UNDULOID FORMATION AND CAUSATION OF CURRENT INTERRUPTION IN CURRENT-CARRYING WIRES

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I. ABSTRACT

Unduloids are a metallurgical phenomenon created by a series of molten swellings which form along the length of wires when wires carry moderate short-circuit currents in air. It is considered that melting of the reduced sections between the swellings precipitates a chain of short arcs to produce a fast rising arc voltage across the wire terminals which limits the current carried by the wire. It is, therefore, widely accepted that the formation of unduloids along current-carrying wires is the principal cause of current interruption of moderate short-circuit currents in wire fuses.

The behaviour of unduloids and the initiation of arcs along wires were investigated using medium- and high-speed video cameras. The video images show that the initial wire disintegration is caused by thermo-elastic vibrations which cause a single break to occur, predominantly, close to one of the ends of the wire and that the break occurs before unduloids form.

Correlation of the video images confirms that classical multiple arcing, in the spaces between all swellings, does not occur, which corresponds with the, relatively, poor current-interruption capacity of this class of wire fuse.

II. INTRODUCTION

The first known experimental investigations into melting of current carrying wires was undertaken by Nairne[1,2], who reported on how wires on 'passing electrical fire', 'melted into red hot balls'. This, hence, was the first reported observation of unduloid-related disruption of current in wires.

Much later observations of unduloid type formation in wires focused on the causation of unduloids and on the current disruption process. Unduloids were considered early on to be caused by surface tension forces acting on the molten wire[3] and, subsequently, it was proposed [4] that unduloid formation was caused by a combination of surface tension and electromagnetic pinch forces. Unduloid formation was later shown to be dependant on wire surface melting - this being a consequence of temperature variation across the wire section due to electromagnetic pinch forces[5]. Magneto-thermo viscous elastic vibrations, produced by the current flow in wires, were also proposed as the cause of unduloid formation[6].

Later observers of disintegration in wires indicated that the occurrence of unduloid formation was inconsistent. Consequently current density [5][7], wire diameter[7], metallurgical conditioning[8][9][10] and wire material properties[11], were all proposed as contributory influences on unduloid formation.

Currently, it is accepted that unduloid formation is associated with moderate current densities, typical of high overloads or low short circuit fault currents in the range 3~5In, corresponding to pre-arcing times in the range 30~300ms. The profile of the temperature distribution along medium and long wires, for these conditions, is virtually constant and wire surroundings and terminal cooling are thought to have insignificant influence on the cooling of wires and hence, on the current disruption process. Unduloids are considered, therefore, to form when the wire's surface is molten but the wire is not fully molten at its centre. Consequently, surface tension, allied with electromagnetic pinch force effects or wave motion, is accepted to be the primary phenomena causing the transition in wires from an unstable liquefied cylinder state to that of a chain of stable spheroids.

Investigations have also been undertaken into the voltage waveforms developed between the wire terminals as a result of the unduloid formation phenomena[4][12][13]. These studies indicated that as unduloids form, melting occurs at points between the spheroids at which short arcs subsequently ignite to create a series chain of arcs. It is considered that an arc voltage, equal to the sum of the individual arc voltage falls, appears across the wire terminals to aid current limiting[14]. Hence, it is commonly thought by many that unduloid formation is a significant current interruption mechanism.

III. EXPERIMENTAL TECHNIQUE

Investigations into conductor disintegration were carried out on silver wires of different orientations in air. The wires were 60mm long by 0.2032mm diameter. The test currents were supplied from a 50 Hz, 200 volt, 14.5 amp rated alternator. The test circuit comprised a thyristor 'crow-bar' switch across the test wire sample terminals. The test arrangement was capable of being accurately switched to enable fault current to flow in the test samples for precise time periods to enable observations of the formation of unduloids, wire disintegration and the initiation of arc ignitions along wires.

Visual observations of disintegrating wires were recorded using standard video (25 frames/s) and fast video (2000 frames/s) cameras. Visual images were stored and viewed using standard magnetic tape and 625 line, 50 field video monitor methods.

Static time-sequence images were acquired from video tape recordings using commercially available video-PC interface hardware and software image capture packages.

IV. VISUAL OBSERVATIONS

IV.1 Wire End/Terminal Effects

The precise control of the joulean energy released in the wire samples enabled visual image capture of the development of unduloids and the instances at which arcs ignite. Figure IV.Ia shows the captured image of unduloid wire melting and the effects of cooling of the wire close to the wire terminal. The image also shows that the axial deformation of the wire in the vicinity of the wire terminal is minimal and that no unduloids occur in the cooled part of the wire.

Figure IV.Ia Observed Cooling Terminal End Effects

IV.2 Unduloid Formation

The unduloids observed along most of the wire length were, in general, evenly spaced and of uniform size, figs. IV.2a, IV.2b. The average separation distance between unduloids (λ), was found, in all cases, to comply closely with Nasilowski's [13] empirical relation (eq. 1).

$$\lambda_{\text{unduloid}} = \frac{16}{3} d \qquad \text{(eq. 1)}$$

The observations indicated that unduloids are numerous and take on the appearance of a string of pearls. Furthermore, if the current is diverted away from the wire just following the formation of unduloids, the main part of the wire comprising fully-formed unduloids becomes catenary in form.

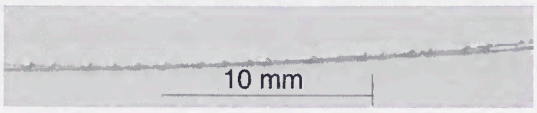

Figure IV.2a Enlarged Image of Unduloid Formation in Wire

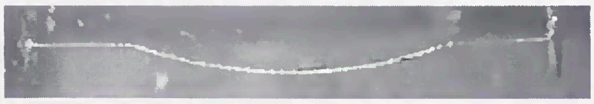

Figure IV.2b Catenary Shape of Wire Section comprising Unduloids,

IV.3 Wave Motion.

Observation of video sequences of the entire period of current melting and disruption showed that rapid expansion of the wire occurred due to thermal expansion. The video recordings also showed that the wires vibrated vigorously, figures IV.3a,b,c. and that during disintegration the wire remnants were seen to be expulsed also vigorously from the points along wires where arc ignition occurred, fig. IV.3d.

Figure IV.3a Current-Carrying Catenary 80ms after Current Injection

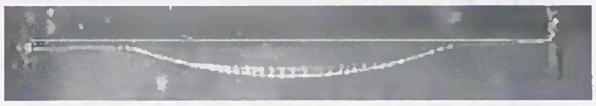

Figure IV.3b Current Carrying Catenary Showing Thermo-elastic Vibrations, 120 ms after Current injection.

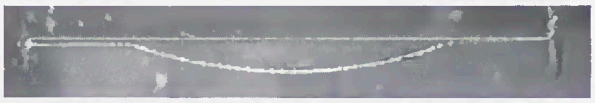

Figure IV.3c Catenary following Current 'Crow-Barring'.

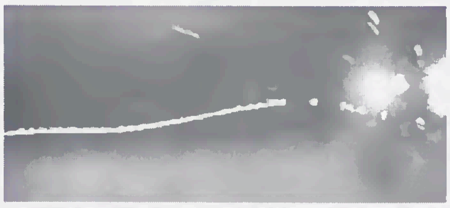

Figure IV.3d Expulsion Wire Remnants at the Instant of Arc Initiation

V. DISCUSSIONS

Surface tension forces acting on the partially-melted surface of sections of wire conductors is not disputed as the primary cause of the occurrence of unduloids in current-carrying conductors. It is reasonable to conclude from the observed vibrations, fig.IV.3b., however, that thermo-elastic vibrations also have a role in the initial unduloid formation process.

The observed uniform formation of unduloids along most of the wire length and the, subsequent, catenary form wires take, fig. IV.2b, supports the notion that the catenary part of the wire is mostly molten and that the temperature of the catenary portion of the wire is, virtually, constant. The deformation in the wire at its ends and the existence of only partially formed unduloids, fig. IV.1a, indicate that a large temperature gradient exists in the regions in the vicinity of the ends of the catenary and that these regions must be more solid in state. It is reasonable to conclude, therefore, that the ends of the catenary, i.e. the points where the wire starts to bend, must also be molten-solid interfaces.

The accepted notion that arc initiation occurs in a gap between unduloids is disputed. Firstly, it can be seen, figures Vb,d, that arc ignitions occur prior to the formation of unduloids. Consquentally, it is reasonable to conclude that the mechanical shear stress, due to rapid thermo-elastic vibrations, is greatest at the solid-molten interface and, hence, wire breakage will, and does, occur at this point first.

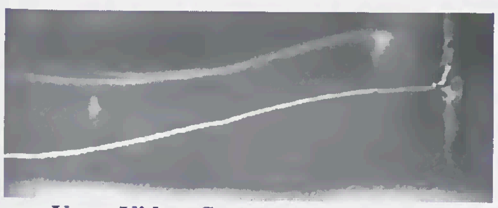

Figure V.a Video Sequence Image of Current Carrying Catenary 90ms after Current Injection

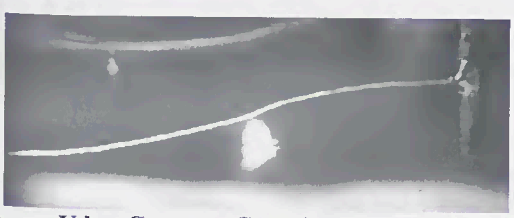

Figure V.b Current Carrying Catenary 130ms after Current Injection Showing a Single Arc Ignition before Unduloid Formation

Figure V.c Non-Current Carrying Catenary - 40ms after Arc Ignition

Figure V.d Current Carrying Catenary 130ms after Current Injection Showing Arc Ignitions before Unduloid Formation

Figure V.e Non-Current Carrying Catenary - 40 ms after Arc Ignition again Showing Minimal Unduloid Formation

Figure V.f Non-Current Carrying Catenary - 80 ms after Arc Ignition Showing the Initial Formation of Unduloids

The images that show arc ignitions can occur prior to unduloid formation, figs V.b,d, reinforce the notion that wire breakage, due to thermo-elastic vibrations, is the cause of wire disintegration and, therefore, current-interruption in wires.

The video sequence images show a whip-like action occurs following breakage of the wire which rapidly parts the wire from a fixed end. The rapid whip-like parting basically breaks the circuit and prevents further arc ignitions along the wire. The circuit current has ceased, therefore, prior to unduloids becoming fully formed and, hence, the assumed classical multiple arc formation is not possible. The images confirm that only between 1~3 arcs ignite during current interruption.

The presented observations also eliminate the influence of electromagnetic pinch forces as a significant influence on unduloid formation, since from figures Vc,e,f unduloids continue to form after current interruption occurs.

VI. CONCLUSIONS

From the video-captured images and observations presented in this paper, it is proposed that current interruption, in the presence or non-presence of unduloids in wires, is caused by thermo-elastic induced wave motion acting at a molten-solid discontinuity or fulcrum point, close to one of the ends of wires. Current-interruption is, therefore, caused, fundamentally, by end cooling of current-carrying wires and the whipping action of the wire due to rapid thermo-elastic induced vibrations and unduloid formation is, at most, only a secondary influence on current interruption in wire fuses.

The presented observations show why the establishment of so-called multiple arcs, induced by unduloid formation, is not possible.

Finally, the occurrence of unduloids following current disruption, rules out electro-magnetic forces as a significant influence on the production of unduloids.

VII. REFERENCES

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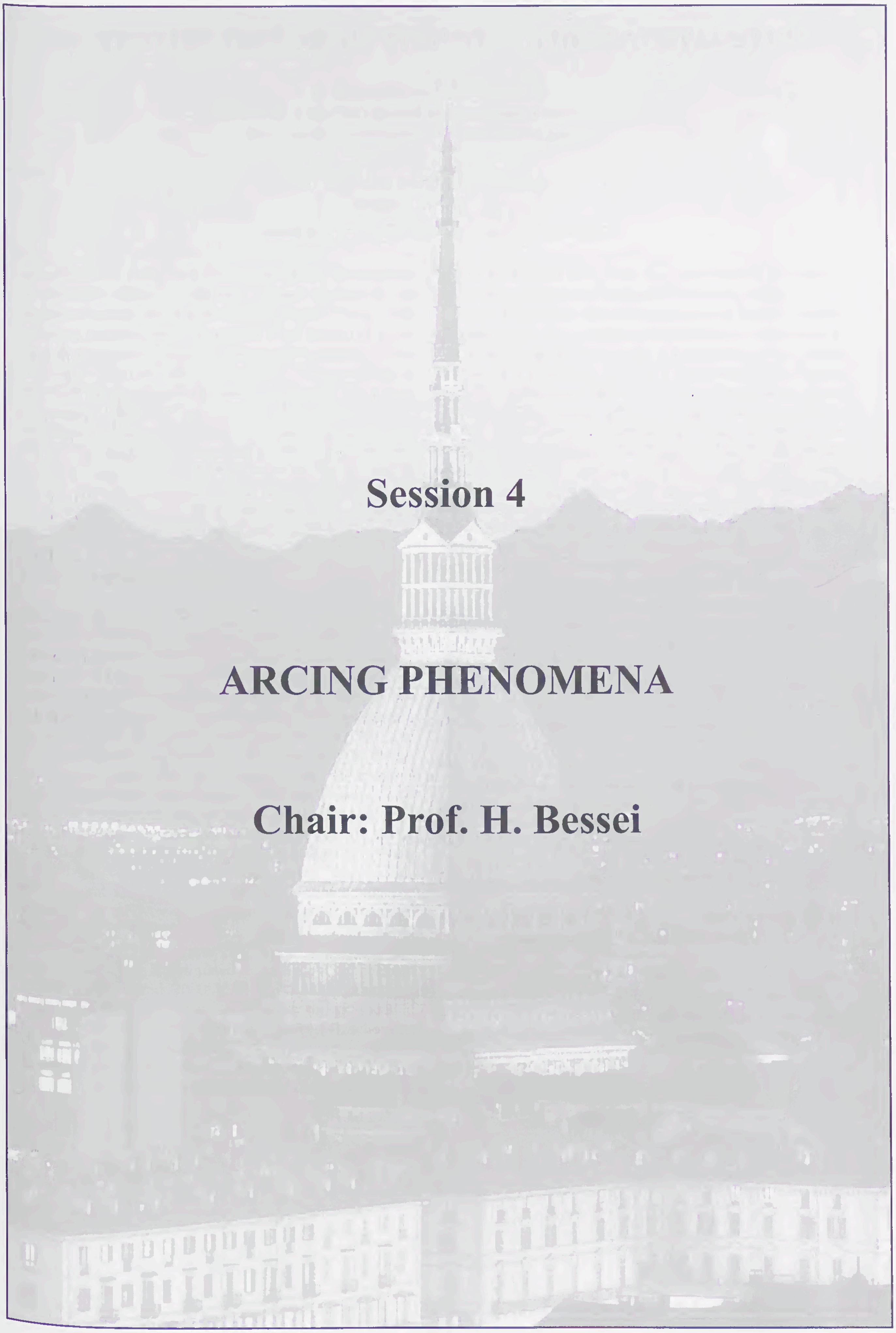

Session 4

ARCING PHENOMENA

Chair: Prof. H. Bessei