APPLYING LOW-VOLTAGE CIRCUIT BREAKERS TO LIMIT ARC FLASH ENERGY

Paper No. PCIC-PH-100

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ABSTRACT – The purpose of this paper is to examine the application of low-voltage circuit breakers to control energy released during an arc-flash occurrence. It contrasts arc-flash incident energy values obtained by calculation with values obtained by direct testing. It examines values at low fault current levels where long duration events may be expected. It also reviews the protection afforded by current-limiting circuit breakers. The paper concludes with an overall discussion of circuit breaker applications for arc flash energy reduction.

Index Terms — Arc flash, circuit breaker, incident energy.

I. INTRODUCTION

The 2004 edition of NFPA 70E, Standard for Electrical Safety Requirements for Employee Workplaces [1] establishes requirements associated with electrical arc flash hazards. The IEEE Guide 1584, “Guide for Performing Arc-Flash Hazard Calculations” [2], enumerates methods for numerically quantifying energy values associated with an overcurrent protective device (OCPD). Actual values from tests with circuit breakers have not been available to the P1584 committee. The authors of this paper have conducted literally hundreds of tests to determine the arc flash energy values associated with low voltage circuit breaker performance. This paper will present the testing protocol, introduce the expectation of values from manufacturers tests and confirm that values from tests are lower than values from IEEE 1584 calculation methods.

II. TESTING PROTOCOL

A major hurdle in determining arc flash energy values associated with the performance of overcurrent protective devices has been the absence of a single industry-wide standard describing the testing protocol. While efforts are underway to establish these common requirements, several IEEE publications [3], [4], [5], [6] have established initial baseline testing parameters.

In order to simulate actual low voltage electrical distribution equipment, all testing reported upon in this paper was performed using the “arcs in a box” setup as follows. (See Fig. 1.) Three ¾” round CU electrodes were mounted inside an unpainted carbon steel enclosure (no cover), 1” from the back. The round electrodes were spaced 1” apart (1.75” center to center). The 1”spacing is the required phase-to-phase clearance through air for low voltage distribution equipment such as panelboards, switchboards, motor control centers and switchgear per low-voltage equipment standards. A bare 18 AWG copper wire was used to initialize the arc at the bottom end of the round electrodes. Insulating support blocks were positioned between adjacent electrodes as needed to prevent them from bending due to forces created by the arc currents. Additionally, as needed, insulating sleeves were added over the electrodes inside the enclosure, between the bottom support block and the inside top of the enclosure, to avoid arcing between electrodes, except along the intended exposed length at the bottom, in the arc initiation area.

Calorimeters were used to obtain the actual arc energy measurements. A calorimeter is essentially a thin slice of copper held inside an insulating block. The copper’s exposed side is painted black and one or more thermocouples are attached on its opposite side. The exact construction details are contained in [6]. An array of 7 Calorimeters was used, all mounted in front of the enclosure, 18” away from the centerline of the electrodes (horizontally). The 18” distance was chosen according to [5] as the “Typical working distance…sum of the distance between the worker standing in front of the equipment, and from the front of the equipment to the potential arc source inside the equipment” representative of low voltage motor control centers and panelboards. On the array, 3 calorimeters are mounted in a horizontal row at the same height as the tip of the electrodes (vertically). A second set of three calorimeters is located in a horizontal row 6” below the elevation of the electrode tips. The middle calorimeter of each set is aligned with the center electrode (side to side). A single additional calorimeter is located 6 in above the center electrode tip.

Low voltage circuit breaker were inserted into the test circuit electrically ahead of where the ¾” round CU electrodes enter the enclosure (external & upstream, from the enclosure/electrodes).

The OCPD was connected from the test station to its line side using cables or bus bars sized in accordance with its continuous current rating but not more than 250 KCMIL. The load side of the OCPD was connected to the ¾” copper electrodes using cables or bus bars with the same size restrictions as those on the line side. Each set of conductors was as short as practical and no longer than 4 feet in any case.

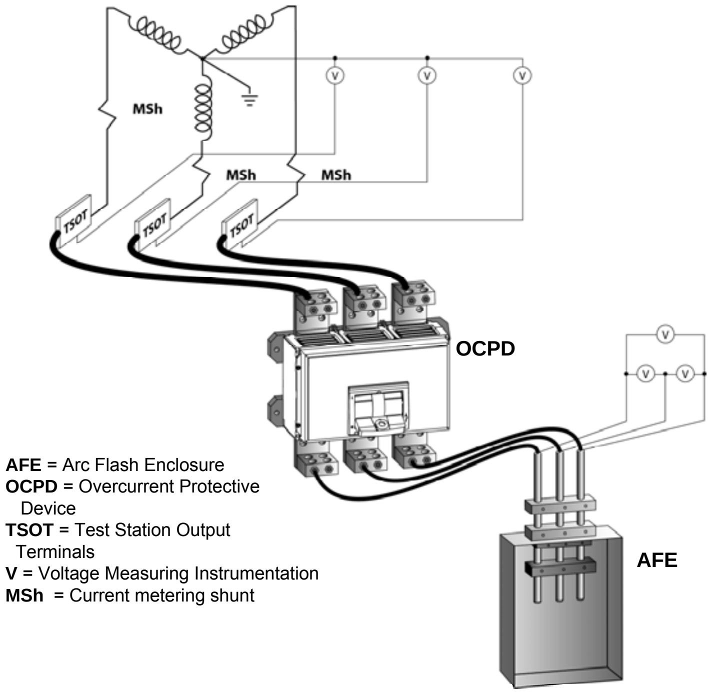

FIG. 1 – SKETCH OF TEST SETUP

The electrical test circuit was calibrated in accordance with UL 489, UL Standard for Safety for Molded-Case Circuit Breakers [7], Appendix C or American National Standard C37.50-1989, Low-Voltage AC Power Circuit Breakers Used in Enclosures – Test Procedures [8], Section 3.9.3 (which are considered equivalent methods for this purpose).

The data acquisition system was calibrated and capable of recording voltage, current, and calorimeter outputs as required by the tests. The temperature acquisition system had a minimum resolution of 0.1°C, a minimum accuracy of 1.5°C and acquired data for a duration long enough to capture the maximum temperature achieved. The maximum temperature rise (actual temperature – pretest reading) obtained from any calorimeter was multiplied by the constant 0.135 to obtain incident energy in calories/cm^2. Current and voltage data was acquired at a minimum rate of 10 kHz.

The circuit breaker was placed in the closed (ON) position, and the test station was then closed to energize the circuit. At least 3 tests were conducted at each circuit level in order to confirm repeatability. The highest temperature value recorded from any of these tests was used for the established value.

III. METHODS OF DETERMINING ARC FLASH VALUES

At this time, there are three basic methods of determining arc flash values for determination of flash protection boundary and for selection of personal protective equipment (PPE):

1. NFPA 70E. Table 130.7(C)(9)(a) for hazard/risk category (HRC) and Section130.3(A) for flash protection boundary. HRC is developed by assumptions of the conditions of installation. Although useful for those who have to work on a system for which little information is available, the assumptions of this approach may not match the system.

2. IEEE 1584 full calculation procedure using OCPD time-current curves. This is the most accurate method in general use. It applies detailed information to calculate values unique to the installation.

3. IEEE 1584 shortcut method for circuit breakers. This method bypasses the need for detailed information about the circuit breaker. However, it is quite conservative in that it applies the full calculation procedure to the longest duration for the circuit breaker having the longest published clearing time for the category.

Another method that this paper is intended to help bring forward is application of manufacturer published values from arc flash tests performed with the OCPD directly in the circuit. This method avoids making assumptions about performance of the OCPD and provides the most accurate information available. The earliest version of this method was employed to establish the shortcut method for fuses in IEEE 1584.

This method of testing with the OCPD in the circuit involves an enormous volume of testing, which is one reason the public has not seen published values earlier. By application of the laws of physics and information regarding the performance of the OCPD, it may be possible to model the occurrence and output the incident energy value. This kind of modeling is a topic to look to for the future.

IV. TYPICAL OUTPUT OF CALCULATED VALUES

Fig. 2 illustrates typical output for 400-ampere molded-case circuit breakers (MCCBs). Results of the IEEE 1584 full calculation procedure for a standard thermal-magnetic circuit breaker and for a current limiting (CL) circuit breaker are shown.

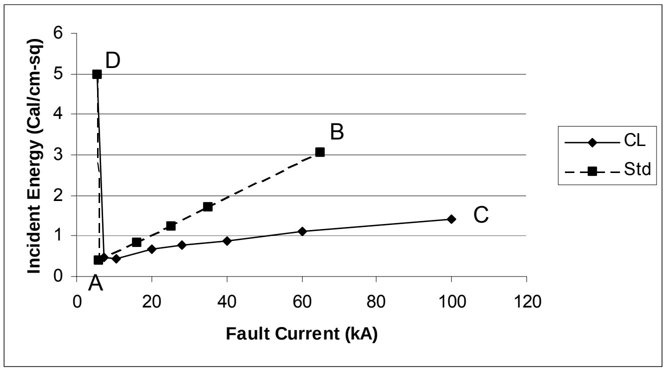

FIG. 2 – TYPICAL CALCULATION OUTPUT FOR 400 A STANDARD AND CURRENT-LIMITING MCCBS

Curve A-B is typical of the characteristic anticipated for incident energy of a circuit breaker using time-current curves and the calculation method of IEEE 1584. That is, as the bolted fault current increases the incident energy increases. The total electrical energy is calculated using equation 1.

(Eq. 1) $$E= \int v(t)*i(t)\, dt$$

Incident energy impressed on a surface a distance away from the arc can be expected to be proportional to total energy. For the standard circuit breaker, clearing time remains much the same for all current levels as the current level increases above the instantaneous trip setting.

Notice that the characteristic has a discontinuity at the point A, such that we see the incident energy rise sharply in curve A-D. The point A is where the available bolted fault current condition results in an arc current equal to the instantaneous trip point for the circuit breaker. Above this current value, the circuit breaker clears instantaneously, without any intentional delay. Below this current value, the circuit breaker clears on its long time characteristic so that the duration will increase considerably.

For the CL MCCB, we see that curve A-C is considerably lower than curve A-B. The difference is because the CL circuit breaker clears within one half cycle and current as well as time are limited as fault current increases.

V. TEST RESULTS

Figs. 3 and 4 illustrate typical output from tests with the circuit breaker in the circuit.

In Fig. 3 we see 5 tests at each current level. Recall that the procedure calls for at least three tests at each current level. The multiple tests are necessary because of the normal variation in arc current from test to test. The dispersion of incident energy values at each current level is evident from Fig. 3. The highest value is used as the published value. Using that criterion, a value indicated by the solid curve would be published.

Fig. 4 is a similar chart for a special 800 A low-voltage power circuit breaker (LVPCB) designed to operate more rapidly than the standard power circuit breaker for the purposes of arc flash protection. Again, three or more tests are done at each current level and the published value is the highest value. The published values are represented by the solid curve on the chart.

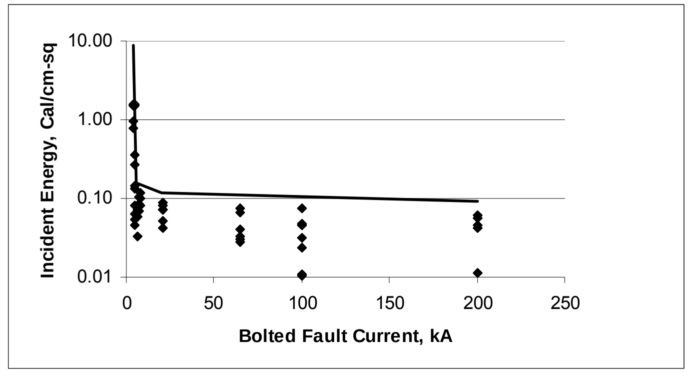

FIG. 3 – TEST VALUES USING 600 A CURRENT-LIMITING MCCB

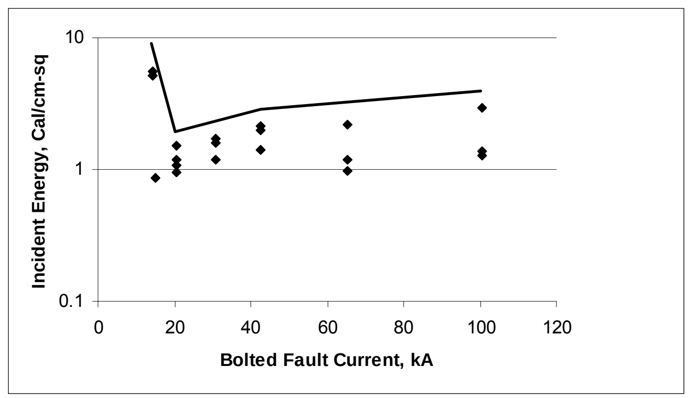

FIG. 4 – TEST VALUES USING 800 A LOW-VOLTAGE POWER CIRCUIT BREAKER

Figs. 3 and 4 illustrate the method and the resulting information. They also illustrate the extensive amount of testing required to provide information for each rating of each circuit breaker. Therefore, the calculation methods are available for the many analyses being done while this test information is developed.

VI. COMPARISON OF RESULTS

Fig. 5 compares incident energy values for a typical 400 A MCCB using three methods of determination, IEEE 1584 full calculation method, IEEE 1584 shortcut and direct test values. As expected, shortcut values are highest because they represent the longest duration MCCB for the industry. Values from direct tests are lowest.

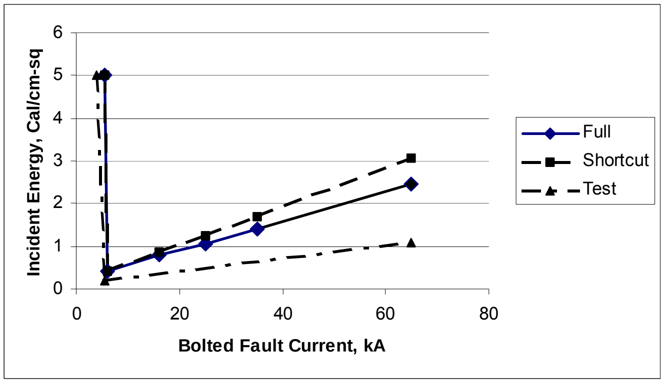

FIG.5 – COMPARISON OF INCIDENT ENERGY VALUES FOR THREE METHODS OF DETERMINING INCIDENT ENERGY

Values from direct tests are lowest because they reflect the actual performance of the circuit breaker as opposed to using values from trip curves. There are two significant reasons for the difference. First, time-current curves are generally drawn to assume a conservatively long clearing of the circuit breaker. Actual values are obtained by test and then frequently rounded up to the next normal current zero for determination of the published curves. For example, if the circuit breaker clears in 11 ms during its longest operation at 600 V, the curve will be drawn to show clearing at 16.7 ms, a full cycle. The same circuit breaker at 480 V may clear within 8 ms, but the time-current curve still shows clearing in 16.7 ms. When trip curve values are used for calculations, they will be conservative in duration.

The second difference relates to current. As the circuit breaker is clearing, it develops an arc between its contacts. The dynamic impedance of this arc will reduce the current flowing and will, in that way, reduce the incident energy. The calculation methods assume full arc current as though the arc in the circuit breaker was not present.

Using Fig. 5 and hazard categories as outlined in Table 130.7(C)(11) of NFPA 70E for a 480 V bolted fault level of 65 kA, we would find that HRC 1 PPE would be required if calculations using either the full or shortcut methods of IEEE 1584 were applied. Category 0 PPE would be required for application of direct tested values. If we were to apply Table 130.7(C)(9)(a) of NFPA 70E, HRC 2 PPE would be required for voltage testing of equipment. The most accurate method is the use of direct tested values and it is also the lowest in this case.

Table 1 shows tested values in comparison with calculated values for a number of MCCBs. By applying the lower and more accurate values, often lighter rated PPE can be applied, which reduces the heat and encumbering effect on workers, and may improve their ability to perform the work safely.

VII. APPLICATION RECOMMENDATIONS

Whenever possible, trip units should be set for instantaneous operation. Operation with no intentional delay greatly aids in reduction or arc flash energy when it can be implemented without reducing needed selective coordination.

Be aware of the fault current that would result in operation below the instantaneous range. Below that value, duration of the fault can be long and calculated incident energy can be high.

Adjust settings to the lowest level that will allow operation of the facility.

TABLE 1
TESTED VALUES FOR MCCBS COMPARED WITH CALCULATED VALUES

	Incident Energy (Cal/cm^2) at Bolted Fault Current		
	Min	Mid	Max
225 A MCCB, Thermal-Magnetic			
Bolted fault current	3.4 kA	35 kA	100 kA
Measured Incident Energy	0.08	0.10	0.11
Via IEEE 1584 & Trip Curve	59.6	1.1	2.3
Via IEEE 1584 Table E.1 Generic	N/A[1]	1.7	4.7
250 A MCCB, Thermal-Magnetic			
Bolted fault current	3.7 kA	35 kA	100 kA
Measured Incident Energy	0.11	0.15	0.13
Via IEEE 1584 & Trip Curve	27.6	0.9	1.8
Via IEEE 1584 Table E.1 Generic	N/A[1]	1.7	4.7
400 A MCCB, Thermal-Magnetic			
Bolted fault current	6 kA	35 kA	100 kA
Measured Incident Energy	0.12	0.2	0.20
Via IEEE 1584 & Trip Curve	72	0.7	1.4
Via IEEE 1584 Table E.1 Generic	N/A[1]	1.7	4.7
600 A MCCB, Thermal-Magnetic			
Bolted fault current	9 kA	35 kA	100 kA
Measured Incident Energy	1.22	0.78	0.36
Via IEEE 1584 & Trip Curve	46	1.1	1.8
Via IEEE 1584 Table E.1 Generic	N/A[1]	2.3	5.7
800 A MCCB, Thermal-Magnetic			
Bolted fault current	12 kA	35 kA	65 kA
Measured Incident Energy	0.86	1.14	1.05
Via IEEE 1584 & Trip Curve	61.4	1.7	2.8
Via IEEE 1584 Table E.1 Generic	N/A[1]	2.3	3.9
1200 A MCCB, Electronic			
Bolted fault current	20 kA	35 kA	100 kA
Measured Incident Energy	1.86	1.20	1.64
Via IEEE 1584 & Trip Curve	218	3.5	5.8
Via IEEE 1584 Table E.1 Generic	N/A[1]	3.5	9.4
2500 A MCCB, Electronic			
Bolted fault current	35 kA	65 kA	100 kA
Measured Incident Energy	3.96	3.48	2.12
Via IEEE 1584 & Trip Curve	110	5.4	6.5
Via IEEE 1584 Table E.1 Generic	N/A[1]	7.7	11.5

[1] N/A represents "Not Applicable" because the parameters are outside the range of the IEEE 1584 Table E.1 generic equation.

VIII. ZONE SELECTIVE INTERLOCKING

Many electronic trip units offer a communication feature known as Zone Selective Interlocking (ZSI). Two or more breakers connected in series are interconnected with a twisted pair of communication wires between their trip units. With ZSI, upstream breakers receive a signal to delay tripping for a preset interval while the downstream circuit breaker clears the fault. However, when no signal is received from the downstream breaker, ZSI bypasses the preset short delay

time and ground fault delay time (when available) on the upstream circuit breaker closest to the fault, which then trips with no intentional delay. This enables instantaneous tripping over a much wider range of fault currents while still maintaining optimal system coordination.

IX. SUMMARY

Direct testing with the OCPD in the circuit provides the most accurate information related to application of the device for mitigation of arc flash injury. Test information is becoming available from manufacturers. The test method is that used for development of IEEE 1584 with the OCPD in the test circuit.

Personal Protective Equipment (PPE) for arc flash protection should be utilized any time work is to be performed on or near energized equipment, or equipment that could become energized! PPE consisting of simple FR shirt and pants typically results in a minimum arc rating of 4 cal/cm^2, HRC 1 and is adequate for many molded case circuit breakers, over a wide range of fault currents, when operating in the instantaneous mode.

Similarly, circuits protected by many low-voltage power circuit breakers operating in their instantaneous mode result in HRC 2 or lower. PPE consisting of conventional cotton underwear, in addition to the simple FR shirt and pants, typically results in a minimum arc rating of 8 cal/cm^2, HRC 2 and is adequate for these circuits. Engineers must be aware that operation in the instantaneous mode for power circuit breakers may result in reduction of coordination.

Extensive testing confirms that Low Voltage Circuit Breakers provide an excellent method to reduce the energy during an arc flash incident. Current-limiting circuit breakers especially reduce incident energy by reducing both duration and fault current during an event. The added protection is not shown by calculation methods, which only consider duration.

Note: All values expressed in this paper unless otherwise stated assume a working distance of 18 inches and the arcing fault in a motor control center unit. The tested values are for specific circuit breakers that will not be identified other than by current rating. They are presented to indicate typical results that may be published by the manufacturers. Values in the paper are not intended to be used for arc flash analysis. The authors recommend contacting the manufacturer of the specific overcurrent protective device for application information.

X. REFERENCES

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XI. VITA

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