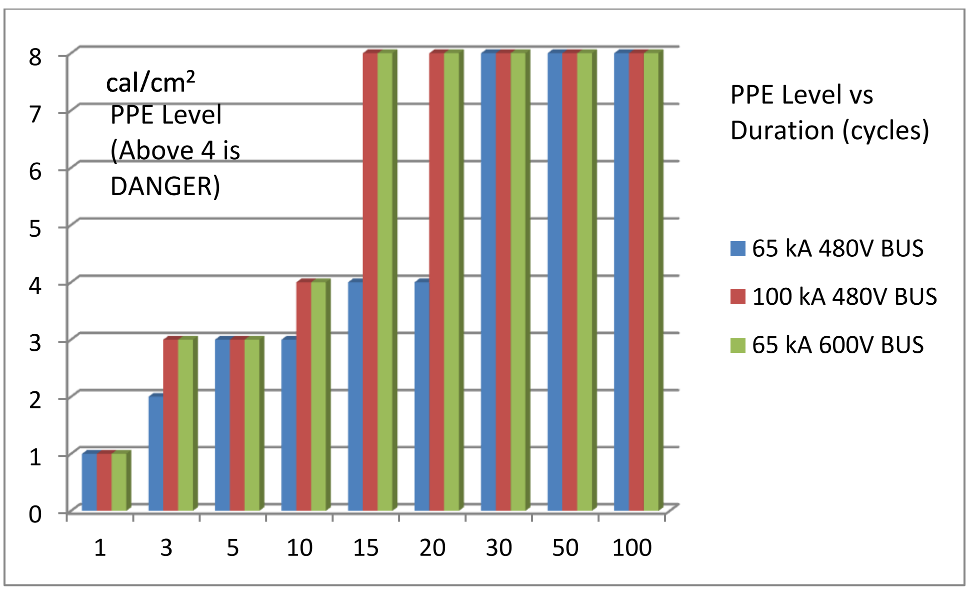

Figure 4: PPE level vs. Duration (cycles) – In order to graphically show above Category 4 PPE – this graph maximum value is 8 for anything greater than 4.

Once the arc flash study has been completed from your software model, a detailed analysis can be performed. This analysis includes providing all information for required labels on equipment and should provide a function of printing labels directly from the software as shown in figure 4.

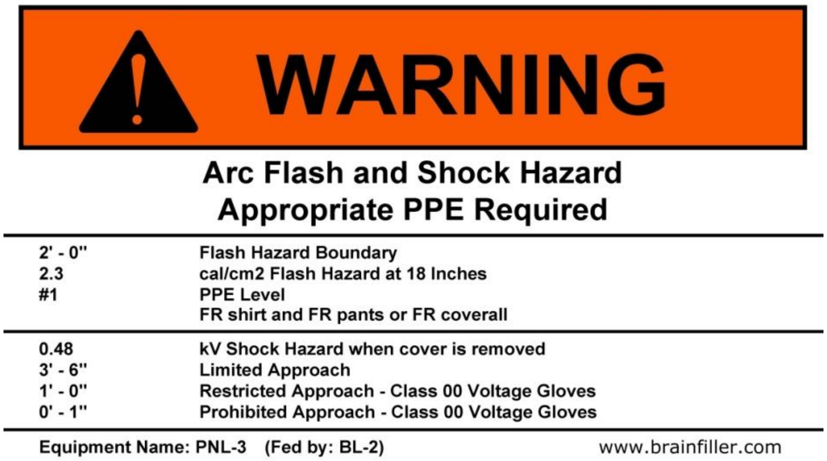

Figure 5: Typical Arc flash label required on equipment

Although NFPA 70E does not mandate calculations be performed according to the IEEE 1584 methods, it is the method most people use. In addition, a credible software modeling tool can provide valuable insight into your electrical system performance.

<u>ARC FLASH TESTING SETUP</u>

Arc flash risk factors within a low voltage motor control center or switchgear lineup are generally associated with the modular design of the gear. A particular risk concern is the primary connection points known as “stabs” which consists of a moveable breaker or unit - connector that engages a vertical bus in the section. The connection is made during the removal and plugging in of the bucket at 480/600Vac levels. The testing comprised of creating an arc flash incident by placing a 10AWG bare copper wire across the three phases creating a bolted fault condition. Testing parameters for this series of tests were defined as:

1. Voltage – Rated maximum voltage of the equipment – 480V or 600V
2. Current (+5, -0%) Tolerance – Applies for prospective SCCR current – 65kA (68.2>x>65kA).
3. (480V@65kA, 480V@100kA and 600V@65kA)
   a) 600V@65kA
   b) 480V@100kA
   c) 480V@65kA
4. Peak Current (+5, -0%) Tolerance – 2.3 Times the values of the internal arcing short-circuit current at 60 Hz
   a) 65kA x 2.3 = 149.5kA + 5% = 157kA
   b) 100kA x 2.3 = 230kA + 5 % = 241.kA
5. Frequency +/- 10% = 60 Hz (66>x>54Hz)
6. Current (+10, -0%) Tolerance – The current shall not be less than the specified value at least for the first 3 half-cycles 25ms.

7. Peak Current – At least 90% of the rated peak value if the voltage at the start of the test is lower than the rated voltage.
8. Arcing duration – 0.5 sec – 500ms preferred

The testing was monitored by an array of thermocouples and cotton indicators. The array captured the amount of incident energy released and simulated cotton clothing worn does not ignite.

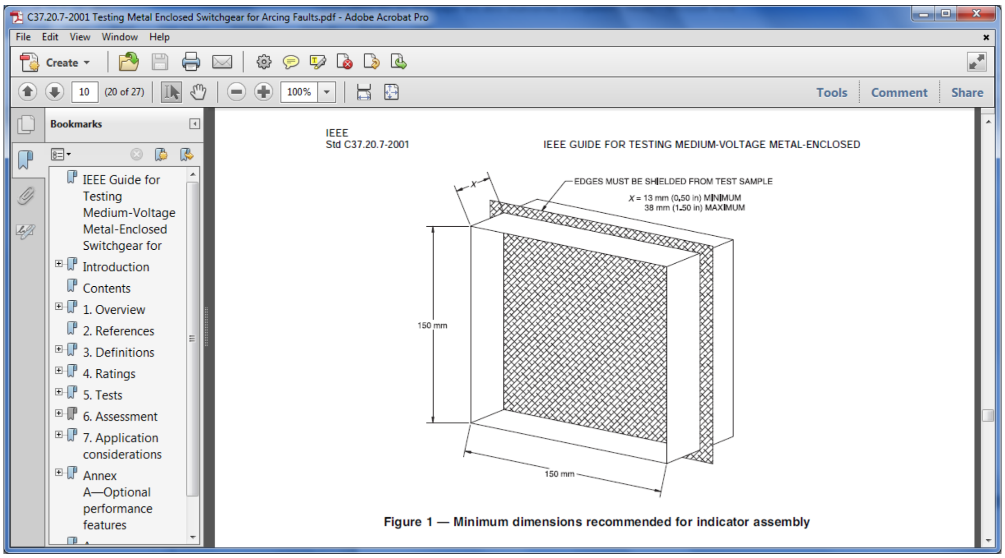

Figure 6: Typical array arrangement per Ansi C37.20.7

TESTING REQUIREMENTS:

IEEE 1584 specifies procedure to determine energy released in cal/cm2. ANSI C37.20.7 identifies specific pass/fail criteria. Testing is performed with covers and doors properly secured, therefore, arc resistance ratings are based on doors and covers being properly secured. Pass/Fail Criteria per ANSI C37.20.7 are:

1. Doors, covers, etc. do not open. Bowing or other distortion is permitted except on those which are to be used to mount relays, meters, etc.
2. That no parts are ejected into the vertical plane defined by the accessibility type
3. There are no openings caused by direct contact with an arc
4. That no indicators ignite as a result of escaping gases or particles
5. That all grounding connections remain effective

ARC FLASH ENGINEERING MODEL VS TEST RESULTS

The arc test results can be compared between IEEE 1584, ANSI C37.20.7, NFPA 70E and actual test results. Designbase software was used and compared to the actual test results from low voltage motor control center testing that was performed in March, 2012 at Kema test labs [10].

Results of arc-flash testing compared to calculated value shall be discussed at the IEEE PES conference in May, 2012 at San Antonio. Actual test results are not available at time of paper submission.

CONCLUSION

Reduction of arc-flash hazards in equipment is an essential requirement for the future requirements of electrical equipment.

There are multiple standards in place ensure to minimize energy released during an arc flash event. Credible design software is a key engineering tool to determine arc flash requirements to protect personnel and equipment. The duration of the arc has a significant effect on incident energy released and incident energy exposure to personnel.

The goal is to minimize personnel exposure to the arc flash incident energy by applying the above solutions into a modern switchgear and motor control center configuration, minimizing arc flash energy levels. Note: 1.2 cal/cm2 max. (Hazard category 0).

The best arc-flash protection for low voltage equipment assemblies needs to be addressed in a comprehensive manner. The best solutions take into account multiple aspects of design, maintenance and operations of equipment. Enhanced design features and capabilities provide a better environment for personnel. The bottom line is to provide a system that reduces the likelihood of an arc-flash hazard to occur! [5]

REFERENCES

[1] NFPA70E: Standard for Electrical Safety in the Workplace®, 2012 Edition
[2] ANSI C37.20.7 - IEEE Guide for Testing Medium-Voltage Metal-Enclosed Switchgear for Internal Arcing Faults
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[4] ARC-FLASH HAZARD ANALYSIS, "Putting the Pieces of the Puzzle Together", John Lane, PE, Electrical Safety Engineer, AVO Training Institute
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[6] "REDUCTION OF ARC-FLASH HAZARDS IN LOW VOLTAGE MOTOR CONTROL ASSEMBLIES" Presented at 2007 IEEE PCIC Conference.
[7] IEEE C37.20.2-1999 - IEEE Standard for Metal-Clad Switchgear
[8] Arc Flash Hazard – Electrical Safety Information. The Electricity Forum. www.electricity forum.com
[9] Study conducted by Power Analytics Corporation
[10] KEMA Power Labs - Generator and testing equipment data

DEFINITIONS

1. Arc flash hazard: A dangerous condition associated with the possible release of energy caused by an electric arc [1]
2. Incident energy: The amount of energy impressed on a surface, a certain distance from the source, generated during an electrical arc event. One of the units used to measure incident energy is calories per centimeter squared (cal/cm2) [1]
3. Arc flash boundary: When an arc flash hazard exists, an approach limit at a distance from a perspective arc source within which a person could receive a second degree burn if an electrical arc flash were to occur. [1]
4. Bolted fault current: A short circuit between two or more different phase conductors in which the impedance is virtually zero. [4]
5. Arcing fault current: Flow of current through a path consisting of vapor. The vapor has a substantial higher resistance than the solid metal. For low voltage circuits the arc consumes most of the available voltage leaving only the difference between system voltage and arc voltage, it is this difference that forces the current through the system impedance. The arc flash is like a laser but not quite as hot. A laser can create heat as high as 100,000 degrees K while the arc-flash can approach 20,000 or 35,000 degrees C. Essentially an arc creates a radiation burn. [4]
6. Voltage levels and ratings: Voltage is a representation of the electric potential energy per unit charge. If a unit of electrical charge were placed in a location, the voltage indicates the potential energy of it at that point. In other words, it is a measurement of the energy contained within an electric field, or an electric circuit, at a given point. Voltage can be rated in mV, V, kV, and MV.
7. Software modeling programs: gives electrical engineering professionals the means to create both a detailed design and knowledge base of the performance specifications of their entire electrical distribution system. [5]