

Statistics of AC underground cable in power networks

Preamble

In the mid 1990s CIGRE Study Committees 21 (HV Insulated Cables) and 22 (Overhead lines) set up a Joint Working Group to compare high voltage overhead transmission lines and underground cables. The report (TB 110) examined the extent to which the two systems were used worldwide and the cost implications. In 2003 CIGRE Study Committee B1 established a new Working Group (WG B1.07) to update the work done in the 1990s.

The terms of reference of WG B1.07 are:

- *To collect statistics for the lengths of underground and overhead circuits at a range of transmission voltages. Only existing lines and projects planned for implementation by 2006 should be included,*
- *To describe significant underground cable projects realised in the period 1996-2006 giving the reasons why undergrounding was selected,*
- *To describe the factors which must be considered when evaluating the cost of overhead or underground connections,*
- *To describe the other factors which must be taken into account in order to make a balanced choice between overhead and underground technology.*

Submarine cables are excluded from the scope of work. DC cables are also excluded since these are predominantly submarine. The voltage range is restricted to system voltages from 50 kV, which limits the scope to transmission systems and the high end of the distribution voltage range.

Introduction

Chapter 1 of the Technical Brochure (TB) sets out the background to the present work and details the scope

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and Terms of Reference of WG B1.07.

Some significant changes have taken place since the 1996 report was published. A number of weather-related incidents on overhead lines have led some utilities to revise their meteorological design parameters leading to increased costs. Technical changes and strong competition in the cable sector have reduced prices. Increased urbanisation and public

concerns have increased the difficulty and time taken to obtain consents for overhead lines. There have been broad changes in the structure of electricity supply and in the nature of demand, for example the load peak in some regions is shifting from winter to summer. In view of these changes WG B1.07 has updated the statistics on circuit lengths and produced guidance on the technical and cost factors influencing the choice between underground cable and overhead line.

The Brochure also looks at some of the main technical factors which influence the cost and complexity of underground cable systems.

Some significant cable projects undertaken in the last 10 years are described. The definition of a significant cable project is difficult. The WG decided that it is a cable project at 50 kV or above, which is likely to be of broad international interest and containing some element of innovation. The project can be significant in engineering, commercial, environmental or social terms.

The brief project descriptions give basic details of the cable type, installation methods and the reasons for their choice. Details of the power carrying capability (rating) are generally included together with information on why underground cable was selected rather than overhead line. ● ● ●

Statistics of installed lengths

Data on the lengths of ac underground cable and overhead line currently installed were collected by a questionnaire sent to Study Committee members. The statistics were divided into five voltage ranges chosen in order to group together similar design and operational principles. The voltage ranges are 50-109 kV, 110-219 kV, 220-314 kV, 315-500 kV and 501-764 kV.

In some cases, data capture proved difficult, particularly for countries with a multitude of small independent utilities (for example the USA and Germany). In addition, the national systems for maintaining such data have been discontinued in some countries, as utilities have been released from state control and experienced reorganisation, merger and acquisition.

Chapter 2 of the TB reports on the circuit lengths of ac overhead line and underground cable currently installed not the increase in length since the 1996 report. The total length of underground cable circuit expressed as a percentage of the total circuit length is shown in Figure 1. The results show that the large majority of circuits are overhead. The proportion of circuits that are underground falls from 6.7% for the 50 to 109 kV range down to 0.5% for the 315-500 kV range.

The TB gives the circuit lengths installed in each country. As an example, Figure 2 shows the proportion of circuits that are underground in the 220 to 314 kV voltage level.

In order to simplify data collection, little technical detail was included in the questionnaire. However, where possible, respondents were asked to split the lengths of underground cable into those using lapped paper technologies and those using extruded polymeric insulation. The results are shown in Figure 3.

The decreasing proportion of extruded insulation used at the higher voltages reflects the incremental development of these cables. Lower voltage, low stress cables were developed first and as the technology improved extruded insulation was applied to higher voltages and used at higher stress. 50 kV extruded cable has been in use since the early 1960s, whereas 400 kV and 500 kV transmission circuits using extruded insulation were not introduced until around 2000.

The data on installed lengths clearly show that utilities have a strong preference for overhead lines rather than underground cables. For the 50 kV to 109 kV range, 93% of the network is overhead. This value increases to 100% overhead at the 501-764 kV level. ●●●

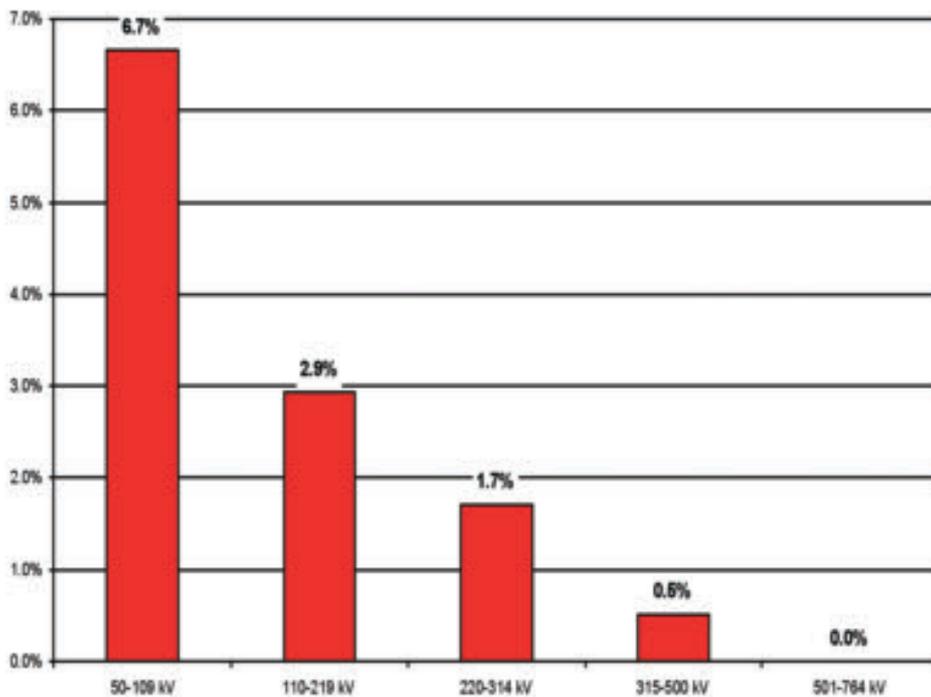


Figure 1: Percentage of the total circuit length that is underground for each of the 5 voltage levels

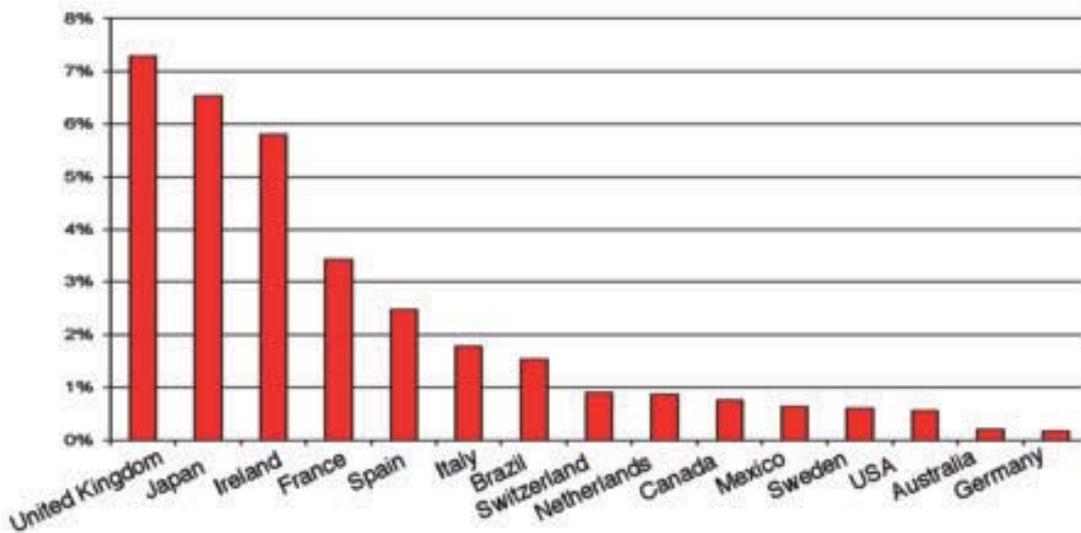


Figure 2: Percentage of the total ac circuit length underground in the 220 – 314 kV voltage range

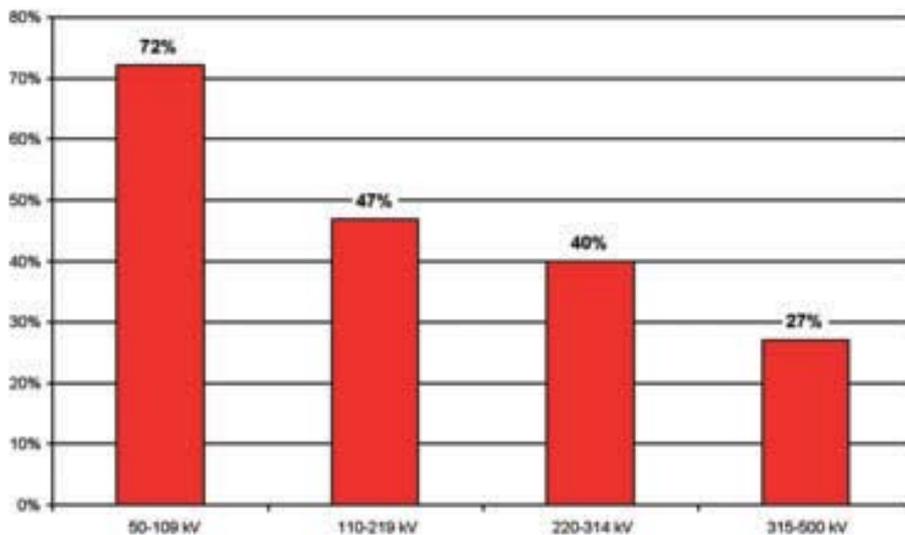


Figure 3: Percentage of the ac underground cable which has extruded polymeric insulation

Technical Considerations

The factors which cause underground circuits to be technically more complex and hence generally more expensive than overhead lines are considered in Chapter 3, together with the reasons why this situation becomes worse at higher voltages.

Underground cables in transmission networks have generally been used in areas where it is not possible to use overhead lines. This is often because of space constraints (e.g. in densely populated urban areas or within

substations) or for technical reasons (e.g. for wide river and sea crossings). The preference for overhead lines is mainly on the grounds of cost and this driver becomes stronger as the voltage level increases.

The brochure describes the main technical differences between the underground and overhead transmission of bulk electric power under 3 inter-related headings:

- Electrical insulation of the conductor
- Heat transfer to prevent overheating
- Construction work necessary to install the circuit



Recent developments to reduce the cost differential between underground cables and overhead lines are also reviewed.

Electrical Insulation

The overhead conductors of the transmission network are operated at a very high voltage with respect to earth or ground. These bare conductors are strung between steel towers which are usually set in concrete foundations. The surrounding air provides the necessary electrical insulation to earth.

When conductors are buried in the ground, insulating material must be applied to the conductors. Traditionally cables were insulated with oil impregnated paper, kept under pressure to maintain the integrity of insulation. More recently solid insulated cables have been developed predominantly using cross-linked polyethylene (XLPE) insulation. These became commonly used at voltages up to 60 kV in the 1960s and 70s. Development has continued steadily and this type of cable is now widely used, even at 400 and 500 kV.

Heat transfer

A significant proportion of the additional cost and complexity of placing circuits underground results from the problem of removing waste heat from the cable.

For an overhead line conductor, energy is lost due mainly to the resistance of the conductor. The lost energy is converted to heat and is proportional to the square of the current flowing in the conductor.

An underground cable has this conductor loss, but also has additional losses due to currents induced in the sheath and to losses in the insulation. This loss is proportional to the square of the voltage on the cable and is present even if the cable is carrying no useful current.

For an overhead line, the surrounding air not only provides the necessary electrical insulation to earth but it also cools the conductors. In an underground cable, the electrical insulation will act as thermal insulation and impede the transfer of heat away from the conductor. The soil can present a significant thermal barrier, particularly if it is dry. It is common practice to surround the cable with a specially selected backfill to enhance the dissipation of heat.

An underground cable not only has additional sources of loss compared with an overhead line, but also has less effective heat dissipation. It is therefore important to keep the cable losses as low as possible, particularly for very high

power circuits. This is often done by using a conductor of larger cross section than the equivalent overhead line, in order to reduce the electrical resistance. A further reduction can be obtained by using low resistivity copper for the conductor. (Overhead lines generally use aluminium alloy conductors to reduce the weight). Whilst the resulting underground cable has significantly lower resistance than its overhead counterpart, the use of a large copper conductor results in a cable conductor that is substantially heavier than that of the equivalent overhead line.

It is more efficient to transmit large quantities of electric power at higher voltages. However, this has two important consequences for very high voltage circuits. Firstly, they must be extremely reliable. Interruption to the supply would affect either a large number of domestic customers or some very large industrial users of electricity. Secondly, the large power transfer is accompanied by the production of a significant amount of 'waste' heat.

The combined requirements of extremely high reliability and good heat dissipation mean that as the power and voltage of an underground cable increase, so does its size and the complexity of construction works.

Construction and Installation

Putting the cables underground is a significant part of the cost of a project. The cost varies widely depending on the ease of access along the route and the amount of power to be transmitted. The TB describes how the need for adequate heat dissipation determines the size and spacing of trenches and the overall extent of construction work.

In urban areas, the costs of cable installation tend to be significantly higher than in the countryside. In the city, there are likely to be a large number of crossing services, for example gas, water and telecommunications. This restricts the use of mechanical diggers and parts of the trench have to be dug by hand. The trench walls usually have to be supported in order to work safely. Additional costs arise from the need to manage the traffic flow and from the restrictions often placed on the hours of working in order to reduce inconvenience to local residents. For minimum disruption, cables can be installed in deep bored tunnels. This is an expensive method, but in major cities it is sometimes the only practical option.

In rural or open areas, the costs of cable installation are likely to be reduced. A mechanical excavator can often be used to dig the trench and there may be sufficient space and suitable soil conditions to dig a trench with unsupported sloping walls. ● ● ●

There may be significant additional costs with large-scale rural undergrounding in order to preserve the natural environment (for example watercourses, hedgerows and woodlands). Special techniques such as directional drilling may be used for crossings under roads, railways and waterways.

Electrical Design

The electrical design of underground systems is briefly described. Aspects covered include: fault clearance and protection, special bonding, and reactive compensation.

Operation

There are significant differences in the way in which underground cables and overhead lines affect the operation of the power system in areas such as: security of supply, fault repairs, routine maintenance and safety.

Reducing the cost of undergrounding

A number of techniques are being used in an attempt to reduce the cost differential between underground cables and overhead lines.

Improvements in cable design are leading to lighter cable and hence longer drum lengths, leading to reduced cost and shorter installation times. The cost of installation can be reduced by the use of mechanised laying techniques, particularly for low power cables in rural environments.

There may be circumstances in which a cable has to be connected to an overhead line whose rating is far greater than the present day need. It may be economic to install a cable that meets the present day requirements and then install a second cable per phase once the load has grown sufficiently. For a ducted cable system it may be more economic to install spare ducts during civil work for the initial installation.

Temperature measurement and real-time rating techniques also provide an option for deferring expenditure by extending the time for which the existing cable meets the need.

Cost Factors

Chapter 4 examines how to evaluate the cost of underground transmission circuits and how to compare these with overhead systems.

Cost Ratios

Cost ratios are often thought of as simple way of comparing costs, for example saying an underground cable is 10 times as expensive as overhead line. In reality there can be a wide range of values quoted for apparently similar circuits and this leads to confusion and mistrust between the various stakeholders.

Small changes in the design of the circuit can produce large changes in cost ratios and, in financial terms, the ratios have little meaning. It is the added cost of undergrounding that is important and must be weighed against the benefits (largely visual) that it brings.

In the 1996 study, the Joint Working Group tried to gather international values for cost ratios, but as might be expected the results were of limited use. For circuits operating at voltages between 220 kV and 362 kV, cost ratios ranged between 5 and 21. The quoted ratios vary widely, because they are highly dependent on local circumstances (including terrain, land costs and power flows).

The present WG considered the option of collecting international costs for a well-defined 'typical' cable circuit, but it is even difficult to obtain international consensus on what might constitute a 'typical' cable circuit. We concluded that it is not possible to collect a consistent set of data for overhead and underground costs that would give more reliable cost ratios than those obtained in 1996.

The only reliable method of comparing overhead and underground costs is on a case by case basis. Generic values of cost ratio are of very limited use and should be avoided. Estimates for the costs of underground and overhead options for a specific project must be calculated and then weighed against the advantages and disadvantages of each option.

Components of cost for cable systems

Costs can be estimated for the various stages of the cable's lifecycle:

- Planning/Design
- Procurement
- Construction
- Operation
- End of Life

In general the early capital costs, particularly procurement and construction, are usually found to be the ●●●

most significant. They are immediate and tend to be larger than later costs such as repair and maintenance and hence have most effect on the financing of projects.

Later costs can be very difficult to estimate. It is particularly difficult to estimate both the magnitude and the cost of future electrical losses. The magnitude of losses are highly dependent on how heavily the line will be loaded and the cost of the losses depends on factors such as the cost of fuel and the availability of surplus generation capacity. None of these factors are easy to estimate even in the short-term. Estimating their likely values in 40 years' time is extremely difficult, particularly in a deregulated environment.

By analysing the underground cable costs for each stage of the cable's life, it is easier to assess which costs are important and which estimates are least reliable. A similar methodology can be used to estimate the cost of the equivalent overhead line.

Comparing underground and overhead options

The only reliable way of comparing the costs of underground and overhead options is on a case by case basis. There is no general answer to how the costs compare. In Chapter 3, technical options for reducing the cost of undergrounding were discussed. These often involve a willingness to be flexible in the design of installations rather than just accepting a standard design solution. This in itself makes the concept of a standard cost for a circuit untenable.

Historic values of underground and overhead costs are often a poor guide to present day costs. The price of underground cable is strongly influenced by fluctuations in the commodity price of raw materials such as copper. It is also expensive to manufacture and store large stocks of cable, particularly for the very high voltages. In consequence the price of underground cable is very sensitive to the balance between demand and manufacturing capacity.

The other problem with using historic values of underground and overhead costs is that underground cable has traditionally been used mainly in the centres of towns and cities with overhead lines being used for rural transmission circuits. There has therefore been a tendency to compare the cost of urban underground cable with that of rural overhead line, which may give an inaccurate comparison.

For each project, the costs of underground and overhead options must be calculated and these can then

be compared. Once the cost difference has been calculated, this can be compared with those benefits and threats which are more difficult to express in monetary terms. These include factors such as visual intrusion, threats to sensitive habitat and damage to archaeological heritage.

There are also land-use issues which need to be considered, where the installation of an overhead or underground line might restrict future options for either agriculture or suburban building development.

Factors such as visual intrusion and threats to sensitive habitat are not generally the same along the whole route. In some cases partial undergrounding is an opportunity for compromise. However, the transition from overhead to underground can have significant impact on the local environment and adjacent short sections of undergrounding are unlikely to be desirable.

However even that generalisation may be unwise without considering the details of a specific case. Only by calculating the cost differential between underground and overhead options for a particular circuit can this be weighed against the other benefits and threats to give a rational basis for a decision.

Conclusions

Chapter 5 summarises the WG's conclusions.

The data on installed lengths clearly show that utilities have a strong preference for overhead lines rather than underground cables. For the 50 kV to 109 kV range, 93% of the ac network is overhead, increasing to 100% overhead at the 501-764 kV level.

Cost ratios are volatile; in particular, they are highly sensitive to small changes in overhead line cost and as a result they must be used with extreme caution.

Small changes in the design of the circuit can produce large changes in cost ratios and, in financial terms, the ratios have little meaning. It is the added cost of undergrounding that is important and must be weighed against the benefits (largely visual) that it brings.

In the 1996 study cost ratios ranging between 5 and 21 were quoted for circuits operating at voltages between 220 kV and 362 kV. The quoted ratios vary widely, because they are highly dependent on local circumstances (including terrain, land costs and power flows). ●●●

The present WG concluded that it is not possible to collect more reliable cost ratios than those obtained in 1996.

The only reliable method of comparing overhead and underground costs is on a case by case basis and generic values of cost ratio are of very limited use and should be avoided. Estimates for the costs of underground and overhead options for a specific project must be calculated and then weighed against the advantages and disadvantages of each option.

Once the cost difference has been calculated, this can be compared with those benefits and threats which are more difficult to express in monetary terms. These include factors such as visual intrusion, threats to sensitive habitat and damage to archaeological heritage.

There are also land-use issues which need to be considered, where the installation of an overhead or underground line might restrict future options for either agriculture or suburban building development.

Factors such as visual intrusion, threats to sensitive habitat, etc. are not generally the same along the whole route. In some cases partial undergrounding is an opportunity for compromise, but the transition from overhead to underground can have significant impact on the local environment and adjacent short sections of undergrounding are unlikely to be desirable.

Underground cable systems are often tailored to meet specific local conditions, but the same solution may not be applicable elsewhere. Hence, even for the same voltage and power, the costs of an underground cable system can vary widely. This makes it difficult to generalise the cost of a typical underground cable system.

Only by calculating the cost differential between underground and overhead options for a particular circuit can this be weighed against the other benefits and threats giving a rational basis for a choice between overhead and underground transmission. ■

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