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EFFECT OF INSULATING BARRIERS IN ARC FLASH TESTING

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Abstract - Low voltage arc flash testing has been conducted using the standard IEEE 1584 test procedure, but modified so that the electrode tips terminated in an insulating barrier instead of in the open air. The barrier prevents downwards arc motion, has a stabilizing effect on the arcs, and produces a strong horizontal plasma cloud flow. It also produces shorter arc lengths, higher arcing currents and higher maximum incident energy density, when compared with the standard arrangement presently used. Erosion of the copper electrodes is much higher when a barrier is used which causes a much larger quantity of copper spray to be directed towards the outside of the box. Similar results can be observed when vertical conductors are terminated in real industrial components. The effect of the barrier and the source X/R on arc sustainability at 208V has also been studied. The barrier test arrangement is believed to be more representative of real-world equipment. It is proposed that an arrangement like this should be incorporated into future revisions of the IEEE 1584 testing standard.

Index Terms — Arc flash hazard testing, effect of insulating barriers, arcing fault sustainability, effect of X/R.

I. INTRODUCTION

The IEEE 1584TM-2002 standard for arc flash analysis [1] uses calculation methods for the determination of arcing currents and incident energy density which are based on the results of test data obtained with 3-phase arcing electrodes arranged in a vertical plane, and with open electrode tips pointing downwards. The calorimeters used to measure incident energy density were mounted at right angles to this plane. Most of the tests were done in metal boxes with no front cover to represent equipment with the door open.

Stokes and Sweeting [2] have criticized the use of this arrangement on the basis that the calorimeters, being "off-axis", will mainly pick up radiated energy from the arcs, and that this does not represent the worst case. Their test setups used long horizontal electrodes in open air, pointing away from the supply and directed at the calorimeters. Very high values of incident energy density were produced, by an expanding plasma cloud, driven towards the calorimeters by magnetic forces and plasma jets.

In a recent paper by the authors [3], the effect of electrode orientation was investigated using a metal box and calorimeters conforming to the IEEE 1584 standard arrangement. Various electrode configurations were used, and the results confirmed Stokes and Sweeting's findings that

the horizontal case is more severe, producing incident energies about three times higher than with vertical electrodes.

Despite this, there is still no clear consensus in industry that the vertical test arrangement should be replaced by a horizontal arrangement, because it is felt that the horizontal arrangement is not representative of much equipment found in the field in North America.

Both the vertical and horizontal arrangements tested previously used conductor tips which terminated in open air. This is not a situation that is found in real equipment, in which the conductors usually enter the terminal block of some device.

This paper describes arcing fault testing done in a high-power test laboratory with vertical conductors in a box, but with the electrodes terminating in an insulating barrier or components such as power distribution blocks or fuse holders. This configuration is believed to be more representative of the majority of low-voltage equipment in industrial control panels and MCCs.

The results show that with vertical electrodes and an insulating barrier, a strong horizontal outward plasma flow is produced, which gives higher incident energies than obtained without the barrier. The nature of the flow is similar to that previously observed with horizontal electrodes.

The effects of the insulating barrier on arc sustainability at 208V and electrode erosion, and the influence of source X/R, are also described.

II. EFFECT OF AN INSULATING BARRIER

The test arrangement with an insulating barrier is illustrated in Fig. 1. Arcing was initiated above the barrier by a copper wire as shown. The testing was carried out as described in [3], and included the use of high-speed videography.

The barrier used was a 200mm x 27mm x 51mm block of glass-reinforced melamine, selected for its ability to withstand the very high electromagnetic forces.

When vertical electrodes are used, magnetic forces cause the arcs to be driven downwards and burn from the electrode tips. If the tips are in open air, plasma jets are formed on the tips, which cause the arcs to be driven further downwards and hit the bottom of the box.

If arcing persists, the whole box eventually fills with a plasma cloud, and "spills out" externally [3]. However, with the barrier present, the downward motion of the arcs is arrested, and arcing tends to be more somewhat more stable across the surface of the barrier, which produces a noticeable

increase in the erosion of the electrodes.

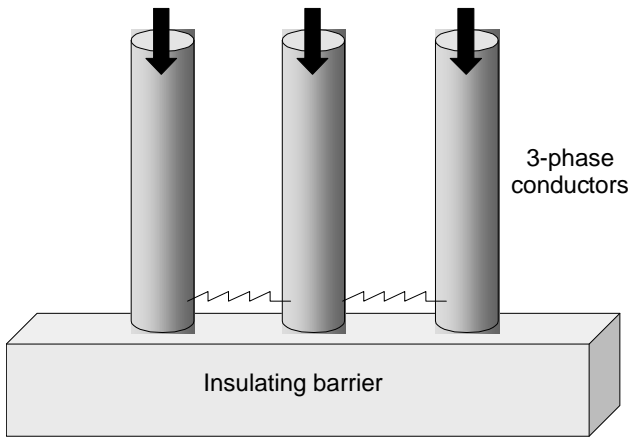


Fig. 1 Test Electrodes Terminated with Insulating Barrier

The following sections give results from 235 tests, at 208V, 250V, 480V and 600V, with vertical electrode spacings of 12.7mm, 32mm and 50.8mm and bolted fault currents near to 4.5kA, 10kA, 22kA and 45kA (the precise levels being dependent on the circuits available in the high-power test laboratory). 144 of these tests used an insulating barrier, while no barrier was used in the remainder. 45 tests were done with a low source X/R (<2), while the rest used a high X/R (>9). The calorimeters were located at a distance of 457mm (18") from the electrode tips.

The mean arcing current was calculated as the mean of the r.m.s. values in the three phases (which vary significantly [3]). In 205 tests arcing was sustained and the circuit was cleared by the test station back-up circuit breaker, which was set to open after 6 cycles (0.1s). (The actual opening times varied slightly from the setting, so the incident energy measured by the calorimeters was corrected to a standard time of 0.1s). For the other 30 tests the arcs were self-extinguishing. This only ever occurred with test voltages of 208V and 250V.

Multiple regression analysis of results from all the tests showed that the mean arcing current was increased by about 20% when the barrier was present. The violent chaotic behavior of the high-current arcs results in considerable scatter in the data, particularly at the 45kA level. Nevertheless, the effect of the barrier can be clearly seen in Fig. 2, which shows a comparison of mean arcing currents with and without the barrier at 480V with an arcing gap of 32mm.

Using Fisher's method [3,5], it can be shown that a 20% increase of arcing current at 480V means that on average the mean arc voltage with the barrier is about 74% of the value with no barrier. It appears that the stabilizing effect of the barrier causes the mean arc lengths to be lower, which causes the reduction in arc voltage.

For all tests the maximum incident energy was increased by 31% with the barrier present. However the barrier effect was increased at the higher test voltages. For all the 480V tests the average increase was 49% and for the 600V tests the increase was 86%.

This is illustrated in Fig. 3, which shows the maximum incident energy density at a distance of 457mm (18"), as a

function of bolted fault current, for tests at 480V with a 32mm gap.

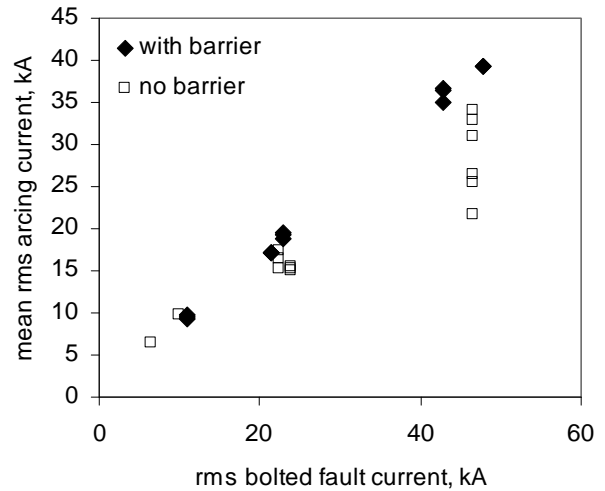


Fig. 2 Effect of Barrier on Mean Arcing Current

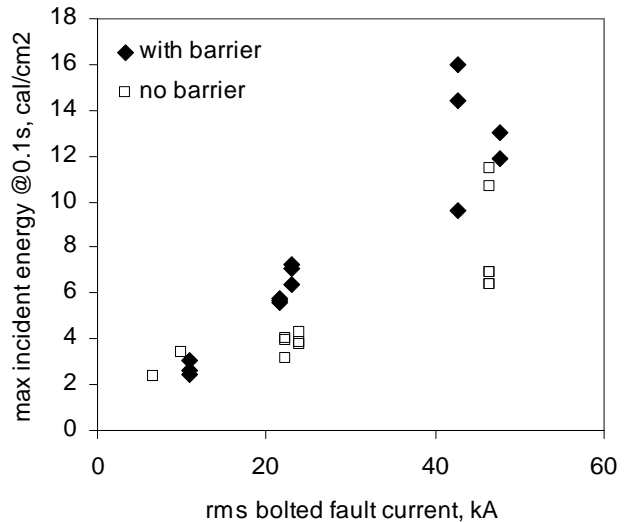


Fig. 3 Effect of Barrier on Incident Energy Density

Part of this increase is accounted for by the higher arcing current when the barrier is present, but a different mode of plasma development was also observed, as shown in Fig. 4.

Fig. 4 shows the plasma cloud external to the box, about 3ms after arc initiation, with a barrier present. The upper picture is a normal image frame from the high-speed camera record. The same picture is repeated in the lower image, but with the contrast greatly increased, so that the box interior and calorimeters are visible.

A strong horizontal flow has developed, and the picture looks very similar to those seen previously with horizontal electrode tests [3].

With the barrier in position, the plasma jets, which produce the plasma cloud, cannot easily develop in a downward

direction, and so appear to develop in directions at right angles to the vertical plane, as illustrated in Fig. 5.



Fig. 4 Plasma Development With Insulating Barrier

The difference in the mode of arcing was also evident in the distribution of temperature rises across the array of calorimeters. For vertical tests without a barrier the bottom row of calorimeters was always hottest, and the temperature rise on the hottest calorimeter was 32% higher than the mean (average for all tests).

By contrast, with the barrier present the calorimeter in the middle of the group was always the hottest, and its temperature rise was 52% higher than the mean. This is an indication of the focusing effect, which can be clearly seen in Fig. 4.

With the barrier, the plasma flow is augmented by gas flow generated by pyrolysis of the organic material, which increases the total enthalpy and adds to the toxicity of the smoke generated, depending upon the chemical composition of the barrier material.

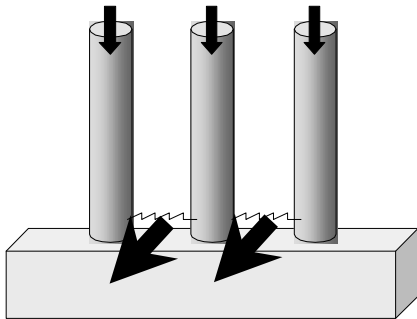


Fig. 5 Outward Deflection of Plasma by Barrier

III. ARC SUSTAINABILITY AT 208V WITH HIGH X/R

A. Without barrier

Sustained arcing faults are more difficult to obtain at lower voltages. In the IEEE 1584 test dataset only one test was listed which gave sustained arcing at 208V [1].

The authors conducted arcing fault tests at 208V and 250V with arcing gaps of 12.7mm, 32mm and 50.8mm. At 208V arcing could not be sustained at 10kA or less, even with the shortest (12.7mm) gap.

Fig. 6 shows the three phase arcing currents for a typical case where the arcs self-extinguished after about 21ms, with a 12.7mm gap at 250V, 13kA. Fig. 7 shows the corresponding line-line voltages (not the arc voltages, which cannot be individually measured).

Note that even if arcing is not sustained indefinitely, some arc energy is released, and although incident energies are usually low, there is still a potential hazard.

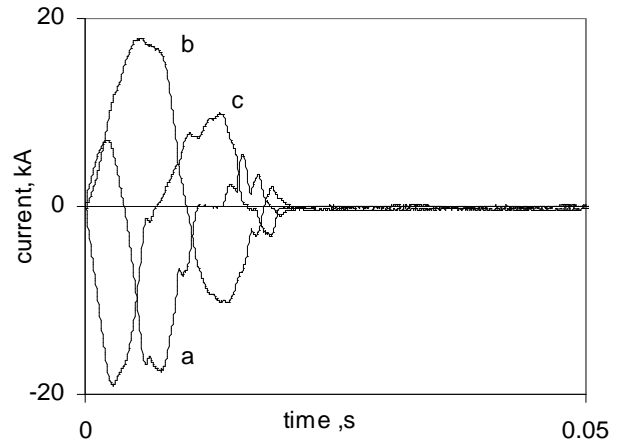


Fig. 6 Arcing Currents at 250V, 13kA - No Barrier

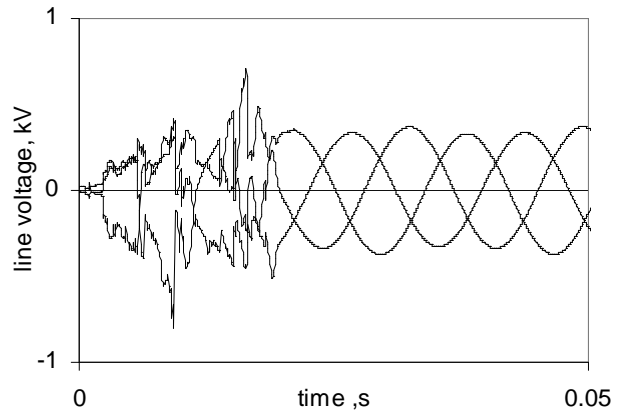


Fig. 7. Line-line Voltages at 250V, 13kA - No Barrier

B. With barrier

The shorter arc lengths and stabilizing effect with the insulating barrier make it easier for arcing to be sustained, and it was found possible to produce self-sustaining arcs at

208V. With a gap of 12.7mm, sustained arcing was obtained at 4.5kA, 10kA and 22kA. When the gap was increased to 32mm, the arcs were self-extinguishing at 4.5kA, but sustained arcs were obtained at 10kA and 22kA. For the 12.7mm gap, incident energies at 0.1s up to 2.7 cal/cm² were measured, while for the 32mm gap this increased to 3.2 cal/cm².

Fig. 8 shows sustained arcing currents at 208V with a bolted-fault current of 9.9kA and a 12.7mm gap. The unbalance between the phases is very marked, but arcing was sustained until the test station breaker opened the circuit after about 0.1s.

Fig. 9 shows the corresponding line-line voltages.

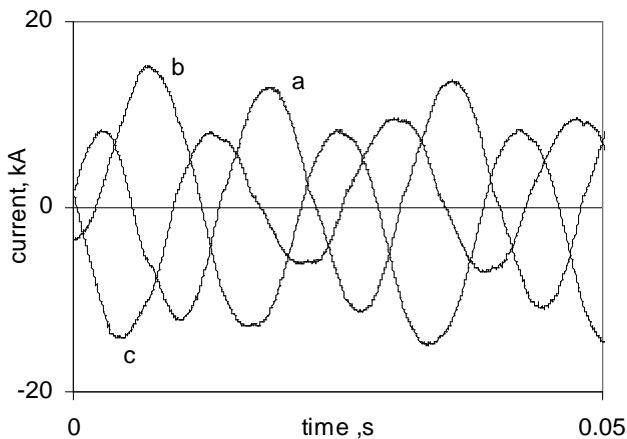


Fig. 8 Arcing Currents at 208V, 9.9kA - With Barrier

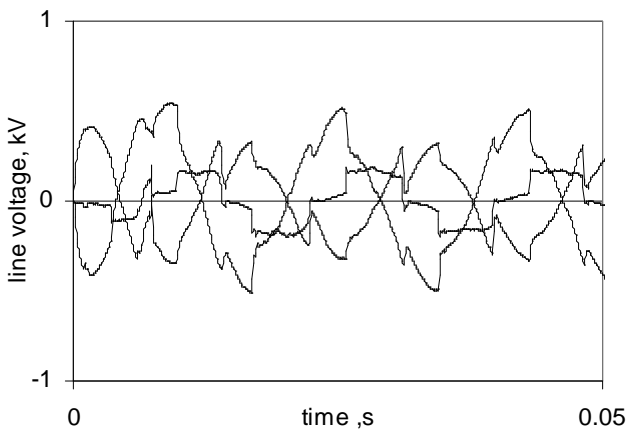


Fig. 9. Line-line Voltages at 208V, 9.9kA - With Barrier

IV. LINE-SIDE ARCING EFFECTS

A further series of tests was carried out using real industrial components (power distribution block, fuseholder, IP20 fingersafe device) instead of the insulating barrier. In each case the device was mounted on a vertical plate and the line-side conductors from the test source were connected into the

device from the top, and the conductor sizes used were those corresponding to the ampere rating of the device. A 3-phase arcing fault was triggered in the usual way at the top of the device (on the line side).

In each case it was found that the presence of the component below the arc roots impeded the downward development of the plasma cloud, in a similar way to that seen previously with the insulating barrier.

Figs. 10(a)-(c) show the development of arcing above a 100A power distribution block. There is some downward flow, (which depends on the physical size of the component), but also a significant horizontal outward component, so that the total flow in the case shown is directed at an angle of about 45 degrees downwards.

In Figs. 10(b) and 10(c) melting of the conductors feeding the component can be seen, which results in additional arcing in that zone.



Fig. 10 (a) Arc Initiation



Fig. 10 (b) after 6ms



Fig. 10 (c) after 12ms

V. ELECTRODE EROSION

It was noticed that if an insulating barrier was used with the IEEE 1584 electrodes, the erosion of the copper electrode tips was significantly higher.

To quantify this effect, some of the tests used detachable electrode tips that were weighed before and after testing to determine the amount of copper lost from the electrodes.

The rate of material loss from arcing contacts is commonly found to depend upon the arcing current raised a power X , where $1 < X < 2$. This was found also to be true for the high-current 3-phase arcing fault, so the erosion rate can be approximated by

$$dw/dt = K I_{ARC}^X \quad (1)$$

The erosion rates and currents for each phase were measured separately. Multiple regression on 114 such measurements gave $X = 1.31$.

The effect of the barrier was to increase the average erosion rate by 66%. The stabilizing effect of the barrier causes a higher proportion of the arc column power to be transferred to the electrodes. Fig. 11 shows measured erosion rates for the middle phase electrode 'B' with a 32mm gap, with and without the barrier present. The lines shown are for values of K that give the best fit to (1).

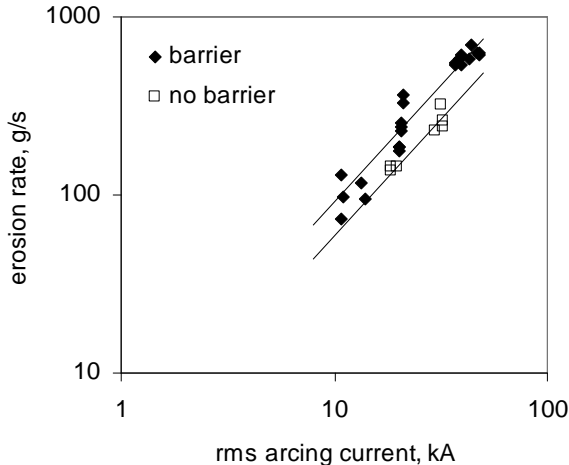


Fig. 11 Erosion Rate for Middle Phase B, 32mm gap

Fig. 12 shows the erosion rates measured for a 12.7mm gap with barrier present. The value of K is higher than found for the 32mm gap, presumably because a higher proportion of the total arc power is transferred to the electrodes when the gap is shorter. Similarly, tests with a 50.8mm gap gave lower erosion rates.

It was noticed that the erosion rates were noticeably less for the two outer phases, 'A' and 'C', and that there was no significant difference in the values of K for the outer phases. There is a higher probability of multiple arc roots terminating on the middle electrode, which could explain this effect.

Table I summarizes the values of the erosion constant K which gave the best fit to (1) using $X = 1.31$.

TABLE I

Erosion constant K for sustained arcing

gap	Barrier present	Outer phases 'A' & 'C'	Middle phase 'B'
12.7 mm	✓	4.82	5.61
32 mm	✓	3.87	4.41
50.8 mm	✓	3.68	4.06
32 mm	x	2.56	2.89

(The values of K in Table I apply with dw/dt in g/s and I_{ARC} in kA).

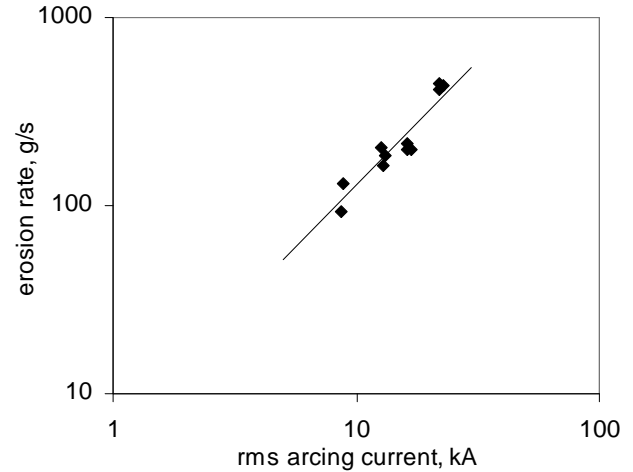


Fig. 12 Erosion Rate for Middle Phase B, 12.7mm gap

VI. EFFECT OF SOURCE X/R

Most of the results in the IEEE 1584 test dataset were obtained with a relatively high source X/R [1]. This is typical of the way tests are carried out on high-power interrupting devices, to represent worst-case conditions where the high source inductance tends to prolong arcing. However in real power systems X/R tends to fall as the system voltage falls [6].

Tests carried out at 208V and 480V with the barrier in place allowed the effect of X/R to be studied.

For low X/R arcs were sustainable at 208V with a 12.7mm gap from 4.5kA upwards, but arcing could not be sustained with 32mm gap at any level of bolted-fault current. Therefore it is more difficult to sustain arcing if X/R is reduced (see results in section IIIB). At 480V arcing could be sustained for all gap lengths.

When arcs were sustained the arcing current was about 20% lower and the incident energy was about 25% lower for low X/R , but these effects were most significant for bolted-fault currents above 10kA.

More testing is needed with lower bolted-fault currents to determine the critical levels, below which sustained arcing is not possible.

VII. CONCLUSIONS

The test procedure used in the IEEE1584 standard for arc flash testing uses vertical 3-phase electrodes with open tips pointing downwards. Phase conductors that terminate in open air are rarely, if ever, found in real equipment.

Tests have been carried out using the IEEE1584 vertical test conductor arrangements, but with the tips terminating in an insulating barrier, and also in real components such as poer distribution blocks and fuseholders.

When terminated in an insulating block, the downward movement of the arcs is arrested, and instead a plasma cloud is ejected at right angles to the plane of the conductors. This produces a pattern of plasma flow which is similar to that produced with horizontal electrodes.

With an insulating barrier arc lengths and voltages are lower, the arcing currents are higher, and the maximum energy density, which is found on the middle calorimeter, is much higher than measured with the standard IEEE 1584 setup. Self-sustaining arcs can also be produced at 208V with relatively low levels of bolted-fault current. For systems with low X/R the r.m.s. arcing current and incident energy are reduced, and sustained arcing is more difficult to obtain.

Erosion of the copper electrodes is also very much higher with the barrier in place, increasing the quantity of copper spray that is directed towards the outside of the box. The effects of large amounts of sprayed copper have important implications for PPE material testing. Different materials may have different propensities to absorb the molten copper and the associated latent heats of condensation and solidification.

All of these considerations lead to the conclusion that the current standard vertical test arrangement with electrode tips in open air should be replaced with one which is more representative of real equipment.

Addition of an insulating barrier to the standard test setup is one option, but a simpler one would be to use a horizontal arrangement with open electrode tips pointing at the calorimeters, as this is close to being a worst case. However sustained arcing can be obtained at 208V with the insulating barrier, and this is an important advantage of using the barrier arrangement.

VIII. ACKNOWLEDGEMENTS

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X. VITAE

Robert Wilkins graduated from the University of Manchester Institute of Science and Technology (UMIST) with a B.Sc.(Tech) in 1962, and a Ph.D. in 1968. He then taught electrical power engineering at UMIST, Liverpool Polytechnic, and the Middle East Technical University, Ankara, Turkey. Since 1985 he has worked as an electrical power engineering consultant. He is a Fellow of the Institution of Electrical Engineers, London.

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