THE QUALITY ASPECTS OF H.V. CURRENT-LIMITING FUSE PROTECTION

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1. INTRODUCTION. The increase in demand on supply systems and the increase in density of both population and load in urban areas has brought members of the public into closer proximity with items of distribution systems plant such as transformers and switchgear. The safe working of such plant and effective and reliable protection is now, more than ever before, of the highest importance.

High voltage current-limiting fuse-links are now the normal means for protecting distribution transformers from short circuit currents and in combination with suitable switchgear provide protection against the full spectrum of fault currents. Increasing use of h.v. c-l fuse-links is being made for the protection of motor circuits up to 11kV in combination with air breal or vacuum contactors.

In both the fuse-switch and fuse-contactor combinations advantage is taken of the fuse performance, i.e. the limitation of peak current and I^2t to reduce the size of the switchgear contacts and conductors and consequently the operating mechanism, allowing a more compact, lighter and cheaper package without any loss of breaking capacity, on the contrary, fused equipments have breaking capacities that would be difficult and certainly expensive to achieve with circuit breakers.

Modern usage demands not only that the performance of the fuse-links, as demonstrated by type tests, be of a high order and compatible with associated equipment, but that the performance of every similar fuse-link be consistent and in accordance with the published data, except as modified by the effect of enclosure or abnormal ambient temperature.

To achieve the necessary conformity in performance, the quality of materials, the methods of manufacture and the testing and inspection must, at all times, be under strict control. To achieve satisfactory service, the methods and rules of application must be well founded and reliable.

The paper discusses the above requirements in more detail.

2. QUALITY OF PERFORMANCE. The primary requirement for a c-l fuse is breaking capacity for the range of currents dictated by its type. For a back-up type all currents between the nominated minimum breaking current and its rated breaking current must be broken without external manifestation. For the general purpose type the range extends, for practical purposes, from that current which causes melting in one hour up to the rated breaking current.

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It is a relatively simple matter to obtain clearance of high values of current and simple element designs will provide the capability, but the quality of performance may be measured by examination of the transient values of current and voltage at the instant of commencement of, and during, the period of arcing. Other aspects of performance during normal current carrying conditions and under fault conditions, before and after melting, can be assessed quantitatively from data obtained by calculation and test.

2.1. Current Carrying. The fuse-link must be capable of continuously carrying the normal load current, permissible overloads and transient currents of the circuit in which it is installed. Depending on the nature of the installation, temperature rise may be of considerable importance and derating of the fuse-link is sometimes necessary where circulation of the ambient air (or liquid) is prevented or restricted. Clearly then, for a given fuse-link, the lower the temperature rise when carrying rated current the better.

2.2. Fault Conditions - Pre-arcing Period. The requirements for the shape of the time-current curve depend on the application and these requirements are quite different between the two most common applications, namely, distribution transformers and induction motors started direct-on-line.

Fuses used in the above applications are not normally used as overload protection, thus consideration of the shape of the time-current curve may be restricted to a range of times from 0.1 seconds to, say, 100 seconds.

For transformer protection the requirements are:

a. That the 0.1 second melting current should be great enough to ensure that magnetising inrush currents are withstood without damage and that discrimination with the secondary fuses or other protection is achieved.

b. For times from, say, 10 seconds up to 100 seconds, the corresponding values of current should be low enough to provide adequately fast clearance of restricted values of fault current such as result from interturn faults on the h.v. winding or secondary earth faults ahead of the secondary protection which may be of limited magnitude due to the effects of arc resistance.

The foregoing considerations dictate that for the range of times nominated the time-current curve should have a "shallow slope".

Consideration of the requirements for capacitor unit fuses, namely, the ability to withstand inrush currents and the ability to disconnect faulted units where the fault current may be restricted due to unearthed star connection or series connected units as quickly as possible also lead to the conclusion that a "shallow" time-current curve is required.

For motor protection the requirements are different, namely,
a) The 0.1 second current should be low enough to provide rapid clearance of fault currents. Where the highest fault currents occur, such as with terminal box flashovers, the clearance should be as fast as possible to prevent disruptive failure.

b) For times in the range of motor run up times, say, 6 to 60 seconds, the melting current should be as high as possible so that starting current is exceeded by sufficient margin.

These requirements indicate the desirability of the time-current curve having a "steep" slope over the range of times considered.

Fig.1. shows time-current curves of practical fuses. The transformer fuse curve shown is one which employs a hybrid type element (British Patent 1294085), designed to give a very shallow characteristic. Other alternative element designs are now becoming available to give moderately fast clearance of mid zone faults.

For limited fault currents, where melting times of many minutes are involved, the temperature which the fuse barrel and endcaps achieve is important. If no control is placed on these temperatures the insulation of switchgear can be damaged and also the fuse barrel may not survive the high temperatures achieved since the fuse elements, normally of silver, must reach a temperature of 960°C before melting occurs. The temperature can be limited by the well known Metcalf effect where a tin bearing low melting point alloy is deposited on the elements and which creates a eutectic effect with the silver elements and limits the element temperature to values lower than 300°C. This consequently limits the temperature attained by the fuse barrel.

2.3. Fault Conditions - Arcing Period. A typical oscillogram of a fuse-link breaking a high value of current is shown in Fig.2.

The salient features of the fuse operation are:

a) The cut-off current. Note that the peak value is quoted. Clearly the lower this value is kept the better since the cut-off current determines the mechanical forces that will be developed between switchgear contacts, cable cores, etc.

b) The I^2t Value. This is the total value of $\int i^2 dt$ over the pre-arcing and arcing periods. This value determines the heating effect of the fault current in the conductors and the amount of damage sustained at the seat of the fault. In certain applications it may be critical in determining the safety of a transformer tank where large volumes of gas are evolved by the fault arcs. (See Section 5). It can be shown that with the type of fuse element used in the fuse from which the oscillogram of Fig.4. was obtained, and which uses deep notch elements that the total I^2t passed by the fuse is less than the pre-arcing I^2t of the unnotched part of the strip. In other words, after arcing commences at each of the restricted sections or notches of the elements, the bulk of the element is burned back by the arcs and not by I^2r heating.

c) Arc Voltage. This stresses the system insulation and is therefore subject to limitation by the various specifications. As shown in Fig.2. the fuse tested gave a peak value of arc voltage limited to approximately 2.25 times the voltage rating of the fuse. Also important is the variation of arc voltage with recovery voltage, since it is this that determines the advisability of using fuse-links in circuits of voltage rating less than that of fuse-links. Fig.3. shows the variation of arc voltage with recovery voltage for fuses of the type under consideration. This curve is supported by Figs.4 and 5, which show oscillograms obtained from identical fuses tested at rated voltage and half of rated voltage respectively, but with all other conditions identical. The arc voltage measured for the 50% recovery voltage test was 59% of that for the 100% recovery voltage test.

2.4. Minimum Breaking Current. In many cases overseas, h.v. fuse-links are applied in such a way that their performance under restricted fault current conditions assumes a high degree of importance. This arises where the fuse-link is used without associated switchgear or where the switchgear is not automatically tripped by a fuse-link striker or where there is a deliberate time delay in the tripping operation. While not in practice always requiring general purpose fuses, low values of minimum breaking current are required. Experience has been that satisfactory service is obtained in many situations where the minimum breaking current is 2 to 2.5 times the fuse-link rated current. Fig.6. shows the breaking of 170 amps by a 15.5kV, 100 amp fuse-link at the end of a 1 hour test.

3. QUALITY AND QUALITY CONTROL IN MANUFACTURE.

The nature of a fuse-link inherently prevents complete testing on a routine basis since it is a one operation device. Controls are therefore necessary on the consistency of materials and manufacture to guarantee that all the fuse-links will provide the performance demonstrated by type tests.

3.1. Materials. Clear unequivocal specifications and drawings are necessary which are agreed between the supplier (whether in house or external) and the engineering department responsible.

Incoming goods are subject to inspection and test on a 100% basis or by suitable sampling. Measurement of compliance with specification may, for some materials, involve special tests, e.g. chemical and grading analysis of sand used as the filler, bursting strength and porosity tests of ceramic bodies.

Where non-critical dimensions or other features fail to meet those specified but a relaxation may be allowed, there is a concessionary procedure to maintain control and ensure consistency of decisions.

Duplicate sets of gauges, where one set is held by the supplier are used.

3.2. Manufacture. It is essential that each and every operator be entirely clear on the methods to be used and standards to be achieved in his or her area of responsibility. Adequate training is given and concise written instructions are provided.

Any changes in methods, machines or parts are preceded by appropriate training and modifications to written procedure specifications.

3.3. Inspection and Tests. Work in progress inspection is ensured jointly by patrol inspection and engendering a responsible self-inspection approach by operators. Concise written standards are provided for inspectors and others to work to.

In the case of the fuse-links discussed in this paper, the following inspections and tests are made on a 100% basis.

Resistance Checks. Every fuse-link has two resistance measurements made and for each, compliance with design values is necessary. Resistance tolerances are based on dimensional tolerances achievable in the manufacture of element material. The first measurement is made when the element assembly is inserted into the barrel. At this point, the fuse-link is assigned a serial number and the measured resistance value is logged against that serial number. Later, when the fuse-link is complete, the resistance is again measured as part of the final inspection and the value again logged adjacent to the previously measured value so that an immediate comparison is made. Discrepancies between the two values, other than those arising from temperature difference and normal errors of measurement, are not permissible.

Tests of Seals. Most fuse-links are required to be sealed against the ingress of moisture or oil. In the case of fuse-links to be used in air, compression type seals are used and these are tested by immersing the fuse-link in water at a temperature of approximately 85°C. The air contained between the grains of sand occupies approximately 35% of the internal volume of the fuse and creates an internal pressure which searches the seals. Leaks are observed by the escape of bubbles.

For fuse-links intended for use immersed in oil two seals in series are used, firstly, a compression type seal similar to that used in air fuses and secondly a back-up epoxy resin seal. Since it is not possible to test these two seals independently only the first is tested as described above before the second seal is applied.

The oil sealing tests described in Clause No. 15.1. of BS 2692: 1975 are made on a regular basis.

Radiographic Inspection. An X-ray exposure is made of every fuse-link and the film identified with the serial numbers of the fuse-links. Each film is viewed by an inspector for the following features:

a) Continuity and even spacing of the coiled pilot fuse which energises the striker.

b) Even spacing between the fuse elements.

c) The presence on each element of the deposit of low melting point alloy.

d) The absence of foreign objects.

The radiographic examination is considered to be extremely important since it is the only method available of ensuring the integrity of the striker pilot fuse circuit. The other information obtainable from the X-ray film is also important from the quality assurance standpoint. The films are kept on file for future reference should this become necessary.

Other tests are carried out on a sampling basis, examples are: the checking of compaction of the sand filler; the energy output of strikers.

4. APPLICATION.

Three main areas of application are apparent as previously mentioned. These are distribution transformers, motors and shunt capacitors.

4.1. Transformers.

The fuse-links must be selected such that they:

a) Withstand the magnetising current inrush. Very little quantitative data is available on the values of magnetising current inrush. For any switching operation on the transformer it will depend on the remenant flux density in the core, the point on wave of switching and the source impedance.

The empirical rule that the inrush current integrates to give the equivalent of 12 x full load current for 0.1 seconds has been proved by experience to be adequate. In North America another equivalent integral of 25 x full load current for ½ cycle, (i.e. ,0083 seconds on a 60 hz system) has been suggested.

b) Withstand permissible overloads as determined by the philosophy adopted for transformer overloading. In the U.K. the maximum overload is specified as 50% for 3 hours with 0°C ambient on the -5% tap which evaluates to 157% of full load current.

Since the thermal time-constant of the fuses is less than that of the transformer, the permissible overload period of the transformer should be taken as equivalent to that which produces a steady state condition for the fuse. Accordingly, the overload current should not be greater than the rated current of the fuse, modified if necessary by the effects of enclosure or ambient temperature. Where higher overloads for shorter periods are specified, especially when repetitive, then these must be considered carefully and the fuse manufacturer should be consulted to ascertain the necessary margin between the overload current and period and the melting curve.

c) Provide acceptably fast clearance of faults of limited magnitude such as arise from turn to turn faults in the h.v. windings or secondary terminal earth faults ahead of the secondary protection. With the secondary arcing faults, the volt drop in the arc may limit the fault current but the presence of the arc increases the probability of fire and thus is an important condition.

The value of a time-current characteristic as shown in Fig.1. can therefore be appreciated.

The U.K. supply industry has specified that a secondary terminal earth fault current should, after being reduced to 60% of the calculated value to allow for arc resistance, be cleared by the h.v. fuse in less than 100 seconds. although the preference is to reduce this time to as low a value as possible. Fig.7 shows the time-current characteristic of a 90 Amp oil-tight fuse of improved design which would be applicable to a 1000kVA transformer in the U.K. system. The secondary terminal earth fault current modified by the effect of arc resistance is shown to be cleared in 1.7seconds.

d) Discriminate with the secondary protection. Depending on the type of secondary protection employed, discrimination may not be achievable. This will generally be the case where a definite minimum time circuit breaker or main fuses are used. More common practice, however, is to use separate fuses for each distribution cable fed from the transformer. In these circumstances discrimination is possible. To determine whether discrimination will be achieved the virtual pre-arcing time-current curve of the h.v. fuse must be compared with the virtual total (pre-arcing plus arcing) time of the secondary fuse when plotted to the same current base, i.e. the transformer ratio must be taken into account. For a delta-star connection, the worst condition for discrimination is for a phase to phase fault on the secondary side which gives a 2:1:1 current distribution in the primary. Fig.7 shows time-current characteristics of h.v. and m.v. fuse-links, (plotted to the m.v. current base). Also included in the figure are the maximum through fault and the adjusted value of secondary terminal earth fault current.

4.2. Motors. The majority of applications involve direct-on-line induction motors with their characteristic high starting current of up to 6 times the motor full load current.

The first consideration for selection is that the fuse-link must be able to withstand repeatedly the starting current for the run up time of the motor which is normally in the range of 6 - 60 seconds. A common requirement is that a false start should be allowed for; this simplifies to selecting on the basis of the starting current for twice the run up time.

The passage of the starting current for the run up time represents an appreciable overload on the fuse and the elements experience a considerable temperature rise followed by cooling as the current falls to the running value. The associated expansionaand contraction of the elements causes increasing mechanical stresses during the cooling period until ultimately a mechanical failure may occur.

This aspect of performance has been improved significantly by modification of the fuse elements such that expansion can be accomodated during the heating period without the establishment of stresses during the cooling period. A typical life test made during the development of these "second generation" motor fuses was as follows.:

Fuse-link Rating 315 Amps   Test Current 1300 Amps
Duty Cycle.

ON 10 seconds
OFF 4 minutes 50 seconds
ON 10 seconds
OFF 4 minutes 50 seconds
ON 10 seconds
OFF 19 minutes 50 seconds.

The above duty cycle repeated 7000 times (Equivalent to 21000 starts at 6 per hour) without measurable deterioration.

Life Tests similar to the above were made over a wide range of simulated run up times. The results make it evident that the necessary ratio between starting current and fuse melting current is sensibly constant over the range of times under consideration, thus simplifying application. The necessary ratio between starting current and melting current is approximately 1.8 to prevent ageing over a very long period of repetitive starting.

The frequency of starting must also be considered, Fig.8 shows the relationship between frequency of starting and fuse-link rating necessary for a given motor and starting conditions.

Where the drive horse-power demands a fuse-rating greater than that available in a single barrel, then paralleled arrangements may be employed. Much test data exists to prove the validity of such arrangements and no doubts need exist on the part of the user. The paralleling of fuse-links is merely an extension of the principle of using paralleled elements within a single fuse barrel.

For 'n' fuse-links in parallel, the total cut-off current for

Prospective current I_p will be 'n' x cut-off current for a single fuse-link with prospective current Ip/n.

The total I^2t appearing in the circuit components will be n^2x I^2t for a single fuse-link with prospective current Ip/n.

With assisted start motors a much lower fuse rating can be selected and for particularly light starting conditions the determining factor in deciding fuse rating may be the full load current and the effects of enclosure on the fuse current rating.

Fig.9 shows a typical application scheme. Co-ordination of fuse characteristic, motor relay characteristic and contactor breaking and through fault capacity must be considered to ensure the full spectrum of fault currents are covered.

4.3. Capacitors. The fuse rating is normally determined by the necessity to withstand inrush currents. The inrush current depends on many factors and specific data is not normally available, but empirical rules, based on many years of experience, are used and found to give reliable service.

Fuses may be used to protect the individual capacitor units or the bank overall.

To protect individual units from bursting due to internal faults, the fuse operation time and fault current must be considered in relation to the time current 'survival' curve of the capacitor unit tank.

In h.v. capacitor banks, the power frequency fault currents are often limited by the bank connections, as stated in Section 2.2. When calculating fuse operating times, no account is taken of discharge currents from healthy units into the faulted one, since although these normally occur and accelerate the fuse operation, it is possible for the unit to fault at a voltage zero, (i.e. zero stored energy) from such causes as vandalism. When overall protection of the bank is provided by line fuses this does not always afford protection against bursting of individual units.

5. EXAMPLES OF CRITICAL FUSE APPLICATIONS.

Under certain and varied circumstances there is no practical or economic alternative to protection problems by means other than h.v. c-l fuses. Examples are given below.

5.1. Protection of Pad Mounted Distribution Transformers.

There is a current problem in North America due to the eventful failure of pad mount and pole-top transformers caused by internal faults. Most of the transformers are protected by non current-limiting expulsion fuses and placed in high fault level systems. The transformer tanks are, compared with British and European practice, of lightweight construction and there have been occurrences where tanks have burst, spreading flaming oil over private property with the attendant possibility of personal injury. It has been demonstrated by tests

(Reference 1) that c-l fuses of up to 200 Amps rating limit the pressure build up and dynamic effects of oil movement to prevent such failures and this allows protection of 50 kVA transformers on a group fusing basis.

5.2. Protection of Large Generator Voltage Transformers.

It is not the practice to employ a circuit breaker between the terminals of 500 MW generators and the associated generator transformer in CEGB power stations. Generator V.T's, normally 4 per phase, are used connected to the generator - generator transformer connections. The fault level at this point is approximately 200kA. Fuse-links were developed for these V.T's and have been in use for many years.

Before acceptance it was necessary to prove their performance by a 'per-element' series of tests, since no testing station could provide a current of 200kA at the necessary voltage. It was also necessary to prove the capability of clearing the current which would cause operation in 1 hour.

References

1. A.A.Smith; A.C.Westrom; Controlling Dynamic Fault Pressures on Pad Mounted Distribution Transformers.

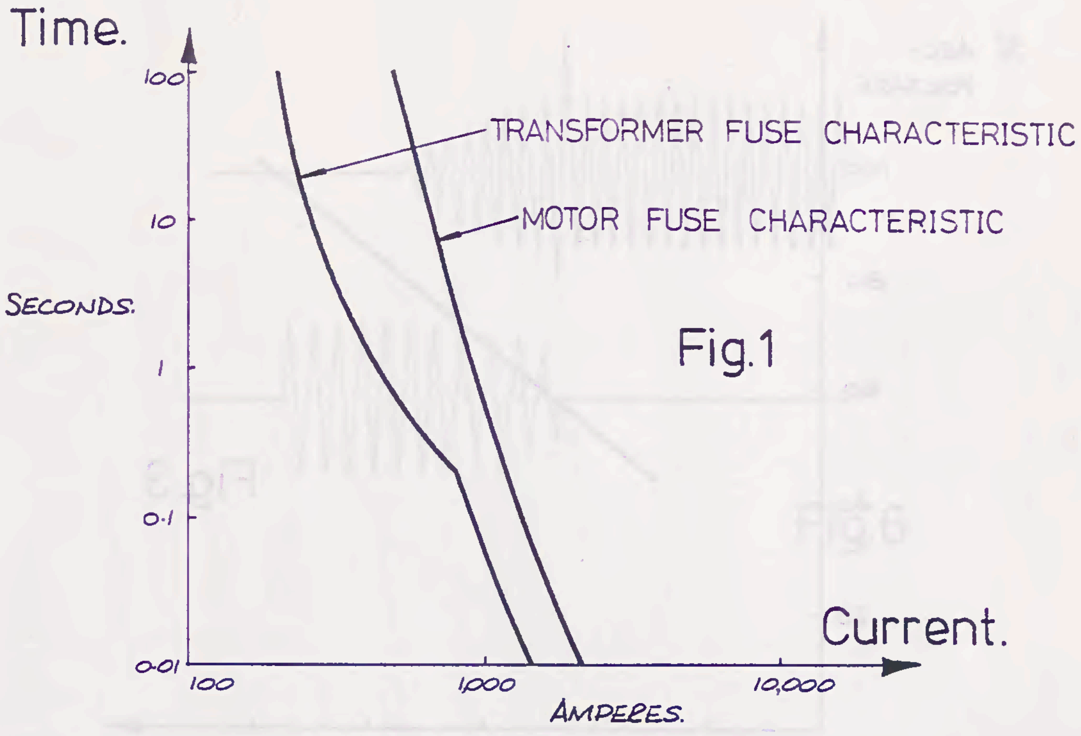
Time.
100
10
SECONDS.
1
0·1
0·01
100
1,000
10,000
AMPERES.
Current.
TRANSFORMER FUSE CHARACTERISTIC
MOTOR FUSE CHARACTERISTIC

Fig.1

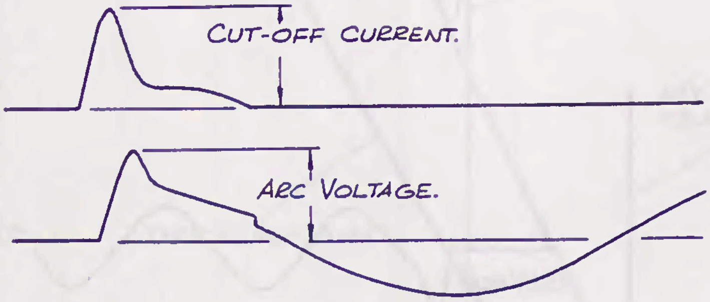
CUT-OFF CURRENT.
ARC VOLTAGE.

Fig.2

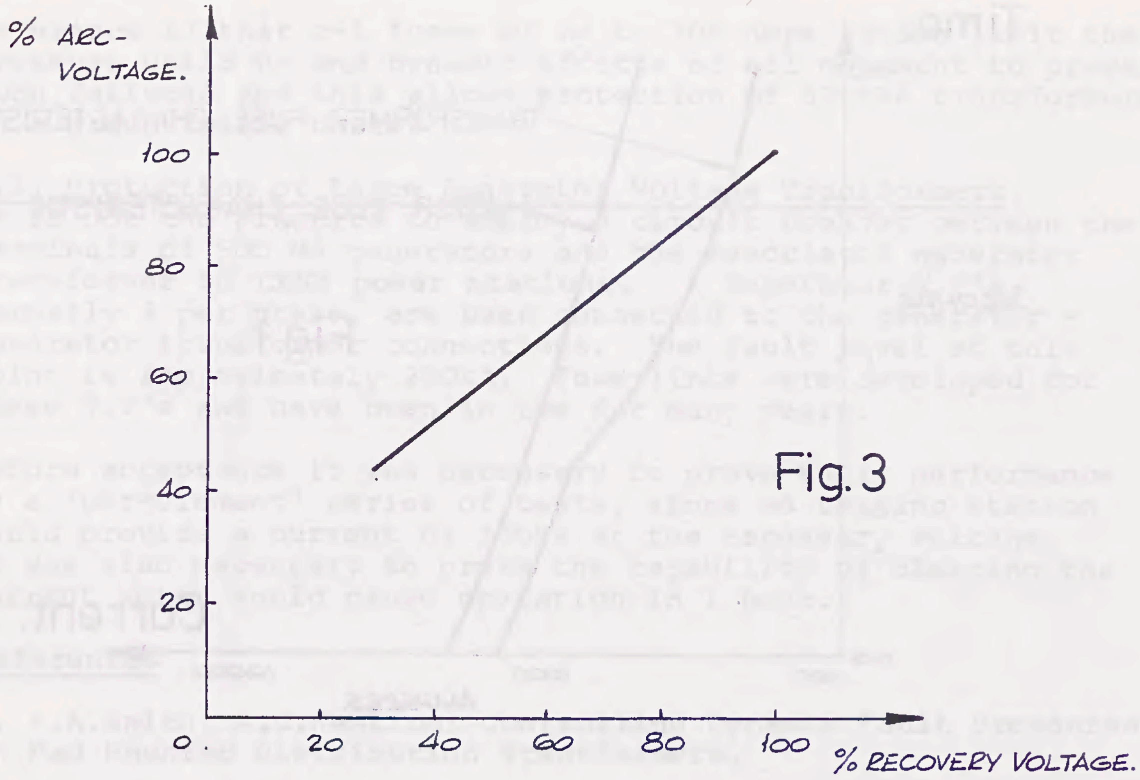

Fig. 3

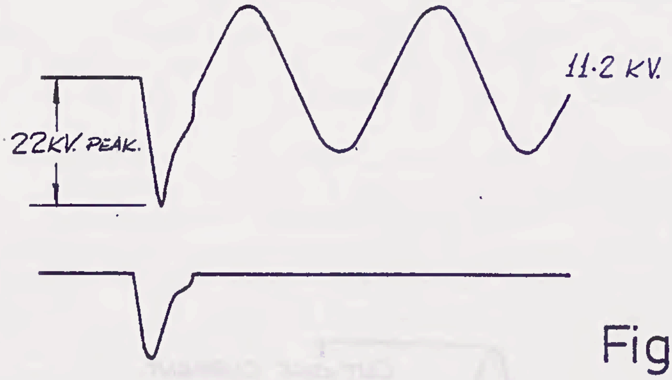

Fig. 4

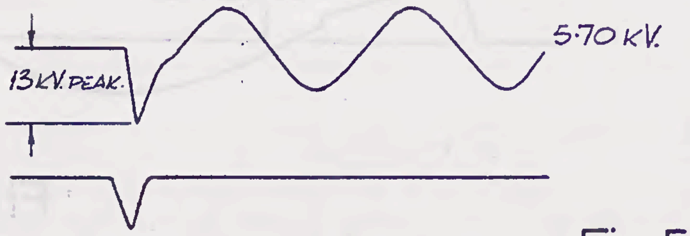

Fig. 5

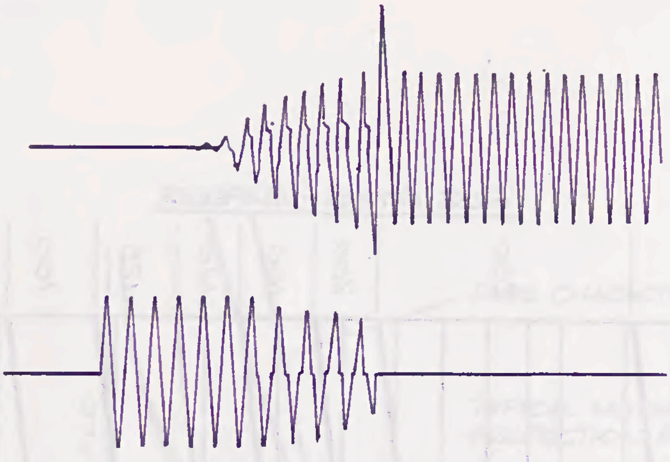

Fig.6

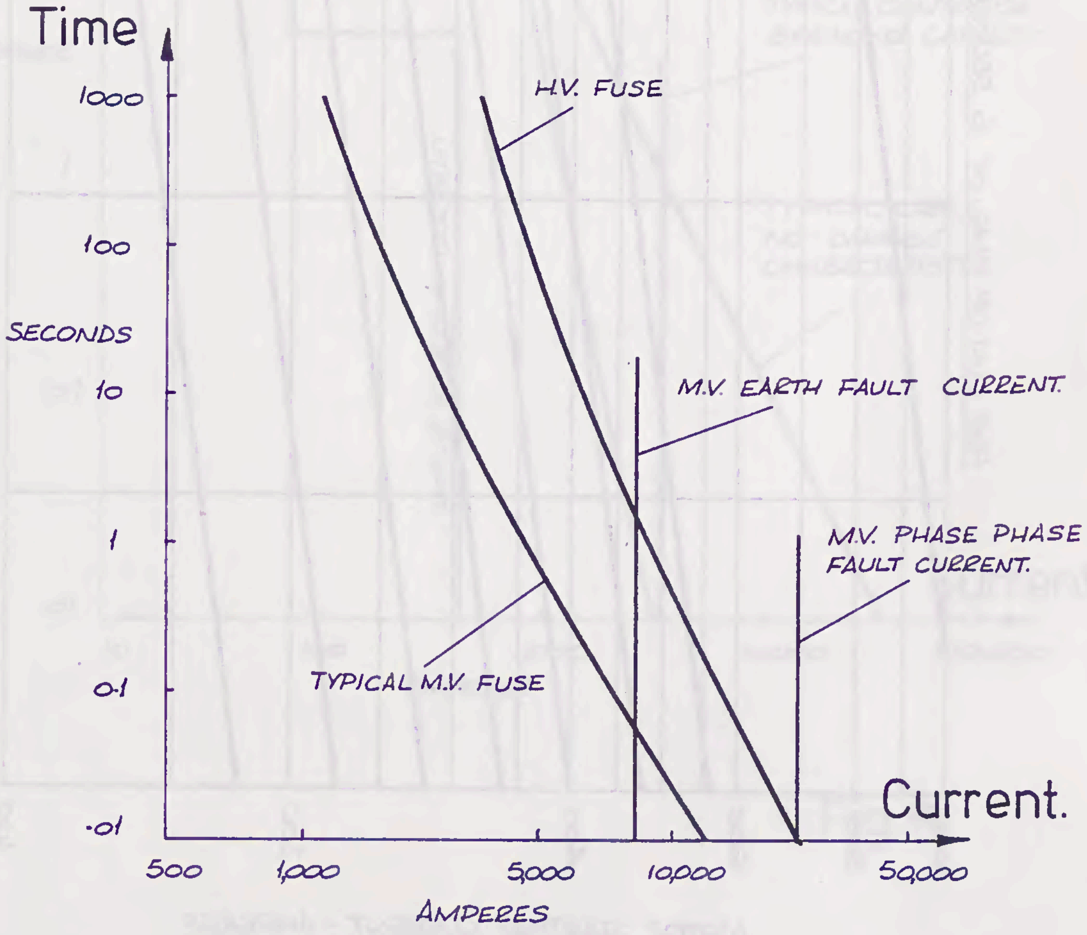
Time
1000
100
SECONDS
10
1
0·1
·01
H.V. FUSE
M.V. EARTH FAULT CURRENT.
M.V. PHASE PHASE FAULT CURRENT.
TYPICAL M.V. FUSE
Current.
500
1,000
5,000
10,000
50,000
AMPERES

Fig.7


FUSE RATING - AMPERES.
250
200
160
140
125
100
80
FOR RUN UP TIME OF 6 SECONDS.
Nº OF STARTS PER HOUR
32
16
8
4
2
1000
800
600
400
200
100
MOTOR STARTING CURRENT - AMPERES

Fig. 8

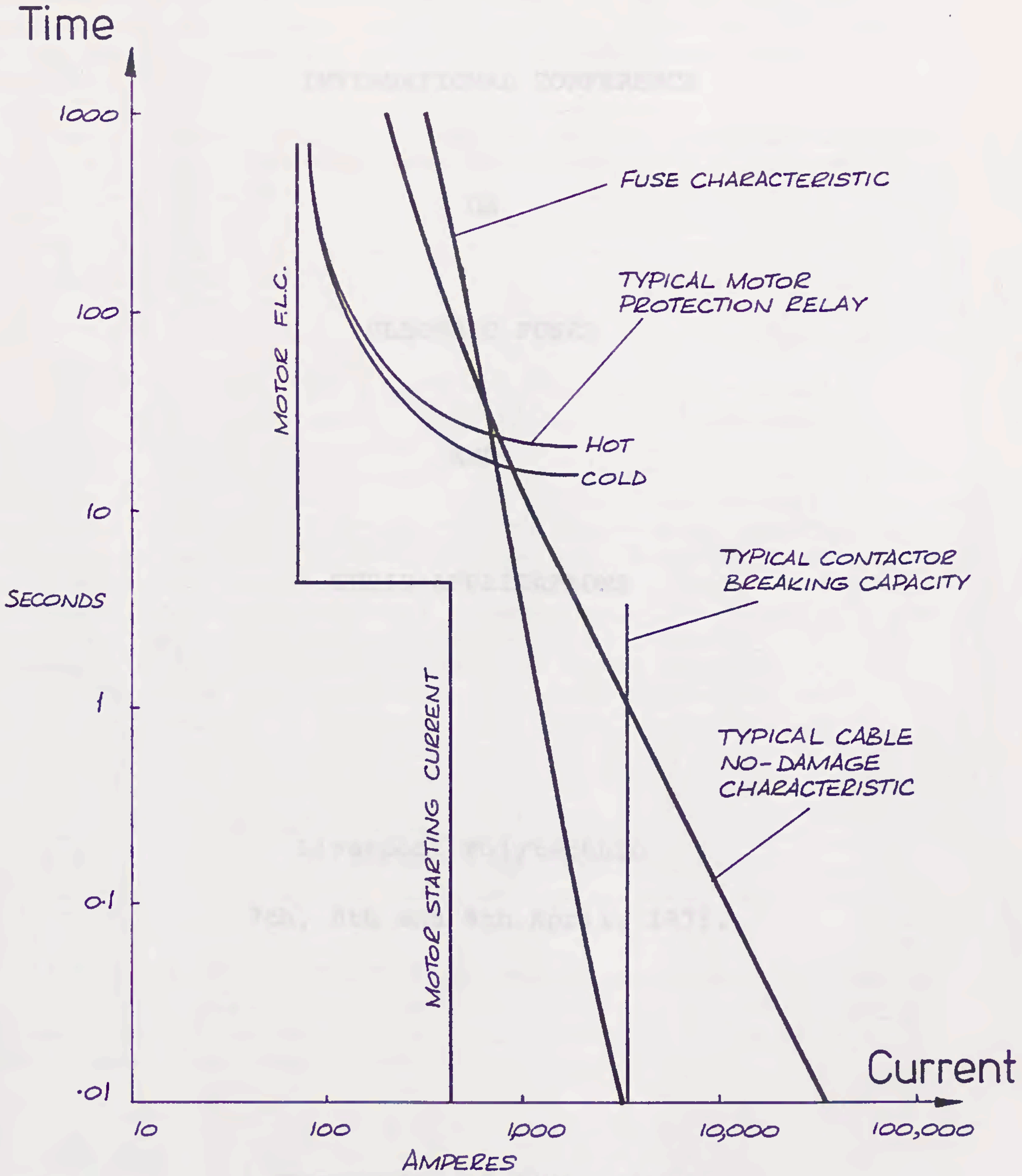
Time
1000
100
10
SECONDS
1
0·1
·01
10
100
1,000
10,000
100,000
AMPERES
Current
FUSE CHARACTERISTIC
TYPICAL MOTOR PROTECTION RELAY
HOT
COLD
MOTOR F.L.C.
MOTOR STARTING CURRENT
TYPICAL CONTACTOR BREAKING CAPACITY
TYPICAL CABLE NO-DAMAGE CHARACTERISTIC

Fig. 9