COST REDUCTIONS IN POWER CABLE SYSTEMS USING LEAN CABLE TECHNOLOGY

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SUMMARY

The application of EHV cable technology has led to the development of a new range of 'lean' XLPE cable systems at 132kV, characterised by higher quality insulation, smaller diameters, longer despatch lengths and fewer joints. Cost savings of typically 29% have reduced the cost ratio of underground cable to overhead lines to 3:1 for specific applications. Three installations in the UK are described.

INTRODUCTION

Underground cable systems insulated with XLPE (crosslinked polyethylene), are increasingly employed for HV (33-132kV) distribution and transmission, in place of those employing self contained, low pressure, fluid filled (FF) paper cable for the following reasons:

a) simplicity in operation and maintenance, particularly important in remote locations,
b) elimination of fluid leakage risk.

The continued rate of application of XLPE cables, has previously been limited by the low electrical performance of the cable and accessory insulations [1]. The inherent high electrical strength of XLPE has been restricted by the achievable purity of the insulation material and the smoothness of the semi-conducting screens. High electrical strength is determined by the quality of the polymeric materials and by the process capability of the factory compounding plant and cable extrusion machines [2]. To achieve a satisfactory service life, the insulation design stress of the first generation of 132kV XLPE cable in the UK was originally set at the comparatively low level of 6kV/mm, producing an insulation thickness of 19-21mm [1]. An increase in design stress to 6.5kV/mm was made in 1994 for the second generation of cables, reducing their insulation to 18mm, however this was still significantly greater than the 8-9mm thickness for the equivalent FF paper cable [2]. In consequence XLPE cables were still larger than paper cables in diameter and material volume, resulting in a significantly higher system capital cost, especially for longer circuit lengths, where the increased costs of the ancillary hydraulic equipment for FF cables is a smaller part [3].

The cost of earlier types of XLPE cables has maintained the high cost ratio of underground cable to OHL (overhead line) circuits and this has previously inhibited the desire to underground both new circuits and sections of existing OHL.

A previous CIRED paper [4] described the objectives set by the Authors' organisations to produce more compact designs of 132kV XLPE cables. This paper describes the first commercial applications in the UK of lean XLPE cable systems employing the new technology. The cables, accessories and installation techniques employ combinations of more cost effective designs of conductors, insulations, sheaths, accessories and installation. (Cable systems embodying the new technologies carry the trade mark, Lean^{TM}, to distinguish them from earlier types.)

The cost savings described in this paper have succeeded in reducing the cost ratio of selected applications of cable to OHL to 3:1, thereby significantly improving the economic viability of underground cable circuits.

Figure 1: 132kV cable trench crossing green field housing development with OHL to be removed

ENVIRONMENTAL PRESSURES

Circumstances continue to change for Utilities seeking to maintain and to expand their networks, driven by an increased public awareness of environment issues and by new legislation associated with electrical industry privatisation [4]. In particular there is pressure on Local Authorities to approve an increasing number of new housing and light industrial estates on the edges of existing towns and cities. An acute shortage of land has led Planners and Developers to earmark arable land previously in use for farming and agriculture, figure 1. The areas involved are usually 'prime' sites giving easy access to road, rail and city centres, thus adding impetus to their development.

In many cases, the land chosen for development contains the route of an existing HV tower line, for example built in the 1930-50's to transmit electricity from a power station to a main load centre. Since the 1950's there are instances of housing estates having been built underneath existing OHLs, figure 2. There is an increasing trend for land developers and residents to call upon RECs (Regional Electricity Companies) to divert, or preferably underground, the lines. East Midlands Electricity, in common with other RECs, has an environmental policy which strives to improve visual amenity and increase safety in some areas by the removal of selected spans of OHL which are prone to damage by vandalism.

The route of HV OHL can be secured by permanent easements, but more usually agreement is by a standard terminable wayleave. In the latter case should the grantor give notice to terminate the wayleave, it may be necessary for the REC to seek a retention order from the relevant Government Authority to keep the OHL in situ. RECs are therefore under increasing pressure to take due cognisance of the planning and legal view when deciding whether to underground lines over existing or new land developments.

Identification of common rights of way for the cable circuit are best made at an early stage of a project, in consultation with Local Planners and other statutory undertakings, to ensure that multiple services can be safely accommodated within the designated area. Common issues when assessing the feasibility of undergrounding OHL schemes are the availability of reliable and environmentally suitable cable systems, [4,5,6], favourable economics and adequate funding and resourcing.

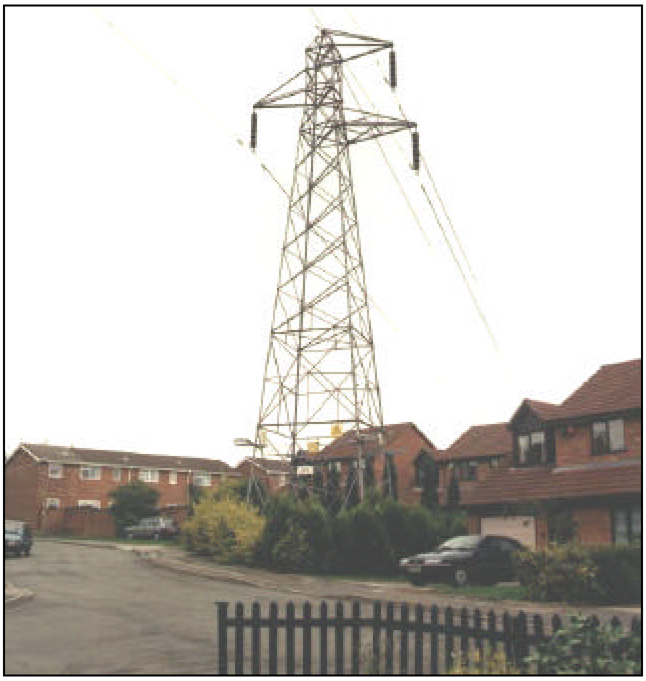

Figure 2: Urban housing site built around an existing 132kV OHL

COST RATIO OF CABLE TO OVERHEAD LINE

There has always been a drive to reduce the cost ratio of underground cables to OHLs to make undergrounding more economical [5,8]. Continuing pressure from environmentalists and developers, has led the Authors' organisations to work together and reduce costs in the design, manufacture and installation of HV cable systems. At 132kV and below, scope was identified to reduce cost by the development and application of the smaller 'lean' designs of XLPE cables.

In 1994 the CIGRE joint working group 21/22.01 [5] carried out a survey of 19 member countries to report what factors needed to be considered when comparing ac HV overhead transmission lines and underground cables. At 110-219kV the survey indicated a general trend to increase undergrounding with a total of 416,291km of existing circuits, of which 3.1% are underground; compared to a total of 8,949km of planned circuits, of which 11% are to be undergrounded. Included within the CIGRE report is a comparison of the capital costs between underground and overhead circuits, covering the voltage ranges 110-764kV. It did not include capitalised running costs (i.e. losses and operation and maintenance costs), because the difference in absolute cost between the underground cable and the OHL was considered to be little affected. For the voltage range 110-219kV the mean ratio of capital costs averaged over the 19 countries was 7:1, with a minimum of 3.4 in Finland and a maximum of 16 in Japan. At 132kV in the UK, the ratio was given as 9.9 for a 270MVA circuit and 8.3 for 200MVA.

These ratios compare favourably with the Authors' records of earlier generations of 132kV circuits in the UK, with cost ratios continuing to fall from 8.2 in 1975 to 6 in 1996. These cost ratios are based on average costs which vary from project to project. They are dependent on installation difficulties i.e. hard ground, or soil with poor thermal resistivity, requiring a more expensive cable system e.g. larger conductor size, a thermal backfill, or special sheath bonding to achieve the circuit rating.

With the introduction of lean cables with smaller diameters, figure 3, it has been possible to achieve a step function in cost reduction, as detailed in the following Sections. For the specific projects described herein, it was possible to reduce the cable to OHL cost ratio to 3:1. It is envisaged that cost reduction initiatives will continue such that the 3:1 ratio can be targeted, subject to installation conditions.

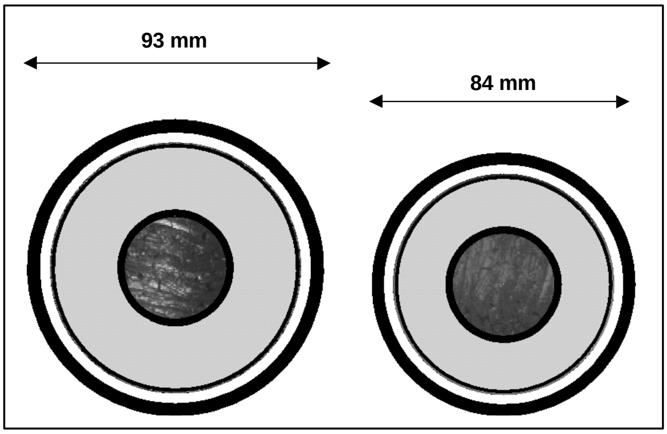

Figure 3: Size reduction achieved by lean 132kV XLPE 630mm² cable compared to second generation cable

LEAN CABLE TECHNOLOGY

Low cost, lean cable systems have been made possible at 33-132kV by applying the technology recently developed to make EHV (200-550kV) transmission class cable systems practicable, [1]. Research on dielectrics has resulted in the development of advanced materials technologies and manufacturing plant. The semiconducting screens and insulation are formulated and compounded in-house to achieve ultrasmooth screen interfaces, ultraclean insulation and increased electrical strength [1,2,4].

At the end of the compounding process the XLPE materials are specially filtered in-house to achieve ultra-cleanliness and ultra- smoothness. The insulation and screens are then immediately extruded onto the conductor in the adjacent VCV (vertical continuous vulcanising) manufacturing line. Vertical extrusion achieves a precise cylindrical and concentric geometry without constraint on the XLPE materials, such that they can be formulated to yield the highest electrical strength rather than be compromised to suit the process characteristics of less flexible manufacturing plant.

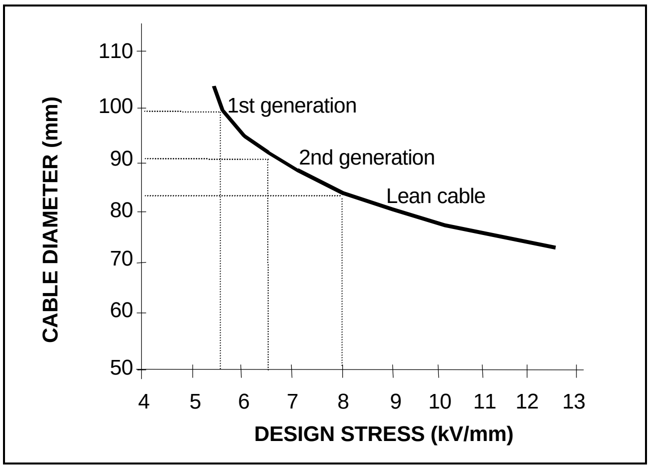

Figure 4: Reduction in diameter of 132kV XLPE cable with increasing insulation design stress

Equally important is the development, based on EHV technology, of a compatible range of accessories (joints and terminations) and their assembly techniques, necessary to operate at the higher cable design stresses [1,2,4].

The lean cable system is an integration of cable, accessories and installation methods utilising EHV technologies i.e. conductor designs, XLPE insulation and screen materials, metallic watertight barriers, oversheaths, accessories and installation techniques:

- The use of thinner insulation results in savings in material costs and the overall reduction in cable diameter and volume. An increase in design stress to 8kV/mm for a lean 630mm^2, 132kV cable permits the diameter to be reduced by 10% [1,2,4] and the material volume by 18%, as shown in figure 4.

- The smaller cable diameter, in combination with a larger drum (4.3m diameter and 2.3m width), permits the despatch length to be increased to 2km [1,2,4].

- In-house formulations of XLPE materials give the cable manufacturer the ability to blend the highest quality materials to meet specific performance [1,2].

- Stringent quality controls which far exceed those cited in generic standards, such as EATS 09-16, IEC 840 and AEIC CS7, mean that higher electrical stresses can be safely achieved. For example at 132kV, where the first and second generation XLPE insulations were 21 and 18mm thick, 14mm is now possible in commercial installations.

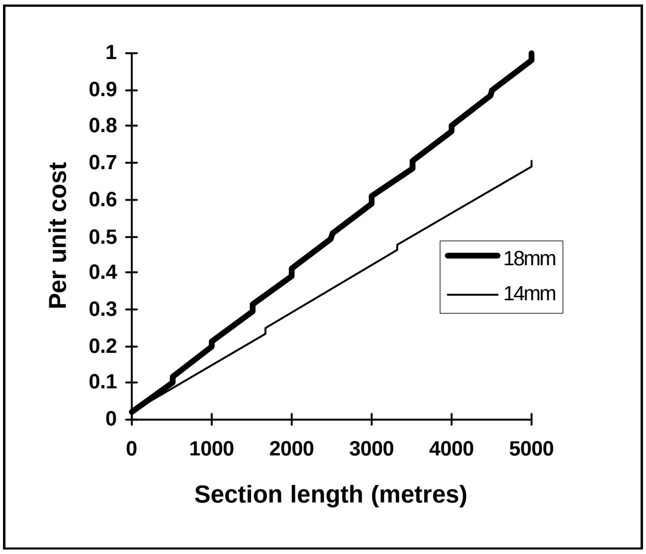

Figure 5: Cost reduction of a lean 132kV cable system (14mm insulation) over a 5km route, compared with a conventional cable system (18mm insulation)

The ability to transport longer despatch lengths and to pull the cable safely into longer trenches, reduces costs and also permits the number of joints and joint bays to be reduced. As part of this technology tensions and side wall pressures on the cable during installation are calculated, bends in the trench route are designed and the pulling tensions are controlled to safe levels.

Advances in cable installation technology have been pioneered for EHV cables to increase despatch lengths and reduce the number of joints. This has been achieved by employing the largest and heaviest drums within limitations set by the load carrying capability of road and bridge surfaces and by the height of motorway bridges. For example, despatch lengths have been increased from 400m to 850m for 230kV 2000mm² XLPE CSA sheathed cables for road and sea transportation from the UK to the Far East, by turning the drums sideways on the road vehicles, increasing the drum length from 2.3 to 5.5m and their weights to 41t. Installation techniques have been developed to permit these large and heavy cables to be pulled into trenches for buried applications. Similarly in Japan [8], despatch lengths for the road transportation of 275kV 2500mm² XLPE cables were increased from 400m in 1993 to 720m in 1995 for installation in cable tunnels. In 1998 this was further increased to 1.8km, for installation in tunnels, by the use of combinations of special road transporters and canal barges, travelling along selected, obstruction free routes. These EHV transportation techniques are equally applicable to the smaller and lighter designs of lean 132kV XLPE cables to permit even longer lengths to be installed.

Figure 5 shows an example cost saving study for a lean cable installation over a circuit length of 5km. The reference 1 per unit cost is the total installed cost of a second generation design of 132kV XLPE insulated cable with 18mm insulation, 630mm^2 copper conductor, extruded lead sheath, polyethylene oversheath and 500m despatch length. The lean cable has the same construction, but with the insulation reduced to 14mm and despatch length increased to 1,700m. The following savings are achieved:

- the unit cost per three phase metre of installed cable is reduced by 17%, (as shown by the reduction in the line gradient),
- the number of despatch lengths is reduced from 10 to 3,
- the number of joint bays is reduced from 9 to 2, reducing the total installed system cost by 12%, (as shown by the reduced number of joint bay incremental costs)
- the total system cost is reduced by 29%.

SERVICE APPLICATIONS

Three 132kV lean cable systems have been installed for East Midlands Electricity in Central England, table 1.

Table 1. Service applications of 132kV lean cable systems

Installation	Green Field	Urban	Brown Field
Route length [km]	1.5	2.4	0.5
Drum length [km]	1.5	1.2	0.5
Number of circuits	2	1	3
Conductor Area [mm²]	630	630	185
Design stress [kV/mm]	8	8	8

‘Green Field’ Development Site

The land development required that 4 spans of a double circuit 132kV OHL be replaced by underground cables, figure 1, to facilitate the development of a new housing estate. To meet the winter continuous rating of 691A, a cable with a 630mm^2 copper conductor was selected, table 2. The two circuits were installed with a 500mm centre line spacing and were each solidly bonded in a closed trefoil formation. The conductor construction was fully water blocked to prevent longitudinal water transmission

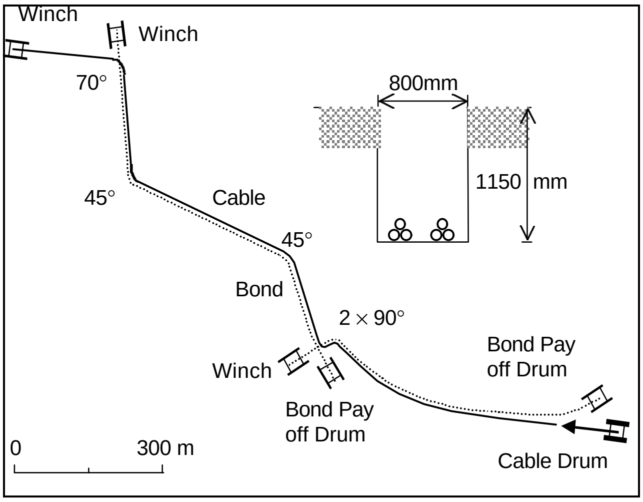

Figure 6: Route profile for installation of 1.5km 132kV lean cable

following third party damage. An insulation design stress of 8kV/mm was selected to give a design life of 40 years using the 'cable probabilistic' and 'cable system endurance' mathematical methods in combination with test results, as given in [1,2]. The insulation and screening materials were compounded in-house and extruded in the integrated VCV line. The gap between core and sheath was also waterblocked. A continuously extruded, seamless, lead alloy sheath was applied, this being selected to give compact dimensions and perfect watertightness. The sheath thickness of 4.4mm was sized to meet the short circuit rating of 26kA for 1s and this significantly increased the cable weight to 20.7kg/m. An extruded, medium density polyethylene oversheath provided the overall corrosion protection.

Table 2. Dimensions of installed 132kV lean cables

Cable details	Dimensions	Dimensions
Conductor area [/mm^{2}²]	185	630
Conductor screen diameter [mm].	21.3	36.2
Insulation diameter [mm].	55.3	65.0
Water blocking layer, diameter [mm].	61.6	68.2
Metallic sheath diameter [mm].	74.0 (CSA)	77.0 (lead)
Polyethylene oversheath diameter. [mm]	81.4	84.4
Cable weight [kg/m]	6.8	20.7

The installation of earlier designs of 132kV XLPE cables would have required 3-4 despatch lengths of cable with 2-3 joint bays with a total of 12-18 joints. Using lean cable technology the cables were laid direct, figure 1, in single installed lengths in excess of 1.5km. The experience gained in routinely transporting and installing large drums of 400kV cable was employed. The despatch drum selected for the 132kV cable was 4.3m in diameter, 2.3m wide and weighed 37t, (note: 1.7km was transported with excess for a diversion).

The route included road crossings in ducts and four sharp bends with angles of 45°, 70° and two of 90°, figure 6. A feature of the installation was the combination of the long cable length of 1.5km together with the high weight of 32t. For the first part of the route the bond pulling technique was employed to transport the cable into the trench, figure 7, whereby a steel hawser is tied to the cable. Having successfully negotiated two sharp 90°, bends a second bond pull was commenced. The cable was nose pulled for the final 200m. The advantage of bond pulling is that the cable is protected both from excessive longitudinal strain and sidewall pressures at bends in the route. Nevertheless, the cable was examined and the polyethylene oversheath then HV tested at 10kV dc for 1 minute and confirmed to be in sound condition and unaffected by the installation procedures.

Figure 7: Pulling-in a 1.5km length of 132kV 630mm² lean cable, the winch for the wire bond is on the left hand side

Urban Development Site

This site was originally a rural single circuit OHL installed in open countryside in the early 1930's and was then de-energised in 1953. A housing estate was constructed in the 1960's and had grown progressively to encompass the towers in the OHL route, figure 2. Following a requirement to re-introduce the circuits into the 132kV system, East Midlands Electricity together with the Local Planning Authority agreed to underground eight spans of OHL as part of their continuing commitment to enhance the environment. The cable was required to have the same winter continuous rating of 691A as the 'green field' installation, thus the same cable design was selected. To minimise the magnetic field at ground level, the circuit was installed in touching trefoil and the ends of the cable were solidly bonded, thereby minimising the external magnetic field [4,6]. The chosen cable route followed a combined cycle track and pedestrian walkway. The route posed no special installation difficulties and permitted the six lengths each of 1.2km, 25t, to be bond pulled in one operation. The cables were connected with straight joints located at mid route.

Figure 8: Brown field commercial development site

'Brown Field' Development Site

This was the location of a recently demolished power station, figure 8. To permit the land to be re-developed for commercial purposes three new cable circuits were installed to re-route existing underground circuits. Lean cable technology was selected for its economical benefits and ease of routing the smaller cables through the congested trench, figure 9. To meet the summer continuous rating of 300A, a 185mm^2 copper conductor was selected. The same insulation and water blocking designs were employed as the 'green field' and 'urban' applications. A 2.5mm corrugated, seamless, aluminium sheath (CSA) was selected to give maximum mechanical protection from third party damage in this congested location. The 500m, 3.4t, lengths of cable were installed by the nose pulling technique, in which the pulling tension is applied directly to the conductor. The trench was reinstated with a selected backfill to give less than a 2.7Km/W thermal resistivity in the dried out state.

It was decided to monitor the operating temperatures of the cables in service throughout their lengths, as a) variations in thermal resistivities were exhibited by the different types of indigenous and reclaimed land and b) local heating

Figure 9: Congested trench in brown field site, with double circuit of 132kV lean cables passing underneath

Figure 10: Inserting optical fibre temperature monitoring cable in centre of trefoil group of 132kV lean cables

could be expected due to the proximity of adjacent cable circuits. An optical fibre monitoring cable was installed in the central interstice of the middle trefoil group, figure 10.

The optical fibre was terminated into temperature profile monitoring equipment installed in the substation control room. The temperature profile was also accessed remotely in the offices of East Midlands Electricity on a PC, via a modem and public telephone line.

A typical temperature profile for September 1998, with the circuit carrying the relatively low load of 114A is shown in figure 11. It can be seen that the temperature along the route varied by 9^{o}C with a maximum temperature of 25^{o}C, this being typical for this low loading.

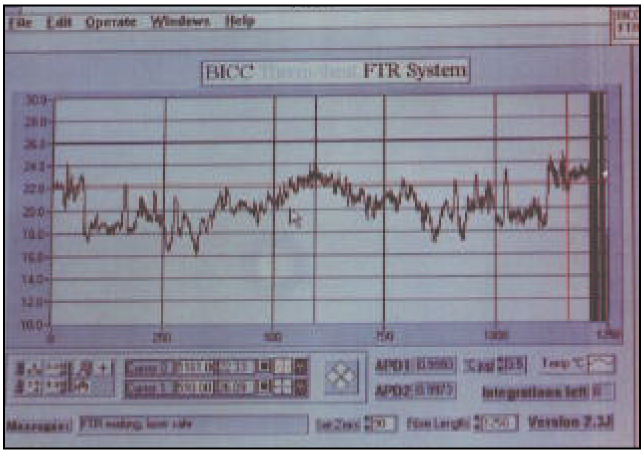

Figure 11: Temperature profile of 132kV cable circuit in a brown field site

TESTING

Type Approval Testing

The philosophy of type testing the 132kV cables and accessories together as a system was based on the CIGRE recommendations for extruded cables and accessories at voltages greater than 150kV [9,10] because the lean cable system employs similar EHV technology and design stresses.

Type Approval Tests were successfully completed and witnessed on miniature 132kV lean cable installations, comprising both the largest and smallest conductor size cables, together with the outdoor terminations and straight joint. Two designs of outdoor termination were tested, one with a conventional porcelain insulator and the second with a composite silicone rubber insulator, the latter being designed for those applications requiring anti-vandal resistance and light weight. The test schedule covered the most onerous parts of international standard IEC 840 [11] and UK national specification EATS 09-16 [12] i.e:

- 20 daily loading cycles at $2U_o$, 95-100^{o}C
- Lightning impulse, 10 +/- shots 650kVp, 95-100^{o}C
- Dielectric security at 3Uo, 4hrs, ambient temperature
- Core and conductor water blocking, 10 daily cycles, 95-100^{o}C, 1m water pressure

After-laying Tests

In addition to lean cable technology, advances have also been made in the techniques of after-laying testing. The previous method of applying a high voltage dc withstand test for 15 minutes to an extruded polymeric cable system has been recognised as ineffective [13] in confirming satisfactory cable installation and accessory assembly and in some cases can be harmful because of a) the generation of space charge within the cable and accessory insulations [13] and b) the increase in dc stress in the accessories. The CIGRE working group report [13] advised that the use of partial discharge measurement in combination with an ac test would provide a “significant improvement in on-site testing”.

A mobile ac test set was designed and constructed, using the variable frequency method to tune a series resonant circuit comprising a test inductor and the cable capacitance. The output was specified to meet the CIGRE recommended test schedules [13] with the objective of applying an ac after-laying withstand test of 1.7Uo for 1 hour, ie 132kV to earth for a 132kV circuit. The maximum output voltage was selected to be 150kV, with a variable power frequency range from 30 to 300Hz on installed lengths of XLPE cables up to 20km [2]. Longer lengths and higher test voltages can be achieved by connecting two test sets either in parallel or series. To provide further verification of the insulation integrity of the installed cable system, partial discharge detection equipment and measuring techniques were developed to be used with the circuit energised, either from the mobile ac test set during commissioning, or from the electricity network as part of diagnostic maintenance. The new test set and measuring equipment have been successfully employed to test 132kV XLPE cable systems in the UK.

CONCLUSIONS

1) The drive to reduce the cost of underground 132kV XLPE cable circuits, together with recent advances in EHV cable technology, has led to the development of a new integrated range of ‘lean’ cables, accessories and installation techniques.

2) Lean cable technology has reduced cable insulation thicknesses, offering typical savings of 17% on installed cable costs.

3) Lean installation technology has significantly reduced the number of joints and joint bays, offering typical savings of 12%.

4) A total cost reduction of 29% is achievable on a typical 5km circuit length.

5) Specific 132kV applications are described in the UK in which the installation of lean cable systems has reduced the cost ratio of underground cable to overhead line to 3:1.

6) The reduced cost of lean cable systems has facilitated the undergrounding of spans of 132kV overhead lines for both a ‘green field’ housing development and an existing ‘urban’ housing estate.

7) The reduced size of lean cable, together with an optical fibre temperature monitoring system, has facilitated the installation of 132kV underground circuits through a congested ‘brown field’ site, freeing its use for commercial development.

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