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Effect Of Electrode Orientation In Arc Flash Testing

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Abstract - The arc flash hazard calculation method proposed in IEEE 1584 is based on tests with the arcing electrodes in a vertical plane and the calorimeters arranged at 90° to this plane. In this paper the results of tests using the IEEE test set-up with both vertical and horizontal electrodes are given. High-speed videography and incident energy measurements show that the arc flash hazard is much worse with the horizontal orientation. However current-limiting fuses are effective in limiting the incident energy, even in worst-case arcing conditions, provided that the bolted-fault current is high enough to cause them to operate in their current-limiting mode. The incident energy values are shown to depend on the size of the trigger fuse wire used. The effect of phase imbalance is also considered.

Keywords — Arc flash hazard testing, effect of electrode orientation, arcing fault currents, high-speed arc videography, current-limiting fuses.

I. INTRODUCTION

The IEEE 1584TM-2002 standard for arc flash hazard analysis [1] gives calculation methods for the determination of arcing current and incident energy density, which can be used to determine the flash boundary distance and/or the level of PPE required when working within this distance. The equations proposed are based on test data obtained with the 3-phase arcing electrodes arranged in a vertical plane and pointing downwards, while the calorimeters used to measure the incident energy were mounted at right angles to this plane. Some tests were done in open air while others were done in metal boxes with one side open, to represent electrical equipment with the door open (like the arrangement shown in Fig. 1(a)).

Magnetic forces cause the arcs to be driven away from the source of supply, and for vertical electrodes this will be downwards. Stokes and Sweeting [2] have criticized the use of this arrangement on the grounds that the calorimeters, being "off-axis", will mainly pick up radiated energy from the arcs, and this does not represent the worst case. They used long 3-phase arcing electrodes pointing away from the supply and towards the calorimeters. High-speed videography showed an expanding plasma cloud, driven towards the calorimeters by magnetic forces and plasma jets, which resulted in very high incident energies.

However, Stokes and Sweeting only tested in the open air, and used arcing times which were much longer than would be obtained in a power system equipped with high-speed protective devices.

This paper describes arcing fault tests done in a metal box, in a high-power test laboratory. High-speed video and calorimetry were used to study arcing phenomena with vertical and horizontal arrangements, and the results confirmed Stokes and Sweeting's findings that the horizontal case is more severe. However when current-limiting fuses were used in their current-limiting range, there was no significant difference between the vertical and horizontal arrangements. It is also shown that the test results can be affected by the size of the trigger fuse wire used to initiate the arcing fault, and that phase imbalances need to be considered when determining the operating time of protective devices.

II. TEST SETUP

The basic arrangement used was as described in IEEE 1584 [1], using a 508mm x 508mm x 508mm steel box with one side open. 3-phase arcing tests were conducted at 600V, ungrounded, with an electrode gap of 32mm and various bolted-fault currents, and an array of 7 copper calorimeters to measure incident energy. In addition to the usual high-power test laboratory instrumentation, a data recorder was used to measure the calorimeter thermocouple responses, and some tests were filmed using a FASTCAM high-speed camera, at up to 10 000 frames per second.

Fig. 1(a) illustrates the first arrangement which was used. This case corresponds to the IEEE 1584 standard, and has the electrodes in a vertical plane, 102mm from the back of the box, and fed from above. For the second series of tests the electrodes were horizontal, fed from the back of the box, and extending so that the electrode tips were flush with the (open) front of the box, as shown in Fig. 1(b). Finally the horizontal electrodes were moved to the back of the box as shown in Fig. 1(c), so that the electrode tips were again 102mm from the back of the box.

Some of the tests used an arcing duration of about 0.1s, the circuit being interrupted by a back-up circuit breaker set to 6 cycles. In the other tests the circuit was cleared by current-limiting fuses, mounted outside the box.

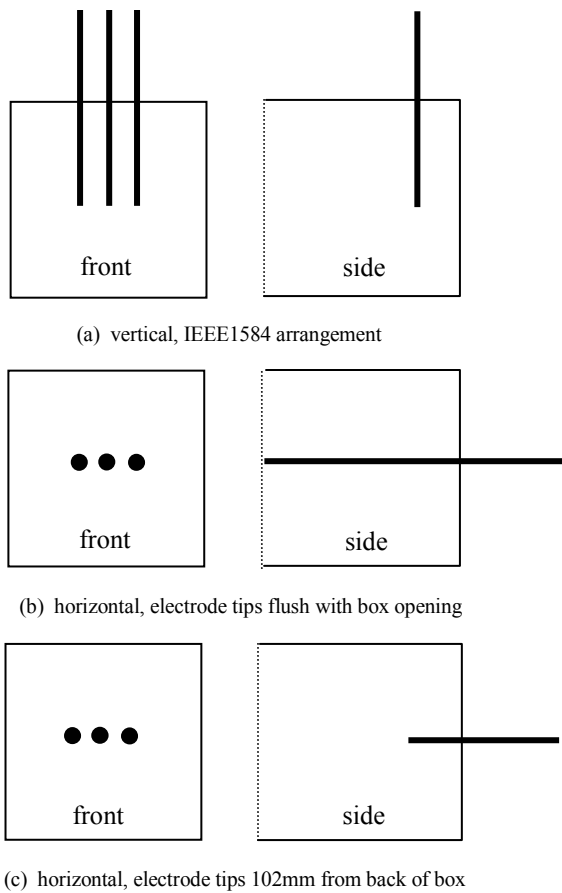


Figure 1. Arrangements of test electrodes.

III. ARCING PHENOMENA OVER 6 CYCLES

A. Vertical electrodes

Fig. 2 shows selected frames from a high-speed video of a test with a bolted-fault current of 23kA (r.m.s. arcing current \sim 18kA), with the calorimeters in place, 18" in front of the arcing electrodes. The camera is positioned to give a side view, and the box opening can be seen on the right-hand side of the pictures. After the initial explosion of the trigger wire the arcs are driven downwards and hit the bottom of the box. The plasma cloud grows within the box, and after 6.5ms it first appears externally, appearing to "spill out". Continued arcing generates increasing quantities of copper oxide smoke from electrode vaporization. Although the whole box is eventually filled with plasma, it is most luminous in the lower part of the box. (For vertical tests, the bottom row of calorimeters recorded temperature rises 43% higher than the average.)

The second frame, marked 106.5ms, shows fully-developed arcing, at the instant that the last phase clears after the back-up circuit breaker opens. While radiation may be the principal method of heat transfer to the calorimeters, it is clear that convection is also important.

However the driving force for the outward convective flow is the thermal expansion of the gas in the box, rather than magnetic forces or plasma jets.

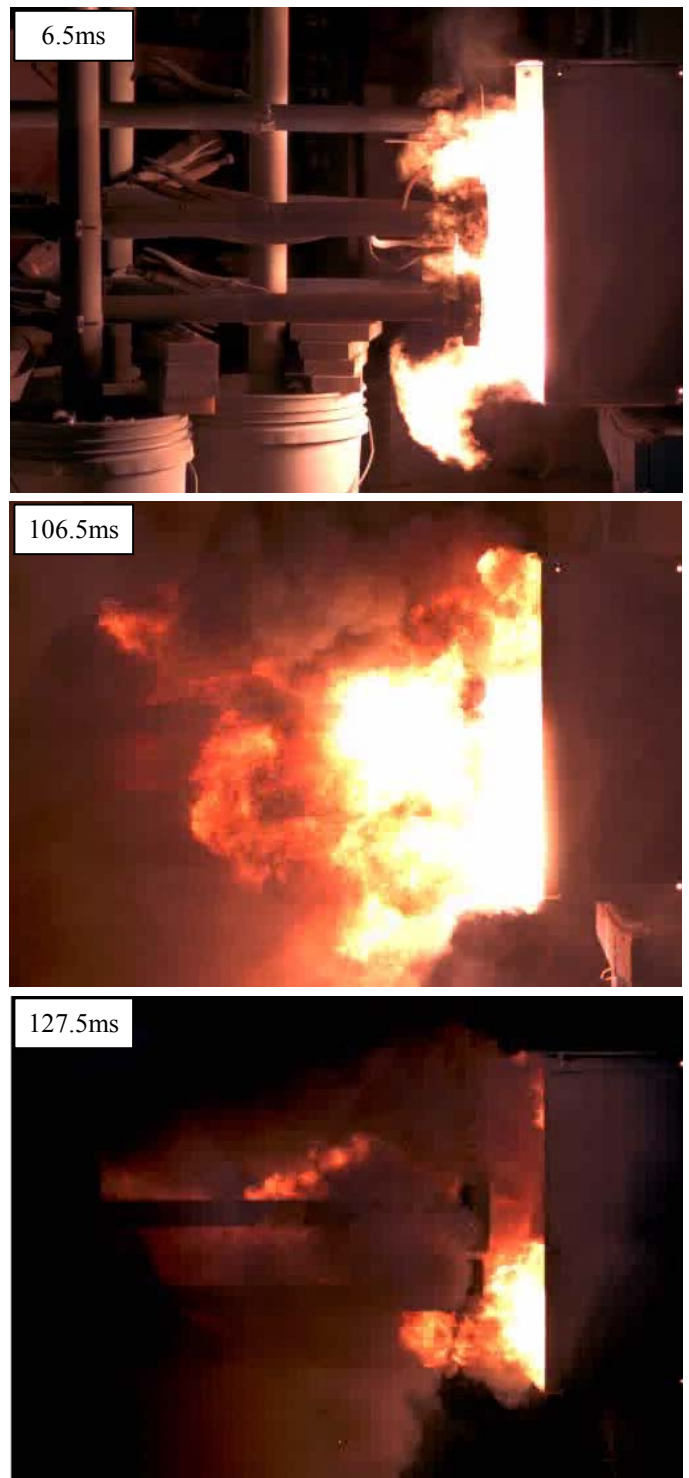


Figure 2. Arcing with vertical electrodes at back of box.

The final frame of Fig. 2 was taken 21ms after circuit interruption. With the electrical power input now zero, the plasma cools and retreats into the box, and all visible light disappears after a further 33ms.

B. Horizontal electrodes flush with box opening

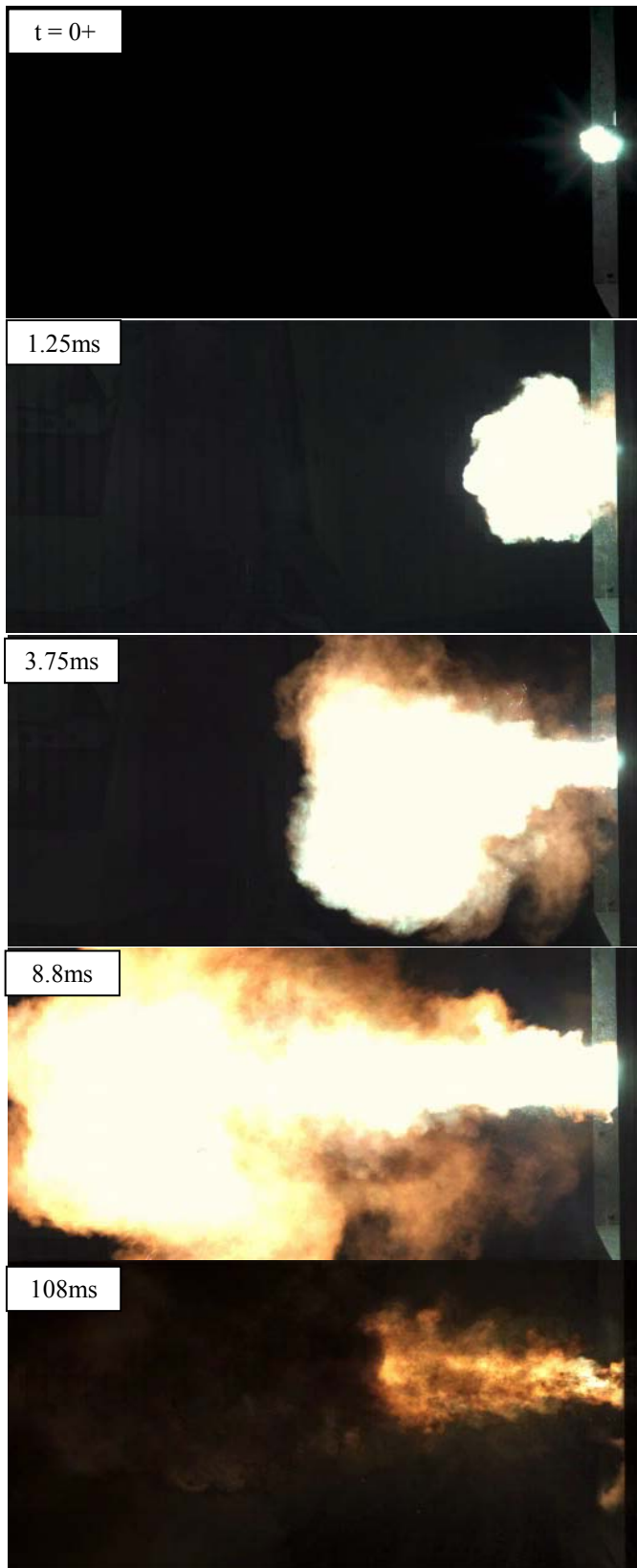


Figure 3. Arcing with horizontal flush electrodes.

When the arcing electrodes are horizontal and fed from the back, the behavior of the plasma cloud changes dramatically. This is illustrated in Fig. 3, which shows a sequence of frames from a test with a bolted-fault current of 44.6kA (r.m.s. arcing current ~ 30 kA), without the calorimeters. The events shown are as follows:

The first frame ($t=0+$) shows a small ball of plasma surrounding the trigger fuse wires just after they have exploded (the time between frames was 250 μ s in this case). It is visible from the side because the electrode tips are flush with the box opening.

At $t=1.25$ ms the ball has expanded and moved outwards (away from the power source), due to magnetic forces. Plasma jets can just be seen forming on the electrode tips.

At $t=3.75$ ms the ball is much larger and the strong influence of the plasma jets is evident.

At $t=8.8$ ms the plasma cloud reaches its maximum extent, about 1m long. Close inspection reveals molten droplets and other debris being carried along with the strong leftward flow, and as arcing continues, large volumes of oxide smoke are produced, partly obscuring the left side of the pictures. Note that there are actually 3 jets, one from each phase conductor, but this is not evident when viewed from the side.

At $t=108$ ms the back-up circuit breaker has opened and the electrical power input to the plasma is zero. The flow has stopped and the plasma is cooling and contracting.

With this electrode arrangement the incident energy was found to be higher than with the vertical case, and the middle row of calorimeters, which are in the direct path of the plasma jets, recorded the highest temperature rises (22% higher than average). However, when the electrode tips are flush with the box opening there is little reflected radiation from the back and sides of the box, and the box has no "focusing" effect on the plasma flow. The "flush" tests are representative of tests in the open with horizontal electrodes.

C. Horizontal electrodes at back of box

Fig. 4 shows arcing 12.75ms after ignition with a bolted-fault current of 44.6kA (r.m.s. arcing current ~ 23 kA), and the horizontal electrodes moved to the back of the box. Viewed from the side, the plasma jets are not visible as they are inside the box. In this case there is an even stronger outward flow, because the box walls give an even greater directional nature to the convective expansion. This results in greater arc lengths, higher arc voltages, and lower arcing currents than found with the two previous electrode arrangements.

With so much of the plasma inside the box, the effect of reflected radiation from the back and sides of the box is very important. When added to the convective effects, very high incident energy values were obtained, making this electrode arrangement the "worst case" of the three variations which were tested. (See section V).



Figure 4. Arcing with horizontal electrodes at back of box.

IV. ARCING CURRENT

Fig. 5 shows the variation of r.m.s. arcing current with bolted-fault current, for vertical and horizontal electrodes (at the back of the box). For the vertical case the arcing current corresponds well with values given in IEEE 1584. However for horizontal electrodes the arcing current is significantly lower, particularly when the bolted-fault current is high. This is due to the longer arc lengths produced by the effect of magnetic forces, plasma jets, and the "funneling" effect of the box (see section IIIC), which contrasts with the vertical case, when the arc lengths are more constrained.

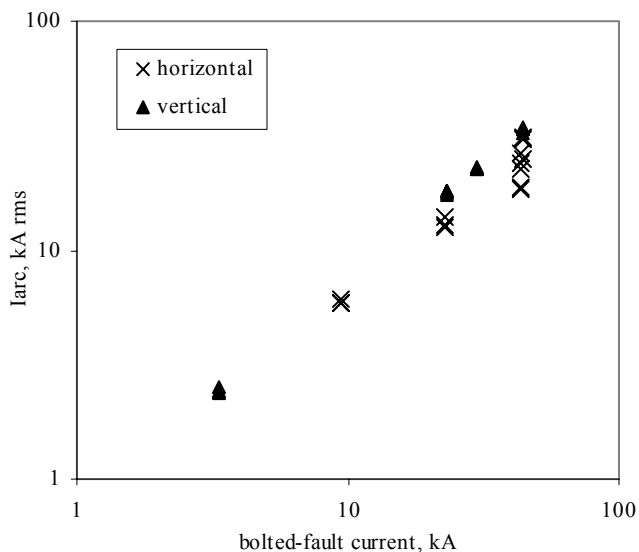


Figure 5. Variation of arcing current with bolted-fault current.

If the 3-phase arcing fault is considered to be a Y-connected set of single-phase arcs, as suggested by Fisher [3], it is possible to estimate the r.m.s. arc voltage per phase. This can be done by computing the arc voltage which would be required to cause the measured reduction current, from the bolted-fault value [3]. However direct measurement of the arc voltage per phase is not possible, since the hypothetical neutral point is located somewhere in the middle of the plasma. In practice only the line-to-line arc voltages can be measured. These are shifted in phase with respect to the currents, and can be very difficult to interpret, as the phases are not balanced.

With horizontal electrodes the longer arc lengths produced at high currents lead to a more violent but less stable arcing mode, in which arc extinction followed by reignition occurs more frequently than for the vertical orientation. This results in a higher scatter in arcing currents, as can be seen in Fig. 5.

For the tests with horizontal electrodes flush with the box opening the arcing currents were in between the two sets of data shown in Fig. 5. They are not shown here for clarity.

V. INCIDENT ENERGY DENSITY

Fig. 6 shows the variation of incident energy density with r.m.s. arcing current, for vertical and horizontal electrodes (at the back of the box), and the calorimeters located at 457mm (18") from the electrode tips. The value plotted is the median of the seven calorimeter readings, to minimize the effect of outlying data points, and has been corrected to 0.1s. For most tests the actual arcing time was close to 6 cycles (0.1s), so the required correction was rather small.

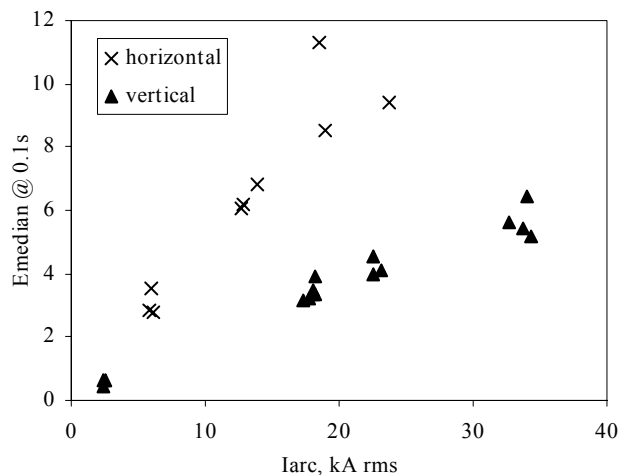


Figure 6. Effect of electrode orientation on incident energy.

Arcing current was chosen as the x-axis variable for this graph, because the different orientations result in different arcing currents, for a given bolted-fault value. The incident energy density with horizontal electrodes is much higher than with vertical electrodes, for reasons given previously, principally the increased outward convective flow. Fitting straight lines to the data in Fig. 6 shows that on average, the incident energy density with horizontal electrodes was 2.67 times higher than with vertical electrodes.

A further series of tests with the calorimeters moved back to 1219mm (48") from the electrode tips gave incident energy densities with horizontal electrodes which on average were 3.3 times higher than with vertical electrodes. These values are in remarkable agreement with Stokes and Sweeting's estimate of a threefold increase when the horizontal arrangement is used [2].

When the calorimeters were moved out to 1219mm, the spread between individual calorimeter readings was reduced,

presumably because of the mixing effects of turbulence as the hot gas moves.

For horizontal electrodes flush with the box opening the incident energies were in between the two sets of data shown in Fig. 6.

A key issue is the orientation of the arcs with respect to the incoming supply system which carries the fault current. The interaction between the arc currents and the magnetic field produced by the system determines the direction of arc movement. However the local design of the arcing electrodes is also important. Some tests were done with short (100mm) horizontal electrode tips, pointing outward, added to the standard IEEE 1584 vertical electrode system. Although only a few tests were done, the maximum incident energies were up to 30% higher than with vertical electrodes pointing downwards. Equipment with components projecting in the direction of a worker could present worse hazards than predicted by the current IEEE 1584 test configuration. Further testing is required to quantify these effects.

The IEEE 1584 standard uses the concept of a "distance exponent" to represent the way in which incident energy falls off with distance. In [5] an improved method was proposed, which takes account of the physical size of the equipment, and assumes radiative heat transfer. However, when strong plasma jets are directed towards the calorimeters, as shown in Fig. 3, the distance effect will be rather different, and there will be a time delay before the expanding plasma ball reaches the measurement point.

VI. IMBALANCE IN PHASE CURRENTS

In previous work it has been assumed that a 3-phase arcing fault can be characterized by a single value of arcing current. However the r.m.s. arcing currents in the three phases are always different. The arcing currents given in sections III, IV and V of this paper were the mean of the three r.m.s. values for each phase, which were computed by numerical integration.

In high-voltage power systems the phase conductors are usually transposed, to achieve a high degree of balance in the impedances of the phase conductors. However low-voltage systems are rarely, if ever, transposed, which results in a phase imbalance which is usually ignored when making short-circuit calculations.

For a layout such as that shown in Fig. 7 the flux linkages of the three conductors are unbalanced, even if the phase currents are balanced. In the case of a bolted fault fed via the three conductors from a balanced 3-phase voltage source, the r.m.s. symmetrical short-circuit current will be different in each phase, and will be highest in the middle phase (B). The magnitude of the difference will depend upon the proportion of the total system impedance which is untransposed (such as busbars and connections), as compared to the proportion of balanced components such as generators, transposed lines and transformers (and, in the case of a high-power test laboratory, the lumped impedances which are used to control the available fault current).

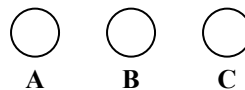


Figure 7. 3-phase conductors in flat formation.

Typically the bolted-fault current in the middle phase is a few percent higher than the average for the three phases, but this can be much higher at high fault currents, when the impedance of the busbars and connections is a greater proportion of the total.

For arcing faults with the conductor layout shown in Fig. 7 this imbalance is accentuated. The electrode tip of the middle phase B is closer to the electrical center of the plasma than are the two outer phases. Using Fisher's concept of representing the 3-phase arc as 3 Y-connected single-phase arcs, this means that the Y is an unbalanced set of 3 resistances, with a lower value connected to phase B.

This is illustrated in Fig. 8 which shows the measured r.m.s. current in each of the three phases, for a large series of arcing tests. They are plotted as a function of the average of the r.m.s. currents in the three phases. Typically, the r.m.s. current in phase B is 10% higher than the average, whereas the lowest phase current is 10% lower. This effect was found for all electrode orientations.

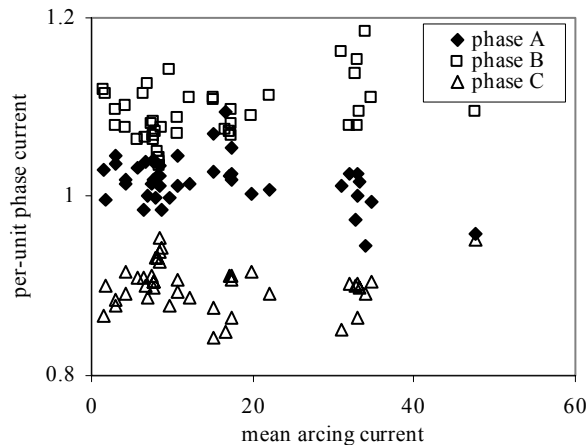


Figure 8. Distribution of arcing current in the three phases.

An arcing fault will always be an unbalanced fault. This needs to be considered when determining the opening time of protective equipment.

VII. TESTS WITH CURRENT-LIMITING FUSES

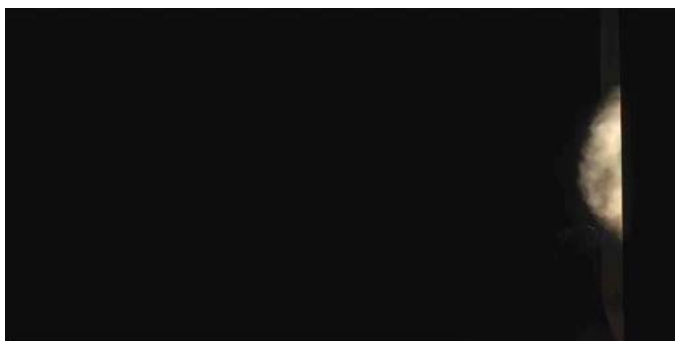
Fig. 9 shows two frames from a high-speed video of an interruption of an arcing fault by a 600A class RK1 fuse (bolted-fault current was 44.6kA). Fig. 9 (a) shows a view, from the front of the box, of the plasma ball just after the trigger fuse wire has exploded. As the current-limiting fuses have not yet melted, this picture is typical of the initial plasma shape in any test. It is included here to illustrate the very bright

flash of light which accompanies the explosion of the trigger wire and illuminates the interior of the box. A few frames later, the plasma ball expands but the bright light disappears.

When the current-limiting fuses begin to limit the circuit current, the expansion of the plasma ball is arrested, and it begins to shrink and retreat towards the electrodes. Fig. 9 (b) is a side view showing the maximum extent of the plasma for the same test shown in Fig. 9 (a), but 3.75ms later. The plasma only just emerges from the box before collapsing.



(a) just after explosion of trigger fuse wire (front view)



(b) at $t = 3.75\text{ms}$ (side view)

Figure 9. Arcing with horizontal electrodes and 600A fuse.

These tests confirmed the dramatic reduction in incident energy when current-limiting fuses are used [4], provided that the bolted-fault current is high enough to cause them to operate in their current-limiting mode. However, they also showed that this is true whatever the electrode orientation. For both vertical and horizontal arrangements, the incident energy for a 44.6kA fault was limited to only 2% of the 6-cycle value, by 600A RK1 fuses. With current-limiting fuses, the circuit is cleared before the strong outward plasma flow can develop fully.

VIII. EFFECT OF TRIGGER WIRE SIZE

In [1] and [4] it was stated that a #10 AWG copper wire was connected across the electrode tips to initiate the arcing fault. If a wire of this size is used then it may not melt if the available bolted-fault current is too low, so that an arcing fault is not produced.

Tests reported in this paper used a #14 AWG trigger wire. However, even with this wire size, tests with 100A and 200A

current-limiting fuses at low bolted-fault currents showed that the fuses opened and cleared the circuit before the trigger wire melted. A small temperature rise was recorded by the calorimeters, caused by radiation from the hot, but unmelted trigger wire.

At higher bolted-faults the trigger wire may melt, but the incident energies are affected by the size of the trigger wire, when current-limiting fuses are being tested. For large trigger wire sizes, initiation of the arcing fault is delayed, and the fuse elements in the current-limiting fuse are preheated before the arcing fault begins, causing them to clear the circuit more quickly. Both of these effects produce a shorter duration arcing fault and lower incident energy values than would be obtained with a very fine trigger wire.

The importance of the trigger wire size depends upon the available bolted-fault current, and the current rating and operating speed of any circuit protection. It needs to be considered whether the use of a single standard trigger wire size for arc flash testing is realistic. The same situation exists in the real world, in which the nature of an arcing fault may be greatly affected by the way it is caused. For example if grounding leads are inadvertently left on a conductor which is subsequently energized, the fault current may be cleared without any arcing if fast-acting protection is used.

IX. CONCLUSIONS

Arc flash tests have been conducted in a manner similar to that described in IEEE 1584, but with three different arrangements of the arcing electrodes with respect to the power supply. The nature of the arcing phenomena was investigated using high-speed videography and the IEEE 1584 system of calorimeters to measure incident energy density.

6-cycle (~0.1s) arcing tests confirm Stokes and Sweeting's conclusion that higher incident energy values are obtained when the electrodes are horizontal, pointing towards the calorimeter, and fed from the back of the box. The worst case was obtained when the electrodes were horizontal, deep inside the box. In this case the arc plasma is driven outwards by magnetic forces, plasma jets and a funneling effect. This produces longer arcs and higher arc voltages, which result in lower arcing current than when the electrodes are vertical. The incident energy for the horizontal worst case was about 3 times higher than for the vertical case, for the same arcing current. This factor is reduced if the comparison is done for the same bolted-fault current.

The test results also illustrated the fact that a 3-phase arcing fault is always an unbalanced fault. This is partly due to the fact that low and medium voltage systems are untransposed, which gives rise to unbalanced short-circuit currents. For an arcing fault the arcing electrode nearest the middle of the plasma has lower resistance and carries a higher current than the other two phases. With the flat arrangement used in IEEE 1584 both of these effects give rise to a higher current in the middle phase.

When the arcing fault was cleared by current-limiting fuses operating in their current-limiting range, there was no significant difference between the vertical and horizontal cases.

Although difference in the shape of the developing plasma ball could be observed, the ball begins to collapse when the current-limitation begins, giving lower values of incident energy. The results are however, affected by the size of the wire used to trigger the arcing fault, and there is a need to standardize the trigger wire sizes use in testing, to match them to the bolted-fault current and protective devices being used.

X. ACKNOWLEDGEMENTS

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