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Investigation of Arc Flash in Single-Phase Vertical Conductors in a Box

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ABSTRACT NFPA 70E and IEEE 1584 are defining standards for arc flash hazard analysis. Both assume three-phase faults for calculations since three-phase power distribution is predominant in utility and industrial applications; however, arc flash in single-phase systems is excluded. Single-phase faults to neutral or ground or single phase-to-phase faults can occur in a variety of circumstances. Such events may have the potential to produce arc flash and blast that would pose a significant safety concern. This paper describes a recent doctoral research investigation of arc flash in one single-phase configuration. Experiments were sponsored by UL and performed at the Schneider Electric High-Power Laboratory in Cedar Rapids, Iowa. This facility provided a test article; a full suite of voltage, current, and temperature instrumentation; and high-speed video recording. Experimental work revealed incident energy values less than 0.2 cal/cm^2 for 240-volt single-phase arc fault events though there was still significant flash and splatter of molten wire residue. 480 V single-phase events produced an order of magnitude greater heat energy, and at 22 kA sustained arcing until interrupted by the test cell controller. Results suggest that 240 V single-phase panels and equipment common in residential and light commercial applications may be at very low risk of yielding arc flash burn-related injuries. However, 480 V single-phase faults can produce levels of incident heat energy known to cause burns, flash, and blast pressure at available fault currents between 10 and 22 kA.

INDEX TERMS 240 V distribution, arc flash, arc flash hazard, incident energy, single-phase.

I. INTRODUCTION AND HISTORY

Since the late 19th Century, electrical safety has focused on shock hazards and the potential for faulty electrical systems to ignite fires [1]. The demand for inspection of the electric power and light exhibit at the 1893 Columbian Exposition (Chicago World's Fair) is an example. A July fire, attributed to faulty sign wiring, resulted in the deaths of twelve firefighters and four bystanders [2].

Arc flash, or high-energy arc fault, as a unique phenomenon separate from burning arcs began rising in industry's awareness in the 1960s. Ralph Lee's 1982 paper [3] suggested that heat from arc flash events could be predicted mathematically. In 1987, Lee offered additional work [4] attempting to explain the explosive nature of arc flash events including blasting molten material and equipment fragments from the site of the event.

At the prompting of the Occupational Safety and Health Administration (OSHA), the National Fire Protection Association (NFPA) created a new standards committee to address worker electrical safety. The first edition of the workplace electrical safety standard NFPA 70E [5] was published in 1979. Arc flash safety requirements were added to 70E in 1995. In 2002, the IEEE published the first edition of Standard 1584, *IEEE Guide for Performing Arc-Flash Hazard Calculations*. This document was based on the accumulated experimental work of various investigators including Richard Doughty, Thomas Neal, Allen Bingham, Landis Floyd, and others [7]–[12].

The experimental investigations, and calculation methods that arose from them, all assume three-phase faults. Three-phase power distribution is prevalent in industrial applications; thus three-phase would naturally be of most interest.

However, a few investigators have considered single-phase faults and their likelihood of producing enough energy to cause injury and ignition.

One well-known single-phase arc flash configuration was employed by Thomas Neal for flammability testing of protective clothing. Two vertical electrodes are oriented coaxial with tips pointing toward each other and spaced four to twelve inches apart. The arc flash is initiated with a fuse wire. System voltages used in early work were 600 V and 2400 V, with available arc currents up to 45 kA [13].

In 1974, Harris Stanback performed a series of experiments on a test article simulating a section of a motor control center. Faults were 277 V to ground and, again, triggered by a section of conductor. While the objective of Stanback's work was to explore destruction of bus bars and the surrounding enclosure, his results offer instruction on the levels of energy that a single-phase arc can produce inside power distribution equipment.

From the early 1970s through the late 1990s, A.D. Stokes collaborated with investigators such as Ramakrishnan, Lowke, and Oppenlander, exploring the physics of arcs between two electrodes [14],[15]. These experiments evaluated conditions across a broad range of arc currents and voltages and provided underpinnings for later work focused on high current faults and the phenomenon that would come to be called arc flash. Stokes and D.K. Sweeting included a single-phase configuration in the experimental setup they used when exploring arc flash and arcing faults in horizontally oriented buses [16]. The focus of their early 2000s work, however, was three-phase faults.

In 2012, Marcia Eblen and Tom Short investigated arc flash in 480 V meter bases and transformers [17]. They included single-phase faults in their experiments but in the test articles used, these faults escalated quickly to full three-phase arc events.

Albert Smoak and Adam Keeth also considered utility meter bases in their 2013 study [18]. Their test article represents the configuration that has historically received little attention: 240 V, single-phase with fault currents under 10 kA – but most closely resembled the type of system considered by the experimental series that is the subject of this article. Arcs in their limited test series all self-extinguished in one-half cycle or less. While they did not measure incident energy, they asserted that calculations showed expected values "…less than 1 cal/cm^2 …" at 18 inches from the events.

II. METHODS AND PROCEDURES

This investigation sought to explore levels of incident energy that could be produced by single-phase arc flash events in a controlled, laboratory environment. The test article most employed by investigators supporting IEEE 1584 development of vertical bus data consists of a 20-inch cubical steel enclosure, open on one side, with copper electrode rods extending through holes in the top rear. Rods may have ends suspended above the enclosure bottom. This configuration is called vertical conductors in a box (VCB). Alternatively, rods may extend to a lower, insulating barrier. This configuration is called vertical conductors in a box with barrier (VCBB).

FIGURE 1. Single-phase arc flash test fixture.

The VCB configuration is widely used in a variety of modeling scenarios to represent open ends of breaker panel buses, and the terminals on circuit breakers or contactors. For this reason, VCB was the configuration chosen for this experiment series. The test article shown in Fig. 1 is a standard enclosure provided by the laboratory facility. The shell is 14.75 inches high, 12 inches wide, and 7.5 inches deep. Copper electrode rods are 3/4-inch diameter, separated by a 1.5-inch gap, and braced by four phenolic blocks. Vertical position is maintained by set screws in each support block. Connections at the top are made with rod clamps.

Power was supplied from two of three available test cell phases via 750 kcmil cables. These cables were restrained with rope to prevent movement from magnetic force.

The heat sensing array consisted of seven conventional 18 g copper slug calorimeters with Type J thermocouples. Calorimeters were arranged in a hexagonal pattern spaced six inches horizontally and six inches vertically between rows. The test cell, ready for the first test, is shown in Fig. 2.

Phase current was measured with Rogowski coil transducers. Phase voltage was measured via directly connected, isolated voltmeter inputs. The enclosure shell was bonded to ground with the grounding conductor passing through a current transformer.

The HBM control station managed all cell functions including measurement of voltage and current data via a Genesis 3t data acquisition unit, and power delivery. Calorimeters were connected to an HBM Genesis 3i high-speed data recorder that provided necessary electrical isolation. Data samples were collected at a 50 kHz rate. Gen 3i thermocouple input accuracy is typically 0.5% and 24-bit analog-to-digital conversion

FIGURE 2. **Test cell configuration.**

FIGURE 3. **Test article with fuse wire.**

yields 0.06 ppm error. Worst-case temperature noise was typically less than 0.02 °C.

Arc events were initiated with a fuse wire tied between the electrodes (Fig. 3). Fuse wire stock was 10 AWG fine strand, tinned copper. Segments were stripped bare and secured by tying around the electrode rods between 1/2-inch and 1-1/2 inches above the bottom ends. Electrodes were burnished with Scotch-Brite$^{\mathrm{TM}}$ between tests to remove black oxide and maintain uniform conductivity.

Testing was performed in compliance with facility requirements. Knowing that arc events tend to be subject to random variability and in order to obtain enough samples for statistical treatment, ten (10) runs per configuration were planned. Allowing for the time required to change available bus voltage and current settings, and ten runs per set, four nominal configurations were chosen for the test day to represent typical single-phase low energy faults:

- 240 V at 10 kA
- 480 V at 10 kA
- 240 V at 22 kA
- 480 V at 22 kA

After the first test run at 240 V and 10 kA, the level of measured incident heat was less than 0.1 cal/cm^2. In the interest of increasing the level of intercepted energy, and thus the temperature difference reported by the thermocouples, the authors decided to move the calorimeters closer to the test fixture – from 18 inches to 12 inches – to improve measurement accuracy.

Test setup steps, repeated for each test, were as follows:

1) Operators configured the test cell and performed verification as required by facility procedure, including confirming correct operation of temperature, voltage, and current sensors.
2) Test article was prepared: electrodes cleaned and new fuse wire mounted.
3) Calorimeter array was positioned: center-middle sensor aligned with fuse wire and spaced by cart position and tape measure.
4) Data acquisition unit and high-speed video camera were armed.
5) Operator followed facility procedure to clear and energize the test cell and trigger the event.
6) Data were collected, post-processed, and stored.

III. RESULTS

Forty-three test runs were successfully completed. Tests 42 and 43 were conducted only for video capture and were not incorporated into the analysis. Test 1 was also omitted because the distance for that run was different from the rest, as described previously.

Heat energy imparted to each calorimeter is calculated with the expression used in IEEE 1584 – 2018 F.3 [19]:

$$q = m \cdot \Delta T \cdot c \tag{1}$$

where

q : calculated heat energy
m : mass of calorimeter slug in grams
ΔT : temperature change in degrees Celsius
c : specific heat of calorimeter slug

Using a value for the specific heat of copper that assumes hot calorimeters, and applying units conversion, yields the expression:

$$q\left(cal/cm^2\right) = 0.135 \cdot \Delta T \tag{2}$$

This equation was used to calculate incident energy on each of the seven calorimeters. Average and maximum values for the 40 runs used for analysis are listed in Table I with corresponding arc duration and maximum current. Maximum current values are scaled to RMS for ease of comparison with available bolted fault current.

TABLE I Average and Maximum Heat At 12″

Run #	Max Amps (RMS)	Arc Duration (ms)	Incident Energy (cal/cm^2)	
			Avg	Max
1-11 - avg measured: 240Vrms, 10.01kA; 2.4MW				
1	omitted			
2	11457	19.8	0.031	0.068
3	11047	28.2	0.012	0.022
4	10985	33.6	0.011	0.013
5	11355	28.1	0.018	0.026
6	10446	31.4	0.020	0.027
7	10153	29.2	0.021	0.029
8	10015	30.8	0.025	0.029
9	11553	25.2	0.016	0.020
10	10093	31.2	0.024	0.028
11	13768	42.9	0.011	0.016
12-21 - avg measured: 487Vrms, 12.83kA; 6.0 MW				
12	14491	188.0	0.055	0.075
13	15466	9.6	1.425	2.565
14	13059	54.9	1.643	3.049
15	16036	27.8	0.133	0.291
16	14339	186.9	0.111	0.147
17	16568	176.6	1.528	2.800
18	16184	190.2	1.486	2.772
19	16226	185.3	1.370	2.474
20	14141	22.7	0.353	0.527
21	16619	157.8	1.371	2.336
22-31 - avg measured: 243Vrms, 22.87kA; 5.6 MW				
22	20573	12.2	0.070	0.082
23	20764	28.0	0.126	0.172
24	25156	13.8	0.092	0.114
25	25115	11.1	0.103	0.170
26	26837	15.7	0.129	0.172
27	26965	26.1	0.121	0.202
28	25844	30.0	0.110	0.140
29	26031	6.9	0.103	0.155
30	26489	16.0	0.124	0.220
31	24208	19.4	0.161	0.233
32-41 - avg measured: 485Vrms, 21.5kA; 10 MW				
32	21539	188.4	2.205	4.403
33	24063	163.9	2.316	4.918
34	20608	170.4	2.653	5.357
35	25932	190.4	2.449	5.142
36	25257	185.0	2.135	3.448
37	23200	188.7	2.391	4.441
38	26882	176.0	2.365	4.220
39	26093	158.2	2.066	3.409
40	27227	184.8	2.223	4.002
41	24685	182.0	2.163	3.740

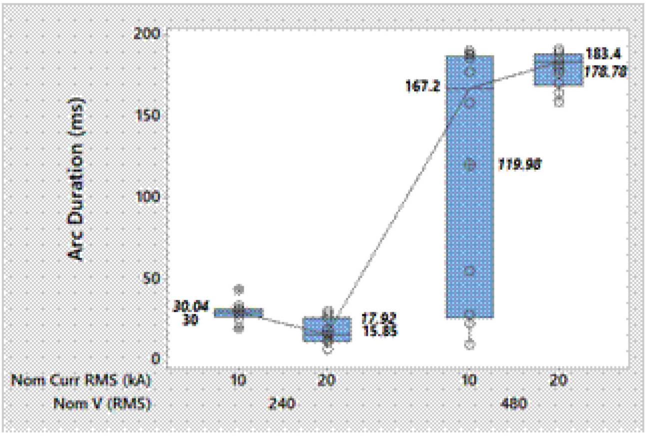

FIGURE 4. Arc flash duration mean values are shown with crosshairs and in italics; median values are shown with center horizontal bar and in regular type. Open circles are individual measured values. Shaded box denotes range of middle two quartiles of data.

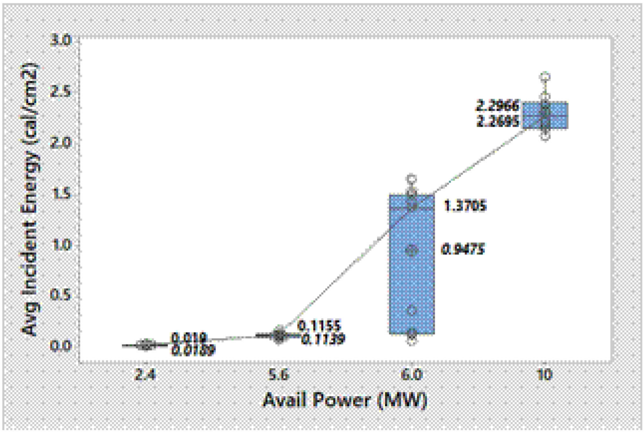

FIGURE 5. Incident energy vs fault power mean values are shown with crosshairs and in italics; median values are shown with center horizontal bar and in regular type. Open circles are individual measured values. Shaded box denotes range of middle two quartiles of data.

Arc duration and incident energy values from Table I are shown graphically as boxplots in Fig. 4 and Fig. 5, respectively. The two 240 V test groups at 10 kA/2.4 MW and 20 kA/5.6 MW show consistently low arc duration and correspondingly low levels of incident energy. There is marked variability in the energy values at 480 V and 12 kA/6.0 MW, suggesting this may be the vicinity of some sort of arc sustainability threshold. The 10 MW group exhibits consistently higher energy.

Past work by others has asserted that single-phase arc events below a certain voltage will self-extinguish in one-half cycle to two cycles [18],[20]. The data presented here found 240 V arc durations varied between 6 ms and 34 ms with 60% lasting more than one cycle. 480 V arcs lasted relatively much longer: all but five arc events in the two 480 V groups persisted for more than 150 ms. These times are an important factor because the relationship between arc duration and incident

FIGURE 6. **Eroded electrodes.**

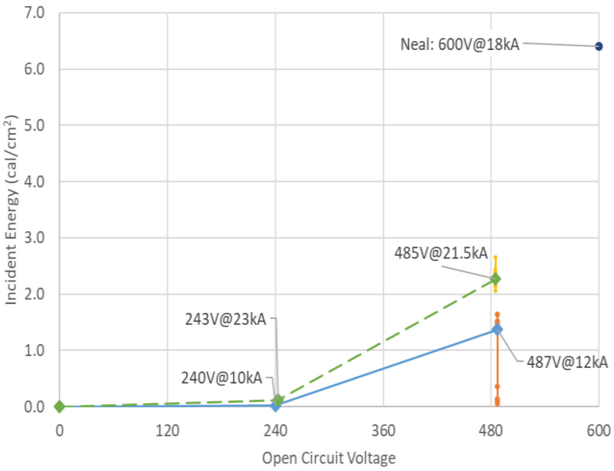

FIGURE 7. **Incident Energy vs Voltage & Fault Current.**

energy is well established [21]. This relationship was also apparent in the data reported here (observable numerically in Table I and visually in Fig. 4 and Fig. 5).

There is a notable increase in arc duration between the 240 V test groups and the 480 V groups. This difference corresponds to extent of electrode end erosion. 240 V tests exhibited no erosion whereas 480 V tests vaporized an average of 0.2 inches per test from the ends of both electrodes (Fig. 6).

The vaporized copper likely increased conductivity in the region around the electrodes, consistent with observations by Babich, Cheminat, Andanson, and Ouajji [22]–[24]. This in turn facilitated arc re-strike, promoted arc persistence, and allowed additional copper to be vaporized which could contribute to further, sustained arcing.

Another way of visualizing the data is shown in Fig. 7. Data points are grouped by test scenario (voltage and current) and plotted as vertical bars. Median values are plotted for each data group. Median points with similar fault currents are joined. A point from testing by Neal [7] at 600 V is shown for reference. This figure suggests a family of curves may exist that would allow prediction of single-phase arc flash incident energy based on open circuit voltage and available bolted fault current. It can be observed that while fault current plays a significant role in determining incident energy, voltage is the dominant factor.

IV. CONCLUSION

Single-phase arc flash events are possible in a variety of conditions. Faults limited to phase-to-phase or phase-to-ground can occur in both industrial and utility installations. Common residential electrical installations in the United States and Europe are single phase or split-phase.

Past investigations have, quite reasonably, focused on three-phase systems known to have significant risk of arc flash and blast. Single-phase systems have received less attention due to the perception of lower hazard levels. This experiment series sought to begin collecting data that would provide an empirical basis for calculations to predict incident energy from single-phase arc flash events.

Data revealed that for the system configuration evaluated, 240 V arc flash events produced very little measurable incident energy at 12 inches for available fault currents up to 23 kA. However, 480 V events at 12 kA and 21.5 kA reliably persisted for 10 to 12 cycles and radiated enough energy to cause serious burns. Arc flash occurrence was observed to be most dependent on voltage, which appears to be the primary governing factor for arc duration, with fault current having a secondary influence. This is particularly observable by comparing the 240 V, 20 kA and 480 V, 10 kA data sets, which are at similar power levels (5.6 and 6.0 MW, respectively). This suggests 480 V is at some physical threshold of arc sustainability, most likely linked to the degree of vaporization of the copper electrodes. This vaporization of copper has been cited in the literature to facilitate arc sustainability, which was observed in this work.

The plot in Fig. 7 is a convenient way to graphically show the relationship of voltage and fault current levels to expected incident energy values. Additional work, particularly in identifying the apparent threshold in the vicinity of 480 V and 10 kA, would support defining this relationship.

It is recognized that incident energy values were measured at 12-inch distances, which is less than the standardized 18-inch distance. The 12-inch distance was preferred in this study as there was an interest in obtaining better characterization at the low incident energies observed at 240 V. Future work would benefit from comparative data taken at both 12 and 18 inches with identical voltage and fault current levels. The dataset would also benefit from including different electrode orientations, as is considered in IEEE 1584-2018.

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