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Underground Power Cables

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V. UNDERGROUND CABLES

Underground power cables

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Up to the present, effectively all underground power transmission needs have been satisfied by the use of conductors insulated with impregnated paper. In particular, in recent years, the oil-filled cable system using cellulose paper impregnated with oil under pressure has been further developed to meet all immediate and near future needs for higher voltage and higher current power transmission underground.

With modern materials and technology, are there more economical solutions and can the needs of the longer future term be met? The basic electrical, thermal, mechanical and reliability constraints which are exerted upon the design of supertension underground power cable systems are considered. The limitations upon further development of the oil-filled cable system are identified. Also, indications are given of the potentials of new insulating materials and novel constructions of cable to provide more economical solutions and greater power transmission capabilities.

Introduction

The first known public supply of electricity in Great Britain began in 1881 when a small river was harnessed to provide electrical power for lighting the streets of Godalming in the county of Surrey. At that time, there were no legal powers to enable would-be suppliers of electricity to bury cables under streets or footpaths. In consequence, the Godalming cables were laid in the the street gutters.

Since this first 'underground' power cable installation, nearly a century ago, the history of underground power cable technology is innovation in the earlier years followed by evolution in the later years. Most power cable engineers would agree, in retrospect, that only four fundamental advances in underground power cable technology have been made in nearly a century of development. Further, that the fourth of these advances was made just over 50 years ago.

For the earliest underground power cables, established telegraph cable practices were adopted, such as the use of guttapercha for conductor insulation.

The first fundamental advance was made by Sebastian de Ferranti in 1890, when he used impregnated paper for the insulation of 10000 V single phase a.c. concentric cable. The cable construction adopted resulted in production of the cable in straight rigid units, each about 6 m long. The cable system, totalling some 43 km of 10 kV tubular main, required the installation on site of some 7000 straight joints.

The second fundamental advance, a year or so later, was the development of a long length, flexible cable construction by combining a stranded copper conductor with a multi-layer insulation of narrow width, impregnated paper tapes and a directly extruded lead sheath. Underground cables could now be made in lengths of several hundred metres, reeled onto drums for transportation, unreeled for installation, curved to follow sharp bends and installed with relatively few joints.

With the general adoption of the 3-phase, alternating current system, three core versions were developed with all 3 cores enclosed in one lead sheath. To minimize cost, these designs were refined by the introduction of shaped conductors and of the belted construction. As transmission voltages rose from 11 to 33 kV, short life failures occurred due to partial discharge in the electrical field in the spaces between the cores of 3-core cables.

The third fundamental advance, made by Hochstadter in 1914, was the invention of the 'H-type' or screened 3-core cable. This construction confined each phase field to its own core insulation by wrapping each core with metallized paper, the metallizing being at neutral or earth potential.

In the following years it was found that if the a.c. stress in the insulation exceeded about 4 MV/m, there was a serious risk of short life failure. Limitation of the a.c. design stress to 4 MV/m results in cable constructions too large to be practicable for 3-core cables of above 33 kV and single-core cables of above 66 kV.

The cause of the limitation, deduced many years after the limitation was overcome, was the different thermal expansions of the several materials in the cable, the impregnating compound expanding much more than the other materials. Heating and cooling of the cable causes the formation of compound starved spaces, or voids, in the insulation, particularly in the butt gaps. These voids are filled with electrically weak, low-pressure gas drawn out of solution in the compound. At around 4 MV/m a.c., the partial discharge energy in these voids is sufficient to cause carbonization of the paper, the formation of carbon trees and ultimate insulation failure.

The fourth and last fundamental advance was the invention of the Oil Filled Cable System by Dr Emmanuelli in 1920, 53 years ago. He reinforced the lead sheath with metal tapes to withstand internal oil pressure, introduced a longitudinal oil passage into the cable conductor, replaced the normal viscous impregnating compound by a very fluid oil and connected oil storage vessels to the cable at intervals along its route. These storage vessels were designed to accommodate cable oil without exposing it to the atmosphere and also to build up a back pressure as the stored volume of oil increased. In this system, the excess oil volume in the cable, due to cable heating, is passed along the oil passages and out from the cable to the oil storage vessels. When the cable cools, its oil pressure drops and the back-pressure in the storage vessel automatically returns oil to the cable. The cable insulation remains fully impregnated with oil at a positive pressure at all times, preventing the formation of electrically weak voids.

The invention of the oil-filled cable system raised the a.c. electrical strength of impregnated paper insulation from around 4 MV/m to above 40 MV/m. This tenfold improvement removed the previous a.c. electric strength design limitation and enabled the manufacture of practicable, long life power cables for transmission voltages of 132 kV a.c. and higher.

Recent advances with oil-filled cable system

Based on these four fundamental advances, the recent advances stem from the formation of a fully integrated supply authority for England and Wales, over 20 years ago. Integration leads to standardization of both design and performance of electrical plant. The key action, for underground power transmission cables, was the formulation of a 'type approval testing procedure'. This procedure requires any new design of cable system to be successfully submitted to a formal series of electrical, thermal and mechanical tests before it can be approved for general operational use.

In most cases, underground power transmission cables are connected to overhead lines and must withstand the transient voltages arriving therefrom; in particular, transient voltages generated by lightning strokes on or near the overhead line. This duty is recognized in the type approval test procedure by the specification of an impulse voltage test. Twenty impulse voltages, ten positive and ten negative, are applied to each of three prototype cable installations. It is specified that all the cable in these test installations shall have previously been submitted to a severe bending procedure.

TABLE 1. COMPARISON OF IMPULSE TEST AND A.C. WORKING VOLTAGES

r.m.s. value system voltage, V_s/kV	r.m.s. value working voltage, V_w/kV	test value impulse voltage V_p/kV	ratio, V_p/V_w
33	19	194	10.2
66	38	342	9.1
132	76	640	8.4
275	160	1050	6.6
400	230	1425	6.2

In table 1 are given the a.c. working voltages and equivalent impulse voltages, between conductor and ground, for system voltages from 33 to 400 kV a.c. It will be seen that the minimum ratio of impulse voltage to a.c. voltage is 6.2 to 1. A safe a.c. stress for long life would be at least 30 MV/m, whereas the impulse strength of oil-filled cable insulation is about 100 MV/m, giving an electrical strength ratio of about three to one. In consequence, if cables were designed to take full advantage of the a.c. strength they would be submitted to impulse stresses in excess of 180 MV/m and break down. Designed to withstand an impulse stress of 100 MV/m, they have very ample safety margins under a.c. conditions. It will be seen that the impulse/a.c. test voltage ratio decreases as system voltage increases, so that higher a.c. design stresses can be employed for the higher system voltages.

With the cable design limited by impulse strength, a major effort in the last 20 years has been directed towards increasing the impulse strength of oil-filled cable insulation. This work revealed that impulse strength could be increased by: (*a*) using thinner paper tapes, (*b*) using paper tapes of higher cellulosic content, that is, of higher apparent density, and (*c*) using paper tapes of higher air impermeability.

In parallel, it was determined that the bending capability of the cable was very dependent upon the physical characteristics of the paper tapes. The greater the transverse rigidity of the paper tape, the more readily it will slide against the inter-layer frictional forces, without buckling and creasing. The higher the mechanical strength of the paper, the less likely it is to tear due to these frictional forces.

Greater paper tape rigidity and mechanical strength can be obtained: (*a*) using thicker paper tapes, and (*b*) using paper tapes of higher apparent density.

Thus, it was found that one very effective way of increasing impulse strength, the use of thinner paper tapes, could lead to insulation damage when the cable was bent. A study of this problem revealed that the thinner the paper tape, the smaller was the tolerance between minimum and maximum permissible inter-layer frictional forces. The inter-layer frictional forces arise from the paper tensions applied during the paper-lapping process, so that more precise control of these paper tensions were essential to the use of thinner papers. This was achieved by the introduction of electrical servo-control of paper tensions, the pre-set tension being maintained precisely whether the lapping heads are accelerating, running, decelerating or even standing still.

At the same time, it was realized that paper lapped in a normal factory atmosphere has quite a high moisture content. When the core conductor insulated with this paper, is vacuum dried before impregnation, the paper shrinks and the inter-facial pressures are altered substantially. In one technique the paper is pre-dried to a low moisture content and then lapped on to the core in a very low humidity atmosphere. The resultant low-moisture content gives negligible shrinkage in the core-drying process and the lapping tension pattern remains virtually unaltered.

To instance what was achieved by this investigational work, in 10 years the a.c. design stress of 132 kV oil-filled cable was raised from 8.5 to 12.5 MV/m. With the much thinner insulation, there was a substantial economy in the use of materials surrounding the conductor coupled with an increase in current rating.

Over the next 10 years, this work was continued to achieve economic designs of cable for higher voltages, up to 400 kV, and higher conductor currents, up to 1600 A.

Increases in transmission voltage are always accompanied by increases in transmission current, requiring larger conductor cross-sectional areas. Since a cable conductor can bend only by the force applied through the insulation, increase in conductor size, with consequential increase in conductor bending force, imposed a more arduous duty upon the insulation. Considerable development work led to the replacement of round wires in conductor strands by rectangular and segmental strips, to achieve conductors which are compact yet highly flexible.

As conductor size increased to above 1000 mm² of copper, segmental stranded constructions had to be adopted to limit a.c. resistance. Such conductors are mechanically less stable, requiring 10 to 15 % reduction in a.c. design stress to ensure adequate impulse strength in the insulation.

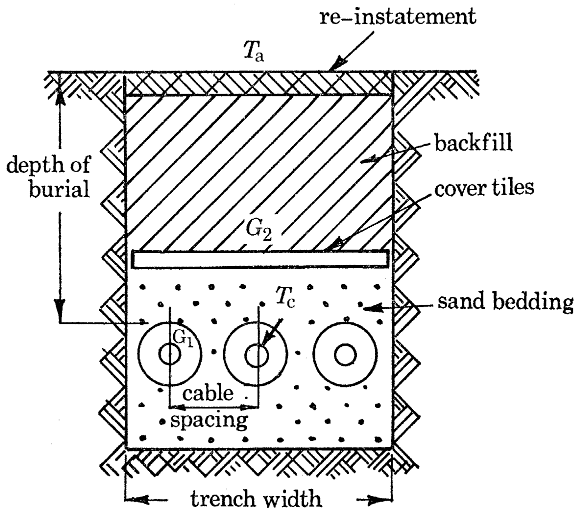


FIGURE 1. Typical direct buried arrangement of single core cables to form a 3-phase a.c. circuit.

Turning to thermal considerations, figure 1 represents the common installation of three single-core cables of flat formation buried in a trench. Supposing that a constant value of 3-phase current has been applied long enough for all temperatures to become stable, the thermal equation for the middle cable is

$$T_{\mathrm{c}} - T_{\mathrm{a}} = I^2R(G_1 + kG_2) + W_{\mathrm{d}}(\tfrac{1}{2}G_1 + kG_2) + W_{\mathrm{s}}kG_2,$$

where T_{c} is the conductor temperature, T_{a} is the ground surface temperature, I is the conductor current, R is the a.c. resistance of the conductor, G_1 is the thermal resistance between conductor and sheath, G_2 is the thermal resistance between sheath and ground for one cable buried alone, k is the factor, greater than unity, which corrects for the effect of three cables sharing external heat paths, W_d is the dielectric power loss in the insulation, and W_s is the power loss in the sheath.

By inspection, the conductor current can be increased by raising the conductor temperature and by reducing the value of every other factor in the equation.

The maximum permissible conductor temperature is decided by the rate of thermal ageing of the cellulose, the rate doubling for every 8 to 10 °C increase in temperature. For a cable on a cyclic rating duty, a life in excess of 40 years can be expected with a maximum conductor temperature of 85 °C.

Increases in conductor resistance, due to skin and proximity effects, become significant for copper conductor for cross-sections in excess of 1000 mm^2. To minimize these effects, a segmental stranded construction, called the Miliken construction, is employed. Use of this construction reduces the a.c. resistance by more than 25 % for a copper conductor cross-section of 2000 mm^2, equivalent to an increase in current rating of over 10 %.

The internal thermal resistance of the cable, G_1, is a function of the dimensions of the cable and the thermal resistivity of the insulation. Higher a.c. design stresses giving thinner insulation walls result in lower internal thermal resistance. The thermal resistivity is dependent to a limited degree only upon paper characteristics.

The external thermal resistance, G_2, is dependent upon cable depth and the thermal resistivity of the cable environment. In normal situations, such as city streets, the cable depth is decided by safety considerations and is usually about 1 m. However, in special cases, such as canal towpaths, the cables can be laid in a concrete trough at the ground surface, with a substantial improvement in current rating and a considerable reduction in civil costs.

The thermal resistivity of undisturbed ground is dependent upon the type of ground and its moisture content. The moisture content can vary day by day, seasonally and even annually. Direct measurements of ground thermal resistivity can be very misleading unless all these factors are taken into account.

In practice, the surround immediate to the cables is not thermally homogeneous since even digging and refilling the trench will alter the thermal resistivity. In addition, it is normal practice to fill the lower part of the trench with imported sand to prevent superficial damage to the cables during installation and operation. Experience has shown that a predictable, reasonably low value of thermal resistivity for the sand can be achieved by selecting sand with a suitable distribution of grain size, placing in the trench with a suitable moisture content and compacting it in the trench to an adequate degree.

If cables are operated at or near maximum current for long periods of time, the sustained high temperature of the cable surface drives moisture radially away from the cable surface and the cable surround progressively dries out. The mechanism is cumulative since dried out material has a higher thermal resistivity and raises the cable temperature. As a crude judgement, all the material at a constant temperature higher than 50 °C is liable to dry out.

The dried out thermal resistivity of even selected sands is often too high for economic system design. To deal with these cases, special backfills were developed, such as cement-bound sand, sand/gravel mixture and bitumen-bound sand, which have relatively low thermal resistivities when dried out. Much more expensive, they require careful control in formulation and installation.

Before stabilized back-fills became available, cooling water pipes were laid alongside the cables in special cases to compensate for the possible drying-out of the cable sand. Current opinion is that stabilized back-fills, even if larger conductor sizes are required, are far preferable to the complications of a closed circuit, water cooling system.

A very recent development, associated with surface trough installations, is the technique of irrigating the cable surround, using controlled water flow from porous pipes, buried jets or pop-up sprays, to maintain an adequate moisture content.

The factor k in the thermal equation is dependent primarily upon the spacing between the cables in the flat formation. Increased spacing gives a reduced value of k.

The dielectric power loss, W_d, is directly proportional to the square of the system voltage, the cable capacitance per unit length and dielectric loss angle of the insulation. With the dependence upon square of the voltage, the dielectric power loss of impregnated paper insulation becomes significant at 132 kV and very substantial at 400 kV.

It must be appreciated that increasing the a.c. design stress increases the cable capacitance. Both insulation permittivity to a small degree and dielectric loss angle to a larger degree can be reduced by using paper tapes of lower apparent density, in opposition to the requirement for improved impulse strength and bending performance.

A worthwhile improvement in dielectric loss angle has been achieved by the use of deionized water in the later stages of paper manufacture to remove residual ionic contamination. This treatment also gives a lower rate of increase of dielectric loss angle at the higher temperature end, reducing any tendency towards thermal instability in the event of a transient thermal overload.

The last factor in the thermal equation is the sheath loss, W_s, resulting from currents induced by the 3-phase a.c. magnetic field. One component is due to current flowing along the sheath and the other due to eddy currents, with both proportional to conductor current and dependent upon cable spacing. The cross-bonding system was introduced to eliminate the sheath circulating current but generates a standing voltage in the sheath which must be insulated from ground. The wider the cable spacing, the greater the voltage per unit cable length and the more frequent must be the sheath interruptions in the cross-bonded system. So increasing cable spacing to reduce the value of factor k, and raise the conductor current, increases the number of cable joints in a cross-bonded circuit.

The magnitude of the eddy current loss can be modified only by choice of sheath material, being lower for lead and higher for aluminium, since the remaining factors controlling it are decided by other considerations.

Thermal loading of the cable has mechanical consequences. If a virgin direct buried cable is submitted to continuous full load current, the conductor temperature will rise to about 85 °C over a period of several days to several weeks. The theoretical expansion of the copper conductor would be about 1 m in 1 km. With the cable prevented from snaking, the expansion has to be prevented by the build-up of a compressive force in the conductor. Due to the stranded nature of the conductor, frictional forces within the cable and the relatively slow increase in temperature, the resultant compressive force is about 40 to 50 kN (4 to 5 tonf) per 1000 mm^2 conductor cross-section. The factors which reduce the compressive force also give the effect of a much lower yield point than for copper itself. When cooled to ambient, the conductor attempts to contract to a smaller length than in the virgin state, so that a tensile force is generated. This effect is cumulative so that after a number of loading cycles, 'hot' compressive force and the 'cold' tensile force are both equal to about half the original compressive force, say 20 to 25 kN (2 to 2.5 tonf) per 1000 mm². Joints and terminations are designed to withstand both the original compressive load and the subsequent tensile load.

Where the cable passes from a fully restrained condition, i.e. direct burial, to an unrestrained condition, i.e. in a duct, there is a possibility of conductor movement within the insulation due to the conductor forces, opposing one another at the transition, being unequal. A special joint, to anchor the conductor, is sometimes employed.

From the foregoing, it is obvious that the apparently simple supertension cable is, in fact, a very complex piece of equipment. Design of cable and cable system is a compromise between opposing requirements; any action to improve performance in any one respect has a consequential weakening effect upon performance in another respect.

Further development of the oil-filled cable system

In recent years, the trend of increasing current has continued without further increase in transmission voltage. The rating of normal duty overhead lines for 275 and 400 kV is being increased above the previous rating of 1600 A by permitting increase in operating temperature. Also heavy duty lines have been introduced with original ratings of 3200 A which are being up-rated in the same way.

The thermal equation for a buried cable can be simplified and rearranged to give, to a crude but adequate approximation that $I \approx K\sqrt{A}$ where I is the conductor current, K is a constant and A the conductor cross-section. This equation reveals that doubling the current requires a quadrupling of the conductor size and, thus, a halving of the conductor current density.

For copper conductors, $I \approx 35\sqrt{A}$, where A is in square millimetres. For 1600 A, a conductor size of about 2000 mm² (3 in²) is required, whereas for 3200 A, a conductor size of about 8000 mm² (12 in²) is indicated, a virtually impracticable proposition.

To transmit 3200 A with a practicable conductor size, say 2000 mm², quadruples the conductor losses compared with naturally cooled 1600 A cable. Forced cooled systems have been developed to remove most, if not all, these losses by artificial cooling.

One artificial cooling system encloses conventional cables in separate pipes through which cooling water is circulated in a closed system, the cable heat being removed from the water by external water to air heat exchangers. The thermal equation for this system is

$$T_c - T_w = I^2R(G_1+G_2+G_3+G_4) + W_d(\tfrac{1}{2}G_1+G_2+G_3+G_4) + W_s(\tfrac{1}{2}G_3+G_4)$$

where T_w is the water temperature, G_1 is the insulation thermal resistance, G_2 is the heat transfer thermal resistance from insulation to sheath, G_3 is the sheath and oversheath thermal resistance and G_4 is the heat transfer thermal resistance from oversheath to water.

For 400 kV, 3200 A it is possible to use conventional cable, 13.5 MV/m a.c. design stress, with a maximum water temperature of about 20 °C. Higher current with conventional cable results in too low a maximum water temperature for heat extraction by conventional water/air heat exchangers. However, a system to carry a peak loading of 3780 A is being installed in a cable tunnel under the Severn and Wye rivers. To carry this higher current, the cable design has been stretched by raising the maximum conductor temperature to 100 °C while increasing the a.c. stress to 15 MV/m and expanding the diameter of the conductor duct to reduce the cable thermal resistance in order to retain the maximum water temperature at an adequate value for water/air heat exchange.

An alternative system employs a large diameter conductor duct through which is circulated cable oil, the heat from which is extracted by external oil/air heat exchangers. The thermal equation for this system is more complicated since heat can flow inwards to the oil and outwards to the environment so that the hottest region in the cable is not at the conductor but somewhere in the middle of the insulation. In the extreme, supposing no heat loss outwards

$$T_s - T_o = I^2 R G_1 + W_d(G_1 + \tfrac{1}{2}G_2) + W_s(G_1 + G_2 + G_3),$$

where T_s is the sheath temperature, T_o is the oil temperature, G_1 is the heat transfer thermal resistance from conductor to oil, G_2 is the insulation thermal resistance, and G_3 is the heat transfer thermal resistance from sheath to insulation.

Prototype aluminium and copper conductor versions of this system are on test at West Thurrock in Essex and the aluminium conductor version has almost completed the full test schedule.

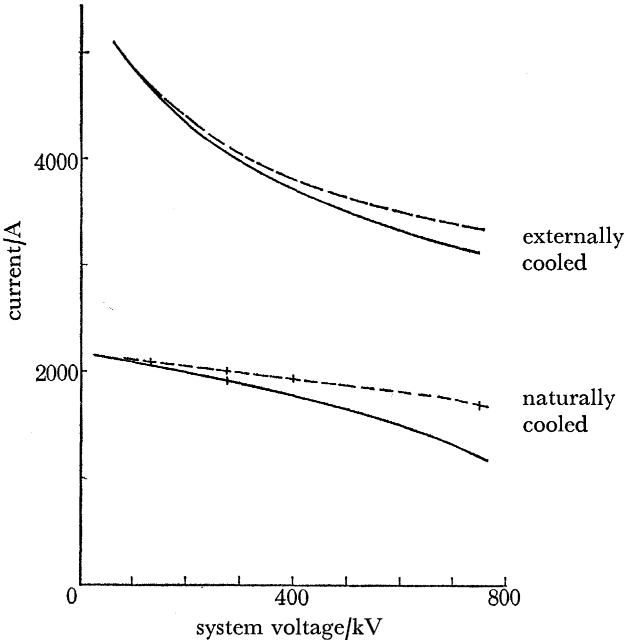


Figure 2. Potential a.c. current carrying capability of oil-filled cable, both naturally and force cooled. ---, synthetic insulation; ——, cellulose insulation.

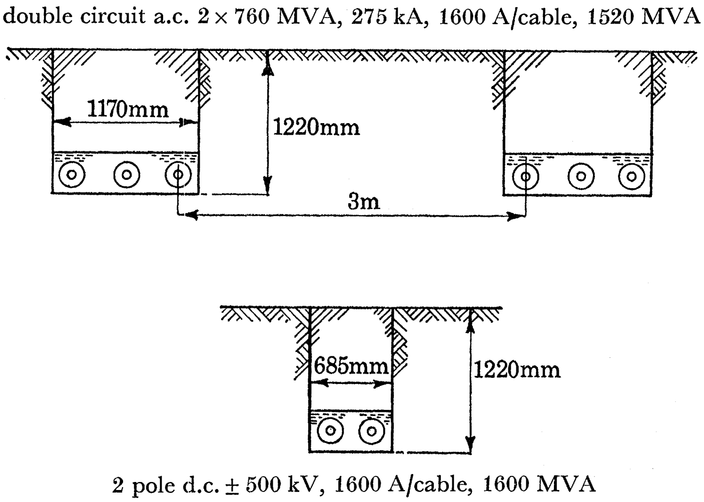
Looking forward to even higher transmission voltages and currents, figure 2 shows the potential capability of oil-filled cable in both natural and externally force cooled versions. The internally cooled version has even greater potential dependent upon practicable maximum cooling section length. The dotted lines indicate the advantage to be gained from replacing the cellulose paper by a hypothetical material of near identical electrical and thermal characteristics except that it has zero dielectric power loss.

The majority of the paper has been devoted to impregnated cellulose paper insulation in a necessarily cursory way. However, it has established that this insulation has potential for even further development to meet the needs of the future.

A.c. or d.c.

Before turning to novel insulations and cable constructions, an alternative method of power transmission must be considered, high voltage, direct current.

With a totally underground d.c. transmission system, design d.c. stresses up to 40 MV/m could be employed. The current Kingsnorth–Willesden 266 kV d.c. cables employ 33 MV/m.


double circuit a.c. 2 × 760 MVA, 275 kA, 1600 A/cable, 1520 MVA

2 pole d.c. ± 500 kV, 1600 A/cable, 1600 MVA

Figure 3. Comparison of a.c. and d.c. power transmission capacities using 2000 mm^2 275 kV a.c. cables.

Figure 3 compares the power carrying capability of one design of cable for both 275 kV a.c. and 500 kV d.c., showing that for about the same power carrying capability, d.c. requires one-third the number of cables and about one-third the excavation volume, so, one-third the cost of its a.c. equivalent. This is no optimistic comparison since with d.c. there would be no conductor skin and proximity effects, no dielectric losses and no sheath losses. However, with naturally cooled or externally cooled d.c. cables a design limitation arises from the temperature dependence of the insulation electrical resistivity. As the temperature gradient between conductor and sheath increases, the electrical stress increases in the outside of the insulation and decreases at the conductor. To avoid excessive stress at the dielectric screen, the heat flow through the insulation must be limited. The limitation results in a maximum current carrying capability of about 3000 A. With impregnated cellulose paper insulation this limitation can be removed and higher currents are potentially available.

Achievement of this potential cost reduction to one-third or even less depends not upon the cable designer but upon the a.c./d.c. converter station designer, who must seek compactness and reduced cost in his design (see Calverley's and Banks's papers in this volume).

From the thermal equations it is obvious for the higher voltages and higher powers with a.c., insulation with a lower permittivity, lower dielectric loss angle and lower thermal resistivity could be advantageous for naturally cooled cables. For force-cooled cables and d.c. cables, reduction in insulation thermal resistivity would be most advantageous.

Novel insulations and cable combinations

Polythene is a material with very advantageous characteristics, and has been so for more than thirty years. It has about two-thirds the permittivity, one-tenth the dielectric loss angle and half the thermal resistivity of impregnated paper.

As extruded solid insulation it suffers from a major electrical weakness from two causes. Partial discharge can occur due to small voids in the apparently solid insulation or be generated by the stress raising effects of discrete impurities. At this time the electrical potential of extruded polythene or any similar polymeric material has not been realized, certainly not on a commercial scale.

To overcome the void problem, attempts are being made to use polymeric film tape insulation impregnated with oil under pressure. A major problem arises from chemical incompatability of polymer and oil, giving substantial swelling of the polymer. Exotic combinations such as polyphenyloxide and silicone oil do minimize this problem but at a greatly increased material cost.

Attention has turned to laminates of paper and polymeric film with which the potential of polymeric material can be partially realized and the incompatability problem is substantially lessened. Prototype 132 kV a.c. cables are currently giving encouraging test results.

Also, work is going on with polymeric paper, a paper manufactured from a pulp of polymeric fibres. Such a material lessens the swelling problem but introduces a major problem of lack of mechanical strength of the polymeric paper.

An alternative route, followed by the C.E.R.L., has been to replace cellulose paper tapes by polymeric film tapes and cable oil by high pressure electro-negative gas. Two fundamental problems arise which could be well on the way to solution. First, electrical contact problems arising from the very different coefficients of thermal expansion of the conductor material and the polymeric insulation. Secondly, additional thermal resistance arising from the thin gas films between the successive layers of polymeric tape.

Turning to novel cable constructions, the first example uses an insulation of pressurized electro-negative gas, such as sulphur hexafluoride. The cable consists of two concentric aluminium tubes held apart by loaded epoxy resin spacers at 2 or 3 m intervals. Prototype commercial installations, being installed and commissioned in the U.S.A., use rigid, thick tubes of diameter of around 30 and 60 cm for inner and outer electrode respectively. The cable is produced in unit lengths of about 6 m. The cable termination is very simple and this rigid, low electrical stress design is suited to short length, very high power and vertical shaft duties but has little potential for the majority of applications. Attempts are being made to develop more compact, higher electrical stress, flexible versions which would be much more likely to be competitive with conventional cable constructions. However, problems multiply disproportionately to the inverse of diameter.

Turning to superconductivity, the concept of loss free power transmission, the details are best left to Baylis (this volume, p. 205) but one comment is well worth making. As with conventional cables, the prime cost of a superconducting cable system could be dramatically reduced by changing from 3-phase a.c. to d.c. transmission, probably with much lower voltages and higher currents than are appropriate to conventional power transmission.

The final major investigation is into the intermediate temperature cable, the resistive cryogenic cable, using aluminium or beryllium conductors operating at around liquid nitrogen temperature. Current assessments show no substantial advantage for this construction.

To complete this contribution, may I make several remarks which I believe are highly relevant. Like any other electrical plant, an underground power cable has to be capable, economic and reliable.

On the question of capability, a nominal rating is specified which does not represent the real duty that a cable has to perform. Particularly, that a sustained maximum current rating may be specified when the real requirement is for a long term but limited period emergency rating capability. This can and does result in a more expensive cable than is really required.

Further that, as shown in the earlier part of this paper, the oil-filled cable system has technical potential for development to meet the needs of the future for some years ahead. In consequence, novel constructions are not essential on the grounds that there will be no conventional cable solution.

On the question of economy, any novel system must not be compared on a cost basis with past designs of conventional cable but with future designs which are or could be evolved. Further, with a total domestic market of about £4000000 per annum for 275 and 400 kV cable systems, to be shared between two manufacturers, the current cable prices are far from representative of what would obtain if the use of underground power circuits greatly increased, as is occurring in the U.S.A. No novel system shows substantial advantage over conventional cable solutions and any such advantage could disappear if the annual demand for cable circuits was even doubled. The same market volume argument applies to a.c./d.c. conversion equipment; replace 'one off' at infrequent, irregular intervals by 'many off' at frequent, regular intervals and the unit cost of underground power transmission could be dramatically reduced. Finally, the questions of capitalized losses and replacement generation costs have yet to be fully explored. It may be that accountancy would indicate that we should invest for the future whereas investment availability prevents us from doing so.

Turning to the question of reliability, underground power transmission cable systems are expected to have lives of 40 years or more, with minimum preventative maintenance and certainly minimum interruption of duty. Outages are of concern according to their frequency and their durations. Underground power cables are expected to be much more reliable in terms of outage frequency because the outage duration, for repair to take place, is much longer than for the overhead line. Recorded outage times for high-power underground cables can be misleading since, when they do occur, both customer and supplier wish to obtain the maximum possible information from the incident, to determine whether any change in design is required.

However, the future reliability of the oil-filled cable system, evolved to cope with higher duties, can be predicted with some substantial confidence from the long experience with previous operational use of this system. Only the possible troubles of the actual limited advance in technology need give grounds for concern. Novel insulations and cable constructions involve not a limited advance with a well-established technique but the introduction of completely novel techniques, each with its own as yet unrevealed installational and operational difficulties.

Summing up, my own organization is fully involved in the research and development of novel insulations and cable constructions in parallel with further development of the oil-filled cable system. We are striving to get the right perspective and balance so that progress is not identified solely by novelty but by the optimum blend of capability, economy and reliability.