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B1
PS1 – Learning from Experiences

Fire risk from XLPE cables in air

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SUMMARY

The Transmission System Operator (TSO) is the owner of a substantial network of predominantly 275 kV oil-filled cables which supply power to the London area. These cables were installed in the 1960's and are now reaching end of life, consequently a programme of asset replacement with 400 kV XLPE cables is currently in progress. As it is no longer practical to install cables in the highway, the new cables are to be installed in dedicated cable tunnels.

As the replacement XLPE cables are installed in air within the tunnels, care has been taken to ensure that the risk of fire is suitably mitigated so as minimise the potential for harm to personnel and avoid the risk of asset loss. However, whilst the tunnels have been designed to minimise potential sources of fire it has been identified that the cables themselves represent a possible source of ignition, although the risk factors were not clearly understood.

It is generally recognised that a cable fire can be initiated by the energy released by an internal cable fault. Whilst this has been a particular issue with fluid filled cables, there are a number of reports of XLPE cables being involved in 'fire accidents'. Whilst it has been suggested that an internal fault event would not generate sufficient heat energy to support sustained combustion, there was an absence of test evidence to verify this conclusion.

In order to gain a better understanding of the risks involved, the TSO commissioned a series of tests to investigate the effect of internal faults on 400kV XLPE cables to a design in accordance with their specifications for tunnel applications. Faults were simulated in sample cables by drilling a small radial hole through the cable and fitting a thin wire to connect the conductor to the aluminium sheath. Fault current was then injected using a short-circuit generator. The observed effects closely resembled in-service cable faults.

It was established that the severity of the external effects of the cable fault increased with the magnitude and time duration of the injected r.m.s fault current. At the higher levels tested, it was found that the cable ignited during the fault and that the fire was sustained following interruption of the fault current. By comparing the test outcomes using I x t as a measure of the energy dissipated in the fault arc, it was established that it was not expected that a fault on the UK transmission system, that was cleared successfully by unit protection systems, would result in a sustained fire.

Further testing was carried out to assess whether a fire initiated by a fault would be sustained in typical operational orientations.

The paper outlines the tests that were performed, the observations from those tests and the conclusions that have been drawn.

KEYWORDS

XLPE cable - Cable tunnel - Fire performance - Fault simulation - London Power Tunnels

1. BACKGROUND

The EHV transmission system in the UK was initially established in the 1950's (275 kV) and 1960's (400 kV), thereby facilitating the siting of large generating plant remote from the major cities. Over time these plants have largely replaced local generating capacity. Whilst the type and location of generating plant supplying the UK has changed radically over the lifetime of the system, there has been no significant change in this philosophy and UK cities are now largely dependent on the TSO's Transmission System to deliver their power requirements.

At the time the EHV transmission system was established, London was already densely developed. Power demands were high and increasing rapidly, necessitating the provision of new Bulk Supply Points and a supporting network of EHV transmission lines close to the city centre. Furthermore, as a historic city, no provision had been made for reserved utility corridors. Consequently, the establishment of EHV transmission in central London made extensive use of 275kV fluid-filled cables, many laid in the highways, as this provided the only available linear corridor. The initial network was established c.1965 and the cable assets are now more than 50 years old and reaching end of life. The asset owner is therefore undertaking a programme of asset replacement.

For practical reasons it has generally not been possible to carry out an in-situ replacement of the existing cables. The TSO has thus based the replacement programme on construction of new cable tunnels in a project referred to as 'London Power Tunnels' (LPT). The first phase of this project (LPT1) has been completed and construction of the second phase (LPT2) is in progress [1].

The design of the LPT tunnels and cable systems draws on experience from earlier cable tunnel projects. Each tunnel accommodates at least two EHV circuits with the cables cleated on support brackets in air, one circuit each side of a central access space. A typical configuration from the LPT1 project is illustrated in Figure 1.

Figure 1: LPT1 Cable Tunnel during Cable Installation [Copyright National Grid]

The cables are XLPE insulated with a seam-welded aluminium sheath and are specified with a fire retardant oversheath having low smoke properties.

Forced cooling is provided (as required) by circulating air through the tunnel using ventilation fans mounted in the access shafts.

Fire safety has been an important consideration in the development of the LPT tunnel designs. Facilities have been provided to ensure safe evacuation of personnel in the event of a fire in the tunnel and best practice has been followed in specifying cables and tunnel mechanical and electrical systems to minimise the risk of fire spread. Circuit protection systems have been reviewed in line with TB720 findings, fault clearance times have been confirmed to comply with network design standards and the use of auto-reclosure facilities onto cables installed in air will be suppressed. However, whilst the tunnels have been designed to minimise potential sources of fire it has been identified that the cables themselves may still represent a possible source of ignition, although the risk factors were not clearly understood.

Cigre Technical Brochure 720 [2] presents an analysis of potential measures to mitigate the impacts of a fire once it has become established. It also provides an analysis of the cause and effects of a number of ‘fire accidents’ involving HV cables. However, the data presented is insufficient to assess the risk of a fire becoming established under operational conditions where the only ignition source is the cable itself.

2. FAULT SIMULATION TESTS

2.1 Introduction

Reference [3] reports the results of fire performance testing of HV cables of various constructions. It is noted in the discussion of these results that:

In many cable tunnels, the cable is the only combustible product present and the only normal means of fire spread could be ignition following a catastrophic dielectric breakdown. This has not been addressed in the current study but in the opinion of the authors, an overload circuit breaker (sic) would not normally allow heat input for sufficient time to generate a sustainable combustion. Nonetheless attempts to reenergise a short circuit … could demonstrably create a severe fire loading.

Although this view was of benefit in developing the design safety criteria for the LPT2 project, it was recognised that the principles had not been verified. Consequently, so as to validate this opinion, it was decided to commission a series of tests to investigate the risk of a fire being initiated by a cable fault under worst-case network conditions. The objective of the test series was to investigate the behaviour of sample lengths of 400kV XLPE cable under simulated fault conditions. In particular, the tests were intended to establish whether the cable will initiate and subsequently sustain a fire following a representative system fault and to explore the risk of collateral damage to equipment in proximity as a consequence of the fault.

2.2 Test Cable

The tests were performed on 3m lengths of 400kV XLPE cable with a 2500mm² copper conductor, a smooth welded aluminium sheath and a bi-layer fire retardant oversheath. The construction of the cable is illustrated in Figure 2.

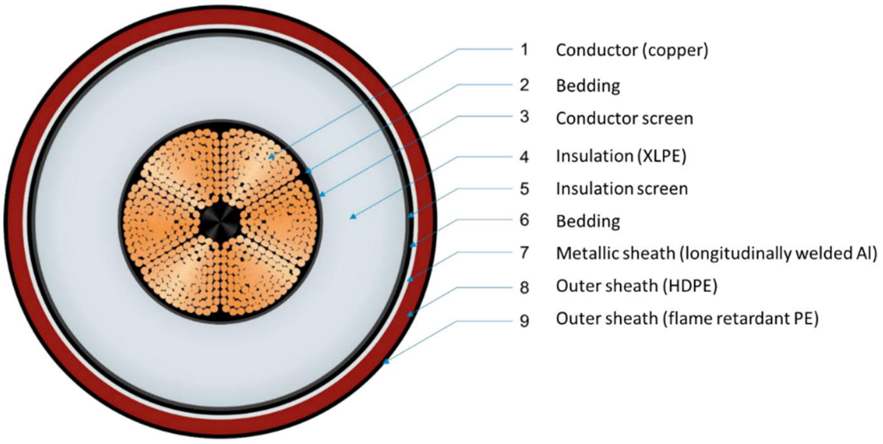

Figure 2: Construction of test cable

These lengths were offcuts from another cable project and were of a design compliant with TSO's specifications and intended for use in tunnels.

The cable had been tested and demonstrated to comply with the tests for fire retardance defined in IEC Standard 60332-1-2 [4].

2.3 Test Procedure

The cable fault was initiated by preparing the cable sample in advance of the test by inserting a fusible copper wire of 0.5 mm diameter in a 2 mm diameter hole drilled radially through the cable insulation so as to connect the primary conductor to the aluminium sheath. A short-circuit generator was connected to the primary conductor with the return current path through the cable sheath. The test arrangement is illustrated in Figure 3.

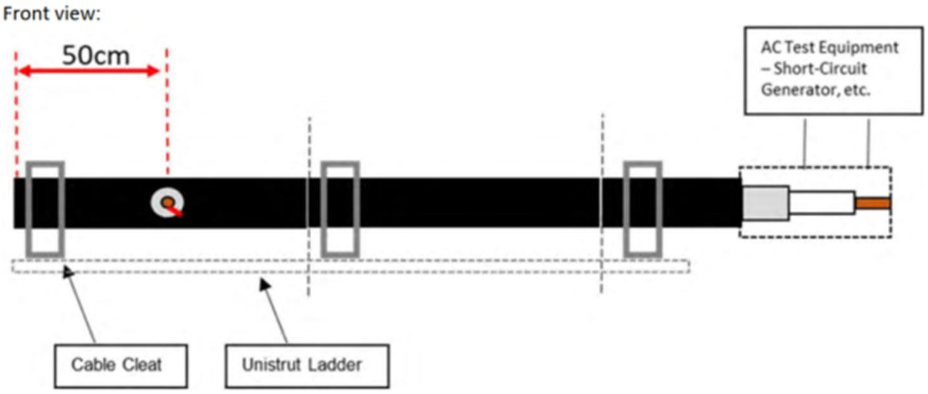

Figure 3: Arrangement of Test Samples

During the test the short-circuit generator was set to deliver an a.c. current into the test sample equivalent to a defined r.m.s. fault current for a duration representative of worst-case fault clearance times on the UK transmission system. The current path passed through the copper wire, which immediately vapourised, leaving an ionised gas column through the insulation carrying the test fault current. Similar procedures are defined in standards to initiate simulated fault arcs where internal arcing performance must be demonstrated and are generally considered to represent the energy release of a true fault arc.

Six tests were performed, as summarised in Table 1.

	Fault current/duration	**I x t (A.s)**
Test 1	35kA / 140ms	4.90 x 10^3
Test 2	45kA / 140ms	6.30 x 10^3
Test 3	55kA / 140ms	7.70 x 10^3
Test 4	63kA / 140ms	8.82 x 10^3
Test 5	45kA / 300ms	13.5 x 10^3
Test 6	63kA / 105ms	6.62 x 10^3

Table 1: Summary of Tests Performed

The 140ms fault duration represents the maximum fault clearance time on the NETS under normal operating conditions. 300ms represents the clearance time under ‘degraded’ operating conditions should a circuit-breaker fail to trip. Test 6 was designed to represent a typical clearance time at maximum fault level and to explore the effects of high fault level and a lower energy injection duration.

For the purposes of the test the cables were cleated to a retaining frame, the intention was not to mimic the actual conditions in a tunnel.

2.3 Observations

As expected, each fault simulation resulted in the ejection of a jet of plasma from the fault point. This jet was very directional along the axis of the hole that had been drilled in the insulation during preparation of the sample. Visual and thermovision records showed that the jet formed a narrow cone with the highest temperatures at its centre. It is noted that visual evidence following an in-service cable fault is consistent with a highly directional plasma jet being ejected, confirming that the test outcomes were as expected from an actual fault event (illustrated in Figure 4).

Figure 4: Example of a 400kV Cable fault in a Tunnel Installation (20 kA rms fault current / 80ms fault duration; I x t = 1.60 x 10^3*)*

Thermal indicator/ thermovision records taken during the tests showed that temperatures at the core of the plasma jet were very high, and in some cases exceeded 1000°C. It was clear that there would be an extremely high risk of serious injury should a person be present in the line of the plasma jet and, although the test was not designed to measure this, it was considered likely that the hazard would extend many metres from the fault position.

There was no evidence of the ejection of fragmented parts in the plasma jet.

The tests were arranged such that the plasma jet was directed at a ‘target’ length of cable mounted approximately 2m horizontally from the fault. This was intended to represent a second circuit mounted on the opposite side of the cable tunnel. As illustrated in figures 5 & 6, it was evident from the test records that the high temperature plasma jet ejected during the fault completely engulfed this target cable.

Figure 5: High speed image during fault

Figure 6: Thermovision image during fault

The ‘target’ cables were visually examined after the tests and, despite the exposure to the plasma jet, no evidence was found of any damage that might impact on their integrity.

The ejection of the plasma jet from the fault was accompanied by a pressure ‘pulse’ which was observed to affect test equipment located outside the direct line of the jet. It must be recognised that the test was conducted in an outdoor open environment rather than a confined space representative of a tunnel and it may be expected that the effects in a tunnel environment would be more intense than those observed.

Following interruption of the fault current the post-fault performance of the cable was observed. These observations are summarised in Table 2.

	I x t	**Observations following interruption of fault current**
Test 1	4.90×10^3	Small flame observed, which was immediately self-extinguished. No sustained fire.
Test 2	6.30×10^3	Small flame observed, which was immediately self-extinguished. No sustained fire.

Test 3	7.70 x 10^3	Flames maintained for a brief period after the fault (see note 1), however the fire self-extinguished and was not sustained.
Test 4	8.82 x 10^3	A small fire developed, centred on the ruptured area of the aluminium sheath. This was allowed to burn for approximately 15 minutes, during which the fire gradually increased in intensity. At the time it was extinguished, it was not judged to be destructive, but had the potential to become so.
Test 5	13.5 x 10^3	A small fire developed of a comparable size to Test 4. This was not allowed to continue burning.
Test 6	6.62 x 10^3	Small flame observed which was immediately self-extinguished. No sustained fire.

[Note 1: The time was not measured, but was less than the 5 minutes required to enter the test bay.]

Table 2: Summary of observations following tests

The condition of the cable following Test 2 is illustrated in Figure 7, and the condition after Test 4 is illustrated in Figure 8.

Figure 7: Cable following Test 2

Figure 8: Cable following Test 4

3. DISCUSSION

As anticipated, the increasing magnitude of the r.m.s. fault current in Tests 1 to 4 was accompanied by an increase in the severity of the external effects. It is therefore reasonable to conclude that these effects are related to the magnitude of the energy released in the fault arc. Therefore, in order to draw useful conclusions from the work it was necessary to be able to compare energy release under different fault scenarios.

The energy released in the fault is only a small proportion of the energy delivered by the short circuit generator; instead, the majority of the energy is dissipated in other parts of the test circuit (as is the case for a fault on an EHV network). Thus, whilst the energy delivered by the generator is approximately proportional to I^2 x t, this relationship does not necessarily apply to the arc itself.

The arc resistance (which is needed to evaluate the arc's power) is nonlinear and it has been reported by others that the voltage drop in the arc is practically independent of current for arcs in free air [5]. Consequently, the results have been assessed on the basis that the arc voltage is a constant and that the energy dissipated in the fault arc is proportional to I x t (i.e. the arc voltage is a constant value during the fault). It is recognised that this assumption is an approximation, however a detailed evaluation of the relationship between fault current and energy dissipation in the fault arc is outside the scope of this paper.

The test observations can be presented graphically as shown in Figure 9. This also shows the assumed maximum energy release for a fault on the UK NETS, which has a maximum design fault level of 63kA r.m.s and an expected fault clearance time of 80ms (where fault clearance is not dependent on operation of inter-tripping).

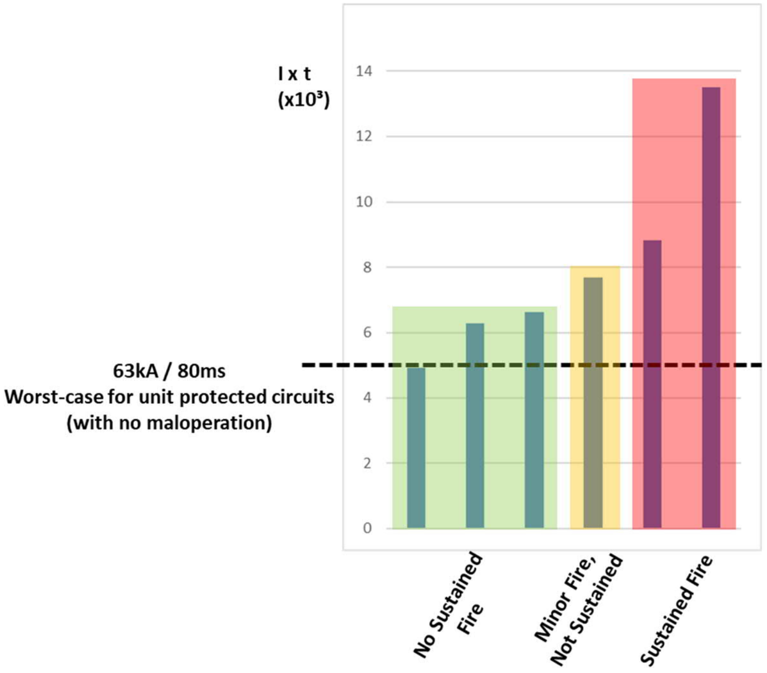

Figure 9: Graphical Presentation of Test Results

4. FIRE PROPAGATION TESTS

Following a review of the results, it was concluded that it would be beneficial to further investigate the propagation over an extended time period of any fire that may result from a fault event. Consequently, a further series of tests were commissioned to investigate these effects on similar 400kV cables with fire retardant oversheath.

In these additional tests, the cables samples were prepared by cutting the oversheath (to represent the post-fault condition illustrated in Figure 7) and creating a 50mm diameter hole in the outer layers so as to expose the XLPE insulation. A propane gas burner was then applied until the fire burnt down to the copper conductor (approximately 15 minutes), after which the burner was removed and the progression of the fire observed. The tests included a number of combinations of cable and fault orientation and considered air flow & still air conditions.

Results indicate that, in most cases, although the fire was sustained after removal of the burner, it self-extinguished in less than one hour. With the cable in a horizontal position and the fire oriented vertically the fire was maintained when air flow was present, but extinguished itself if air flow was eliminated.

5. CONCLUSIONS

- The laboratory fault simulation tests have indicated that, under normal operational conditions on the UK NETS, 400kV XLPE cables with a fire-retardant oversheath are not expected to initiate a sustained fire as a result of an internal fault.
- There is, however, a risk that at higher system fault levels a fault, that is not cleared by fast main protection systems, could result in a sustained fire.
- The immediate effects of the fault that were observed in all the test cases would present a significant risk to personnel in the immediate vicinity. Whilst the plasma jet ejected from the fault was highly directional, the effects in the confined space of a tunnel could be unpredictable and the pressure pulse may present hazards over a wider area.
- The tests demonstrated that the plasma jet did not present a serious risk to the integrity of other cable assets at a separation distance of 2m, representing the separation between circuits installed on opposite sides of a cable tunnel. The plasma jet/pressure pulse may, however, affect other tunnel equipment that is not adequately protected
- Where a sustained fire was initiated by the fault, the post-fault effects did not present an immediate risk to personnel or other assets. Following Test 4 the fire was left to develop over a period of 15 minutes and over this time the effects were very localised.
- The results of the fault simulation tests provide strong evidence that the risk of a sustained fire is linked to the energy released in the fault.
- Due to the non-linear electrical characteristics of fault arcs, it is understood that the energy released in a fault is proportional to I x t, where I is the rms fault current and t the duration of the fault.
- The above information has allowed the TSO to carry out probabilistic analysis of cables catching fire using cable fault frequency, fault levels and protection operations information. This has then informed the life safety aspects of the LPT tunnels design.
- The TSO have undertaken further tests to determine if a sustained fire can propagate to an adjacent phase or ramp up in intensity. Results indicate that this is not the case, and that in most cases the fire self-extinguished in less than one hour. However, this performance will clearly depend on the construction of the cable.

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