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APPENDIX 2

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Conductor Clashing Characteristics of Overhead Lines

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SUMMARY Results are presented of an investigation of the characteristics of clashing arcs on overhead lines, with particular emphasis on the arc duration and I^2t and their bearing on protection. The particle emission rates have also been investigated. Arc properties were measured over a range of current for voltages of 240 Volts and 6.6 kV, for both copper and aluminium conductors. The results show that aluminium particles represent a much more serious problem in terms of fire initiation, because of their higher temperature. The arc durations and I^2t values at currents from 65 to 860 amps indicate that normal fuse protection would be unlikely to operate in the event of such faults.

1. INTRODUCTION

Arc discharges between the conductors of overhead lines have important ramifications in the Australian environment because they represent a potential cause of fire by ignition of flammable material under the line. The arcing may be initiated by a number of causes. Clashing of conductors may be caused by strong, gusting, winds or by movement of conductors as a result of electromagnetic forces due to fault currents. As a result of clashing, whether between two phase conductors or a phase and neutral conductor, a short circuit current flows at the instant of contact making, followed by arcing when the contact is broken as the conductors separate. The likelihood of such clashing occurring is increased significantly if the sag of the lines is excessive, due either to higher than normal line and/or ambient temperature or as a result of incorrect tensioning of the line during erection. Alternatively, arcing may result from foreign objects bridging the lines. Most typically, this would include tree branches across the lines. At voltages above about a kilovolt, there is a substantial current flow (of at least tens of milliamps) through the wood initially. This current gradually increases in magnitude due to carbonization of the wood until eventually there is a full, open, arc initiated along the wood surface, at which time a short circuit arc between the conductors occurs, with the current magnitude limited considerably by the arc impedance.

In the case of the clashing fault, fires may be initiated by high temperature particles which fall to the ground after being generated by melting of the conductor both at the initial separation and later at the arc root points on the conductors. When wood bridges the conductors, the current flow through the wood, though small, causes the wood to eventually ignite, particularly at the contact points and to drop burning embers to the ground. The subsequent full arc along the wood surface will, additionally, produce high temperature metal particles from the molten arc roots on the conductors.

While these faults have such potentially disastrous consequences, they are often difficult for the system protection to detect and thus are not always isolated quickly enough to prevent fires occurring. In the case of clashing faults, the problem lies in the fact that, in general, it is difficult to sustain a free-burning arc over the length resulting from inter-conductor separations. This is a result of the natural bowing of the arc due to convective buoyancy and to other factors such as wind generated dissipation of arc power. As a result, the voltage required to sustain such arcs is considerable (of the order of 15 Volts per cm) and the arc self-extinguishes as a result of its own instability. This tendency to extinguish is most evident in the low voltage (415/240 V) lines because of the limited voltage available to sustain the arc. As a result of the self-extinguishing process, in many cases the arc duration may not be sufficiently long to cause any protective device (fuse, recloser etc.) to operate. The problem is further exacerbated by the current limiting effect of the high arc voltages generated. Thus although the clashing and arcing may occur repeatedly over a prolonged period of time, the individual clashing and arcing duration and the arc current may not be sufficient to trip the protection, thus allowing the arcing to continue for a prolonged period with prolonged production of molten particles.

The fault which results from a piece of wood across overhead lines is a typical example of the high resistance fault. The current flow through the wood is, initially, much less than the normal load current and is thus not seen as a fault. As a result, the fault may exist for a considerable period, during which time burning embers may drop to the ground, possibly resulting in ignition of ground cover. After some time (5 - 30 minutes) sufficient surface carbonization of wood may build up to allow a free-burning arc to be initiated along the wood surface. When this occurs, the arc current mangitude and duration will probably be sufficient to activate the protection, although as with the clashing arc the substantial arc impedance will result in significant current limitation.

The problem presented by such faults to the protection designer is made more difficult by the lack of detailed information concerning the characteristics and properties of such faults. In particular, such basic details as fault duration, voltage-current characteristics, arc movement and fault I^2t are not known, not to mention other properties such as rate of production of particles, their temperature decay and trajectories.

A programme of investigation aimed at determining some of the basic properties of such faults has been undertaken at UNSW and this paper describes some of the results of initial investigations of the arcing resulting from clashing of single phase conductors at 240 Volts and 6.6 K Volts.

2. MECHANISM OF PARTICLE EMISSION

There has been very little work done on the problem of clashing arcs, and in particular, there is no information available with regard to the factors which determine the arc current duration, arc movement and the erosion of material. Apart from the work of Strom (1946) on long arcs, the only work on arc characteristics of any real relevance has been concerned with short arcs on low voltage busbars at relatively high currents (tens of thousands of amps) (Fisher, 1970; Wagner and Fountain, 1948). Similar problems with protection operation occur even on such systems (Kaufmann and Page, 1960), but to a lesser degree because of the lower arc voltage of the short arc and the consequent decreased tendency to limit current.

The important characteristic of clashing is the rate of erosion of conductor material and the form and quantity of the particles when ejected from the clashing site. In particular, it is not clear whether the initial melting of the contact bridge at separation or the subsequent arcing provides the major source of ejected material. The only reported investigations of particle production by clashing are contained in a report of the State Electricity Commission of Victoria (SECV : 1977). The investigations reported there were concerned only with the particle production and the temperature decay and trajectory of the particles. There was no investigation of the arc properties and its effect on erosion.

The rate of erosion of material by the arc is dependent on the power dissipated at the anode and cathode roots on the conductors. This power is determined by the arc current, the sum of the anode and cathode fall voltages, and the stability of the roots. The anode and cathode falls are insensitive to current and do not vary significantly for different metals, being usually about 25 - 30 Volts total. Thus the maximum energy per second available for producing erosion is typically 25 Kjoules per kilocoulomb. Not all of this will be used for conversion to erosion as some will be used for maintaining the arc, some will be dissipated away by conduction and radiation and some will be used to vapourise conductor material – a loss process which is distinct from loss in a macroscopic particle form.

The actual mechanism of particulate loss due to conductor clashing at the relatively slow rates of contact separation encountered here will be similar to that of normal contact erosion. Power will be developed in the current flow constriction at the point of contact : this will be generated in a sphere of radius a - 5 x 10^{-3} cm, where a is the radius of the contact area. As the contacts separate, a decreases, the contact resistance increases, as does the contact voltage drop and hence the power developed in the contact. Thus the temperature of the contact increases until it reaches the melting point of the conductor material. At this point, a molten bridge forms between the separating contacts to carry the current. When true separation occurs as the bridge is broken, the temperature at the contact points is high enough for vapourisation of metal and electron emission to initiate an arc discharge. When the arc forms, the cathode and anode spots are maintained at high temperatures (2500 - 3000° K for non-thermionic materials) by the cathode and anode falls. In general, these temperatures are above the boiling points of the metals.

Consequently, there are two ways in which particles may be emitted. At the instant of contact separation, before the arc has established, the rupture of the molten bridge will cause emission of significant numbers of molten particles. This mechanism will produce increased emission with current. After the arc has established itself, the arc roots will be essentially molten pools of conductor material and thus this material may be lost both by vaporisation to a gaseous state or by macroscopic particle loss of molten metal. The pressure gradient established by the arc at the cathode in particular will help the latter process by effectively blowing the molten material off. The loss rate due to arc heating is dependent on arc current and duration and on the stability of the arc roots.

In addition to arc and contact heating, other factors determine the amount of material ejected. The conductor material and its melting point, its electrical resistivity and specific heat are important factors. In general, the higher the melting point and boiling point, the less is the loss by the arc processes in general (including vapour loss). Thus it would be expected that steel would have less loss than copper, which would be less than the loss from aluminium. Wilson (1955) has measured arc erosion losses for a number of materials and found the total loss from aluminium to be almost twice that from copper, with the molten liquid loss having the same relativity. Because of the method of arc initiation, Wilson's experiments did not include a loss component due to contact bridge rupture.

Arc motion will also have some bearing on the losses - if the arc roots are stationary then there may be enhanced heating, whereas if the arc roots move then the loss may be substantially reduced. However this may be counteracted by the fact that an erratically moving arc may produce a greater fraction of larger particles than a static arc where the major loss will be by vaporisation. As the electromagnetic forces on the arc are significant, there will usually be some arc movement, particularly at high currents. The force will be given by $\frac{1}{2} I^2 \frac{dL}{dx}$ and thus the motion will be away from the source, but the variable separation of the conductors during clashing and the effects of buoyancy and wind will result in a quite erratic arc movement.

3. THE EXPERIMENT

The essential aim of this initial phase of the project was to investigate the arcing characteristics of clashing faults on overhead lines. The experiments included the determination of voltage-current characteristics, current-arcing time relationship, number and size of ejected particles and arcing I^2t. All of these were obtained for a range of current, for 240 V and 6.6 kV and for aluminium and copper conductors.

The apparatus used comprised a short span of two-wire line set up in the high current laboratory at UNSW. The span length was 3.1 metres and conductor separation was0.4 metre. Current through the arc and voltage across the conductors at the end support insulators were measured with an oscillograph. The voltage measurement thus includes some inductive drop due to the inductance between point of measurement and the arc. This was taken into account when constructing the dynamic volt-ampere characteristics.

Clashing was initiated manually by inducing conductor motion, with an insulated length of twine, when the active line was live. In addition to current and voltage measurements both high speed and video films were taken to record particle emission. In addition, a 35 mm camera with open shutter during clashing was used to provide a very clear indication of the numbers and trajectories of emitted particles (Fig. 1). The number and size of particles emitted was determined by collecting all solid material emitted during clashing.

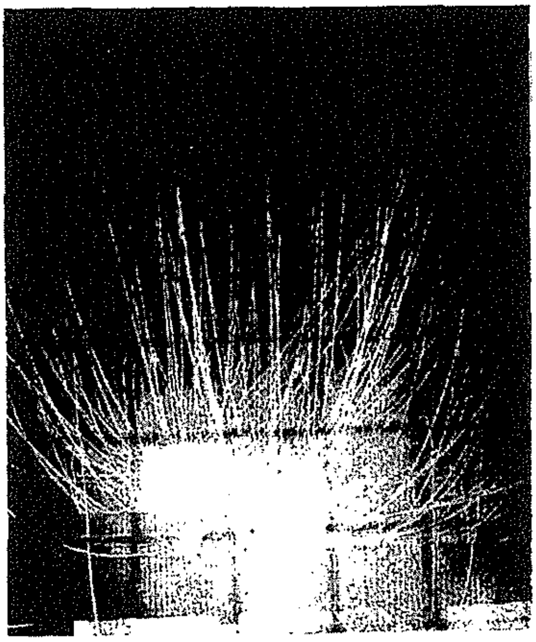

Fig. 1. Clashing Arc particle Emission. Aluminium conductors at 575 Amps. Total of eight separate clashes over a 10 second period.

At 240 Volts, a range of current from 60 amps up to 860 amps (prospective values) was used. At 6.6 kV, because of supply limitations, the currents used were only up to a maximum of 10 amps. Although the high voltage arcs do not produce any significant particle emission because of the low current, the results are, nevertheless, of importance in determining the arc duration at high voltage. For long arcs (in contrast to the situation with short arcs) the current magnitude does not have a strong effect on arc duration. Thus the 6.6 kV results obtained provide useful detail of the arc duration after clashing, even though the I^2t values are very limited. By using the low current data to estimate arc duration at higher currents, we are making the implicit assumption that the arc voltage (and hence electric field) does not have any significant dependence on current, so that the growth of arc voltage to extinction is independent of current. This assumption is supported by Strom's measurements in that he found an almost constant electric field for currents up to 5000 Amps, for both 1.2 metre long and 0.3 metre long arcs. Under those conditions, the average electric field fell in the range 10 - 15 Volts/cm with no significant current dependence.

4. RESULTS

4.1 Low voltage clashing.

4.1.1 Arc characteristics.

Figure 2 shows the maximum and minimum arc durations for aluminium and copper over the full range of current at 240 Volts between conductors. As can be seen, the arc between aluminium conductors is consistently of longer duration than that between copper conductors. Ten individual clashings were performed at each current level for each type of conductor.

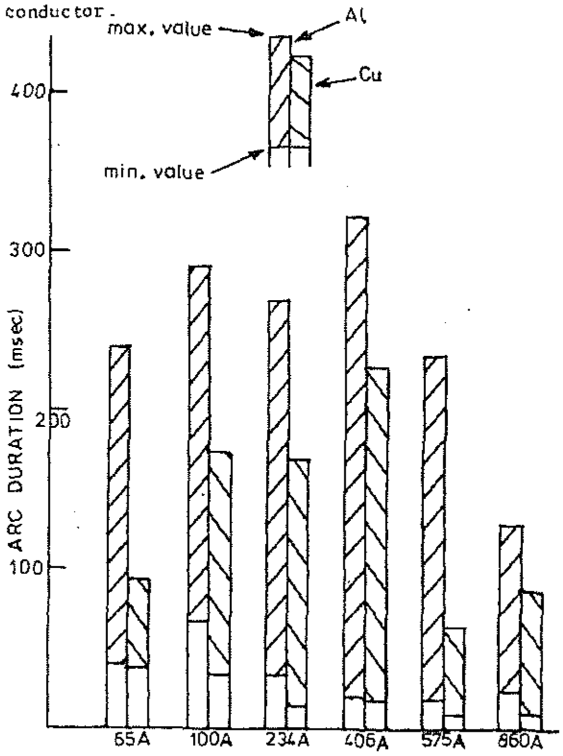

Fig. 2. Arc duration at 240 Volts for Cu and Al. Ten arcs were used at each condition.

Voltage traces during the arcing exhibit a very erratic amplitude variation, with sudden increases in voltage at various times causing a decrease in current magnitude due to the current limiting effect of the arc-circuit interaction. The arc was observed to move during each individual arcing period; only rarely did the arc anchor at one position. The erratic voltage was associated with arc movement, with sudden changes in arc voltage coinciding with sudden changes in the arc root positions on the conductors.

Table 1 shows the values of total I^2t obtained from the current waveforms at maximum arc duration for the two materials at the various current levels. These are of importance in that they will determine, for fuse protected systems, whether a particular rating of fuse will operate in the event of a clashing fault.

4.1.2 Particle emission.

Table 2 details the sizes and number of particles emitted at the various current levels. The particles have been grouped into three size allocations viz. diameter less than 0.3 mm, between 0.3 and 1.0 mm and greater than 1.0 mm. It can be seen that for both aluminium and copper, most (> 50%) of

Current/amp	Aluminium	Copper
	I^2t (Amp^2/sec)	
65	752	88
100	1 284	456
234	2 512	1 686
406	17 153	14 507
575	17 211	4 394
860	4 510	4 227

Table 1.

Total I^2t ($\int i^2dt$) from current waveforms at maximum arc duration.

the particles emitted were less than 0.3 mm at each current level. However, at the higher current levels, the aluminium conductors tend to emit more large particles while at lower currents, the copper particles tend to be larger than the aluminium. There is not a significant difference in the total number of particles emitted.

I. (amps)	d<0.3	0.3<d 1.0	d>1.0	Total Count	Largest size (mm)
65	30 (18)	25 (2)	2 (0)	57 (39)	2.0 (0.7)
100	30 (18)	18 (2)	1 (1)	38 (40)	1.7 (1.3)
234	50 (35)	5 (10)	3 (1)	58 (46)	3.0 (1.0)
406	50 (50)	12 (25)	1 (6)	63 (81)	1.5 (2.5)
575	50 (50)	30 (25)	2 (8)	82 (83)	1.8 (2.3)
860	50 (50)	40 (40)	2 (13)	92 (103)	1.7 (1.7)

Table 2.

Number and size of collected particles.

Each count is the accumulation of ten clashes for each material. d is particle diameter.
Figures for aluminium are shown in parenthesis under the corresponding figure for copper.

The various photographic records show a large number of particle tracks for aluminium conductors (e.g. Fig. 1). From the high speed film, a maximum of 88 visible aluminium particles were observed to leave the conductor during one clash, but only 50% of these were observed to reach the ground before burning up. A number of the larger incandescent particles were observed to disintegrate into smaller particles on hitting the ground. In some cases, incandescence lasted for more than one second after reaching the floor.

In contrast to the above, the photographic records for clashing with copper conductors showed apparently very few particles emitted. Thus, from the fact that the numbers do not differ greatly from those collected for aluminium, it would seem that the copper particles are at a much lower temperature than the aluminium. This is somewhat surprising in view of the respective melting points : 767°C for Al and 1083°C for Cu. However, the likelihood is that the oxidation reactions of the metals may be significantly different in terms of their energy of formation. It is known, for example (SECV 1977) that the aluminium oxidation is very exothermic.

4.2 High Voltage Clashing.

In addition to the low voltage (415V) system, where the fault currents may be quite high, clashing is also a common occurrence in 11 kV lines, although the clashing will be somewhat different in character. With the much higher voltage available, the arc length can be much longer before it extinguishes and as a consequence, the arc duration will be much increased and even though the lower fault currents give a lower rate of particle emission, the longer arc duration compensates for this. At the same time, the arc was observed to be much more stable than at low voltages. This may have been partly due to the decreased electromagnetic forces acting at the lower currents. Fig. 3 shows the maximum and minimum arcing durations for clashing at 6.6 kV for both copper and aluminium. Again, it can be seen that the arc duration for aluminium is substantially greater than for copper although there is some anomaly in the minimum values at low currents, where the difference between minimum and maximum for aluminium is very great. As expected, the arcing times are much longer than those at low voltage..

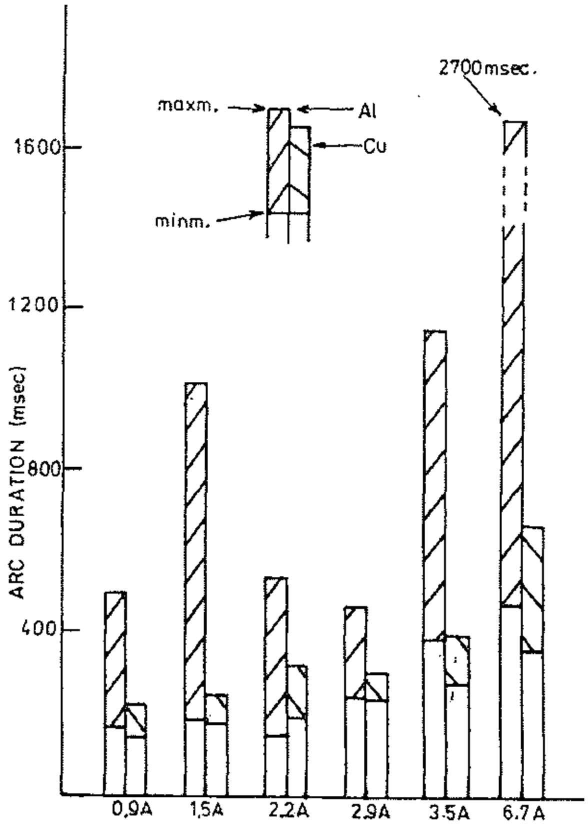

Fig. 3. Arc duration at 6.6 kV.
Maximum and minimum times are shown for Al and Cu at various current levels. Five arcs at each condition.

At the low currents there is effectively no particle emission - the only loss was by vaporisation. Because the arc is much more stable than at low voltages, the voltage trace shows a very smoothly varying nature with a steady increase in arc voltage as the arc bows upward and lengthens due to its buoyancy. There is a simultaneous decrease in current due to current limiting action. The individual voltage cycles show very well-defined ignition and extinction peaks with, in general, the copper showing considerably higher ignition and extinction voltages, as would be expected from the difference in arcing times of the two metals.

5. DISCUSSION

The arcing times of Fig. 2 acknowledge the fact that aluminium is a poor arcing material in that its low melting point promotes erosion by arcing and the fact that the resultant high vapour densities near the electrodes at current zero reduce the arc ignition voltage. As a consequence, the aluminium based arc burns for longer periods than copper, which has a significantly higher melting point and higher arc ignition voltages.

The measured arcing times and I^2t values for the clashing tests show that in most cases, fuse protection would not operate during such faults. If the clashing is repeated periodically, the preloading effect on the fuses will cause some reduction in operating I^2t values of the fuse (Turner and Turner, 1981) but the reduction relies on repeated clashing and thus cannot be expected to be reliable. Thus, it must be concluded from the measurements that fuses will be unlikely to give any reasonable degree of protection against clashing at low voltages. At high voltages, where the arc durations are much longer, the situation is somewhat different, but the cause of the increased arc duration, the long arc, also has a detrimental effect in that the arc resistance may be high enough to limit arc current sufficiently to keep the operating I^2t down to values low enough to cause fuse operation to be significantly delayed. The situation thus may approach the high resistance fault. Thus it is necessary in regions where lines are prone to clashing to design protection that will sense the fault quickly and operate to isolate the fault before damage is caused. In some cases this may require more exotic forms of protection than are generally in use in distribution systems (Aucoin and Russell, 1982).

The particle erosion measurements, which show approximately similar numbers for aluminium and copper appear to contradict the results of Wilson, who found Al losses to be much higher. However there is no real contradiction as Wilson measured a mass loss, and there is a significant burn up rate of aluminium, where the oxidation process is very exothermic and rapid. The exothermic oxidation process also produces much higher aluminium particle temperatures. There is, in fact, an increase in temperature of the aluminium after emission (SECV, 1977) whereas it appears from the optical records that the copper particles are much cooler. Thus, although similar quantities of particles may reach the ground, it is apparent that copper is a much preferred conductor for clashing because of its lesser probability of causing fire. From the experiments of SECV, (1977), it is apparent that only particles of size greater than 1 mm diameter are likely to cause ignition of flammable material.

At this stage of the experiments, it is not possible to determine how the particle production from contact separation and from arcing are apportioned in the total. The particles of most interest, i.e. greater than 1 mm diameter, show a significant increase with current, but both mechanisms would produce this result (Slade and Nahemow, 1971; Wilson, 1955). The arc motion, which increases at higher currents has the apparent result of decreasing the total emission because of the lack of concentrated heating at any particular electrode spots. However, experiments performed in our laboratories on busbar arcing indicate that while the total erosion loss is decreased, it is the vapour loss that is reduced, while the emission of large macroscopic particles may, in fact, be enhanced.

6. SUMMARY AND CONCLUSIONS

Details of the properties of arcs resulting from clashing have been presented together with details of particle emission resulting from clashing of both aluminium and copper conductors. The results show that aluminium particles represent a much more serious problem in terms of fire initiation because of their higher temperature. The arc durations and arcing I^2t values over a range of current from 65 amps to 860 amps indicate that normal fuse protection would be unlikely to operate in the event of such faults.

7. ACKNOWLEDGEMENTS

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