RECENT ADVANCES IN FUSE TECHNOLOGY

By C Turner

INTRODUCTION

The subject of fuses remains a lively one in the technical world, and it is interesting to consider developments and changes since our last meeting in 1984. These changes and developments may be due to a shift in emphasis, because of the developments in other areas, in particular the growth in automation and electronic control of processes in industry and the enormous expansion of home electronics and computers, or they may be related to the greater importance given to safety and reliability of electrical supplies and circuits, as witnessed by the developments and improvements in Standards and Regulations.

In the last meeting the papers were classified into sessions dealing with:

Pre-arcing and temperature rise
Disruption and arcing phenomena
Protection and co-ordination problems
Applications and developments
Tests and Standards
Models of fuse behaviour
Ageing and deterioration.

The shift in emphasis during the three years can be seen from the subjects for the different sessions in the present Conference, in particular the separate session on miniature fuses, related to the expanding field of electronics and low voltage circuits. During the past three years there have been at least 1400 papers worthy of note in the field of protective devices (1), and so it has been necessary to make some selection for this presentation.

It seemed most useful to me therefore, to relate the information published during the last three years to the subjects covered in the sessions of the present meeting. These published papers include the nine papers in the Lodz Conference, which is the only other Conference specifically concerned with fuse operation.

PRE-ARCING PHENOMENA

A number of papers have been published in this period dealing with pre-arcing phenomena of various designs and types of fuses, for instance the low watts-losses required of 500 V supply fuses, to obtain the necessary low temperature rise in consumer units (2); or measurements of the heat loss mechanism of fine wire fuses in vacuum or in air (3), showing that operating power has to be derated considerably for a vacuum fuse compared to a wire fuse sealed in air in a small tube.

Cyclic loading of fuses, which may cause premature operation, has been investigated (4) and related to the shape of the tape elements. The importance of heat dissipation and uniform current distribution in preventing tensile rupture forces is stressed, for elements which have bent shapes in air. When elements are embedded in sand, cycling stability is greatly improved, because of improved heat dissipation, uniform current distribution between elements and prevention of direct tensile rupture forces. There is no corresponding improvement in stability when straight elements are used.

A new controversial theory of current density distribution in a wire during electrical explosion is proposed (5), calculated from the effect of a single dc pulse. It is suggested that the current increases more rapidly in the non-inductive axial area of the wire, so that initially current density is greater in the centre than on the surface, but as the current also decreases more rapidly in the centre, the current density during current fall is smaller in the axis than on the surface. This 'skin effect' is an instantaneous process governed by fluctuations in the circuit current.

Temperature measurements for thin-film fuses of single layers of silver on silica or alumina substrates are reported (6) using a special transient thermography method to study the behaviour under ac and pulsed conditions. This study is a continuation of the work discussed in Trondheim. Important differences for the two substrates are shown up, in particular a much lower temperature rise for alumina substrate in pre-arcing conditions.

The papers in the present conference show that the above problems continue to occupy a place in fuse investigations, in particular with regard to the possibility of more accurate calculations and modelling methods.

ARCING AND DISRUPTING PHENOMENA

The operation of fuse-links under various environmental and circuit conditions remains one of the main topics of investigation, as this is directly related to their co-ordination with other protective and control devices, their ability to protect various circuits and equipment and the safety of personnel. It is therefore not surprising that a substantial number of publications on this subject has been produced both during the period between this meeting and the Trondheim meeting, and at the present meeting itself.

I will give a short resume of the most interesting papers produced in the last three years.

The exploding foil (7,8) is probably not directly relevant to this conference, but the methods employed in modelling of the phenomena prior to and during vaporisation would equally apply to the operation of more conventional fuses under high short circuit conditions. Two models are used, one based upon observation of the fractional increase in resistance of the foil on vaporisation, which is determined by the energy per unit mass supplied to the foil by ohmic heating; the other model using tables of specific energy, pressure and resistivity to compute the ohmic heating, translation and expansion of the exploding foil. The effects of filler material are included in the model.

The phenomena in the corona of an exploded wire have been investigated (9) with time-resolved X-rays, showing that the development of constrictions in the corona is preceded by the appearance of superheated ring-shaped structures.

Exploding wires remain a subject of some interest. Several papers have been published on this subject, for instance in the Gas Discharge Conference in October 1985 (10,11).

Optical and electrical investigations of a wire with a single neck (10), subjected to a slow energy input show up a series of voltage peaks due to partial explosions causing microscopic arcs. If the initial energy is increased, the number of partial explosions is increased correspondingly. The spherical shock waves from these partial explosions produce a cylindrical shock wave. The generation of a heavy current arc depends upon the way the partial explosions occur. In the vaporisation stage, a cylindrical phase of heated air appears, which assists in the promotion of a shock wave consisting of cylindrical wavelets.

The literature on the pressures produced by heavy current interruption in an hrc fuse is reviewed (11). Two phases of the generated pressure are considered: The explosion of the element producing a sudden pressure elevation, followed by subsequent burn-back producing a slow pressure rise.

For more conventional fuses, a model hrc fuse has been used (12) with a copper wire element and sand filler, to investigate the pressure on the wall and its movement through the sand filler and the change with time after element interruption. The shock waves in air, due to the disruption of a copper wire have been investigated (13), where partial disintegration due to a slow energy input rate produces microscopic arcs, and spherical shock waves which have a cylindrical envelope. The process is analysed theoretically using Taylor's flow equations. The radial distribution of the pressure and particle velocities behind the shock waves are related to specific heat and gas temperature.

A theoretical, computational and experimental study of the factors which govern the arcing I^2t integral of current-limiting fuses has been made (14). These include the effect of closing angle and the influence of test voltage. It is shown how the values obtained at one voltage should be corrected for application at different test voltages. The electrical and dimensional parameters of hrc fuses have been correlated with the arc energy at short-circuit interruption (15). Model tests are used to measure and analyse the internal pressure due to arcing and vaporisation of the element. It is shown that the pressure is related to the element material, size and shape of the fuse, rather than the arc energy.

The arc voltage for interruption of a uniform copper element in sand has been related to the resistivity of the element material, its length and cross section (16) using a method of calculation in which the average voltage for a single interruption is determined by division of the total voltage by the number of arcs in series. This number is determined from the striations observed in the fulgurite. The disintegration modulus is defined as the distance between consecutive striations, and is proportional to the cross sectional area to a power 0.3. The theoretical results differ by about 20% from the experimental data.

Copper elements with necks in sand have been subjected to short circuits (17) to obtain experimental relations between arcing I^2t and number of necks. It is shown that for a number larger than 7 the dependence is a weak one.

The effect of element material on the arcing process in sand-filled fuses has been investigated (18) using copper, aluminium and silver elements with a single neck. It was found that arc quenching deteriorates with increase in thickness, arc energy increases, length of element consumed increases and the maximum pressure on the fuse body increases. For less than 0.15 mm thickness, it is shown that arc extinction is better for copper than for silver, while aluminium is better than both. An increase in width increases arc time, arc energy and arc integral, but not length of element consumed. Cut-off potential decreases with increased width. Expressions are obtained to relate energy liberated in the arc to thickness, width and length consumed.

DEVELOPMENT AND DESIGN ASPECTS

The great advances made in computers and the fact that computer modelling is now much more widely available have been reflected in the developments in fuse design. It is now feasible to investigate fundamental changes in parameters and their likely effects on fuse operation without the need for extensive and costly manufacturing and testing, although eventual likely designs obviously still require to be made and tested.

A number of new developments have appeared, some of which were already mentioned in Trondheim, but have been developed further into higher ratings, like the Fullran fuse (19).

A fast-acting high capacity current limiting fuse has been developed by using direct forced cooling of the fusible tubular element (20). Several coolants were investigated but water was found to be the most effective. The design can be incorporated into both ac and dc high voltage current limiters for the protection of thyristors in ac/dc substations. Other high voltage fuse developments include the cadmium element high voltage fuse-link (21) which can be constructed with concentric elements for high ratings, as the elements do not require support, as opposed to silver elements which need a core.

A general analysis of the design of fuses on the basis of optimisation and identification theories has been given (22), in which the principle of maximum and non-linear programming methods is developed. Step-by-step approximations are sometimes necessary to approach the optimum design.

A special design for interruption of dc high voltage current has been developed (23) using a composite resistance commutator system with three parallel circuits: an electrode, normally passing current; a high voltage generating fusing element; and an energy dissipating non-linear resistance. High voltage interruption is obtained by using a multi-stage fusing element. High current is interrupted by having an additional gap in series with the fuse.

A special electromigration fuse is used for protection at the other end of the spectrum (24) for electronic components, utilising the heat generated in the component when it enters a runaway condition to increase electromigration in a constriction to create high resistance or open circuit.

A high interrupting capacity, low deterioration, small dimension high voltage vacuum fuse has been developed (25). These properties are achieved by application of an axial magnetic field during arcing, and structural arrangements to provide power dissipation when carrying current. The element is copper, with copper arcing electrodes in a ceramic barrel, together with a magnetic field generating coil. The fuse can have general purpose or motor protection characteristics.

Further developments in the self-restoring fuse field include experiments on various dielectric inserts and different liquid metals (26). These include quartz glass, corundum, steatite, cordierite and beryllium oxide in conjunction with the eutectic of indium, gallium and lead, a potassium-sodium alloy and pure sodium.

A further development of the two-part fuse already described in Trondheim has a long arcing element in sand in parallel with a short main element in air (27). The period of switch-over of the current from the main element to the arcing element is of particular importance, and this can be related to the time current characteristics of the two parts. Special problems still exist for the application of the principle to high voltage fuses, but for low voltage fuses it is now feasible and has a number of advantages.

New devices for interruption of high-voltage faults are being developed, for instance the 'electronic fuse' (28) consisting of an electronic control module providing a large selection of time-current characteristics and the energy to initiate interruption, and an interrupting module which carries the current normally and interrupts when a fault occurs. The control module is re-usable. The interrupting module consists of a main current carrying section and a current-limiting section in parallel. Both elements are copper in sand.

Improvements in element design, shape and materials, as well as improvements in filler have been made (29). These include the use of aluminium elements, and improvements in thermal conductivity of the filler by means of binding agents. Gas-evolving materials on the core or on the elements provide arc control.

New developments in thermal fuses (30) include new alloys which can be used for intermediate currents between the organic chemical compounds used for large currents and the low melting point alloys used for low currents.

AGEING AND M-EFFECT

The problems of ageing of fuses, and in particular the influence of M-effect materials continues to be of interest. A number of papers have been published, dealing with this subject, and with tests to determine the physical processes involved. A general survey of these processes has been published (31), in which diffusion, temperature and the effect of shape and material of the M-effect pill on the time-current characteristic are dealt with as well as the shape and material of the element, and the position of the pill in relation to necks.

Ageing of copper elements with or without M-effect for elements with or without constrictions, when subject to current cycling has been investigated (32), using a model fuse element in air, with Sn or Sn/Pb 60/40 as the M-effect material. A number of regions of cyclic loading are considered: For relatively low currents and long periods of current carrying, the diffusion of the solder into the element has the most effect, but for higher currents and shorter periods the melting point of the solder becomes more important. Without M-effect, the ageing is due to oxidation and grain growth at the constrictions. This is a relatively slow process. For elements with both M-effect and constrictions both mechanisms take place, dependent upon current and duration of cycle. At high currents and short durations the neck-ageing mechanism is prominent, but at low currents and long cycles the diffusion process predominates.

Long-time behaviour of Al and Cu fuse-links with various M-effect materials has been investigated (33) with the aim of producing fuses with low loss and low temperature rise, by making the shape and size of the element such that the reaction temperature needed for operation lies only slightly above the melting point of the M-effect material.

Ageing of fuse contacts has also been considered (34). Investigations into the resistance of fuse-links with silver-plated, nickel-plated and tinned contacts at high environmental temperatures on no load, show that silver-plated contacts retain a low contact resistance even after long periods of slow temperature cycling, while the resistance of nickel-plated or tinned contacts tends to rise.

MINIATURE FUSES

The main developments in miniature fuse design have been concerned with thin film or thick film fuses for use in electronic circuits. High-speed thick-film fuses have been developed (35) compatible with modern assembly procedures in electronic systems at low voltage and low current. Three-layer co-fired thick-film fuses are capable of very high speed protection. They can be incorporated in a total circuit, or made as surface-mounted chip components. Semiconductor protection can be closely controlled by using a metal film (36) applied to an insulating backing.

The number of publications in this field has been very limited, and there is scope for further development.

STANDARDISATION

In standardisation of low voltage fuses 1986 marked a major advance in the issue of a world standard, containing a single band of characteristics for all general purpose fuse-links, offering discrimination world-wide on a ratio of rated currents of 1:1.6. This standard, IEC Publications 269-1 and 269-2, is a major advance on all previous standards. This advance ensures a uniformity of performance throughout the world, which has the practical advantage that any item of electrical equipment designed to be protected by a given fuse rating in the country of manufacture will now be equally well protected by the local product if it complies with IEC Publication 269.

In the North American Continent it is difficult to exploit this satisfactory situation because of the independent line of reasoning followed by those who establish the testing requirements of the Underwriters Laboratories, which are completely out of line with those of the rest of the world in certain fundamental aspects. Not least of these is the basis of rating, which results in an IEC rating approximately 80% of the UL rating for identical fuse-links.

In the case of miniature fuse-links, a concerted attempt was made to resolve this ridiculous situation and agreement was achieved on the technical plane with a universally accepted compromise solution. Unfortunately, this technical agreement could not be translated into practice, because of administrative and political obstacles.

A completely new type of miniature fuse-link called the 'Universal Modular Fuse' (UMF) is being developed and a framework of standards is being created to accommodate it. This new concept is designed for use in conjunction with the new technology associated with solid state circuits, which have now largely replaced the electronic circuits for which the original miniature fuse-links were designed. The UMF takes into account the lower voltages at which such circuits normally operate and seeks to accommodate the requirements of automatic insertion of fuse-links into PCB's. These developments have the potential to completely revolutionise the field of miniature fuse technology.

In the standardisation of high voltage fuses, the third edition of Publication 282-1 was issued, representing an advance over previous editions and incorporating Amendments introduced since the 1974 2nd edition. The on-going problem of the definition of a general-purpose/full-range fuse, as opposed to a back-up/high-minimum-breaking-current fuse is again seeking resolution, stimulated by recent developments in the technology of fuse design in this field. There are proposals for reducing the energy required in testing to Test Duty 3 by the use of a 'two power factor' method. There are also new proposals on waterproof testing, energy delivered by strikers, switching voltages of fuse-links of small current rating and simplification of the homogeneous series rules.

APPLICATION ASPECTS

One of the most widely considered fields of study for fuses is still their application, as the range of applications changes towards the protection of more and more complicated electronic circuits and towards ever closer protection of devices and circuit components.

In the field of semi-conductor protection, very fast-acting current limiting fuses are necessary, and various solutions have been investigated (37), for instance flat pack fuses with water cooling, which can carry high currents, and which have low let-through I^2t for protection of large medium voltage semiconductors. Conditions and circuits are very varied, and a useful guide for selection of fuses for typical circuits has been provided (38).

Transformer protection has been improved in various ways. One solution to the problem of surges from fuse operation causing damage to the transformer (39), is to use expulsion fuses and metal oxide arresters. A special device for transformer protection (40) uses a disposable single-phase fault thrower mounted within the high voltage cable entry of the transformer, operated by a chemical actuator fed by a resistor circuit, using time-limit fuses for time grading. Another possible solution is to use an expulsion fuse backed by a current-limiting fuse in one envelope. Expulsion fuses have been improved by using replaceable elements and increasing their breaking capacity (41).

Protection of motors and co-ordination with other protective devices has been improved by the design of special fuses for motor circuits (42), and by using permanent power fuses in cascade protection of mccb's (43). The necessity for derating fuses for use in SF6-gas insulated tanks (44) has been shown.

Computer programs can now be used to calculate co-ordination of operating and tripping characteristics of breakers and fuses in series (45), and for determining the optimum economic selection of cable sizes and fusing (46).

Special internal fuses have been designed for internal protection of capacitors (47).

The above selection of publications is by no means exhaustive, but is merely an indication of the wide variety of fuse applications, and the particular problems associated with them.

FUTURE DEVELOPMENTS

After this short survey of the main publications on fuses during the last three years, the questions of future developments remains. It seems to me that the task of the present conference is to show the way to further improvements and developments in the fuse field. The particular directions to be followed should be formulated at the end of the conference, when it will hopefully have become clear in which directions our efforts should be concentrated to ensure the continued improvement in fuse protection and application.

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Session I

PRE-ARCING PHENOMENA 1

Chairman: Prof. Dr. M. Lindmayer