STATISTICS OF AC UNDERGROUND CABLE IN POWER NETWORKS

Steve Swingler
CIGRE WG B1-07

With collaboration of Members of WG B1.07
Presentation overview

- Background to CIGRE WG B1-07
- Technical Brochure 338
- Questionnaire
- Statistics
- Technical differences Overhead v Underground
- Relative Costs
History

Mid 1990s JWG 21/22
- Questionnaire sent to utilities 19 countries
- Paper to the 1996 Session
- Technical Brochure 110

Events since 1996
- Weather-related incidents
- Technical changes
- Strong competition
- Increased urbanisation
- Public concerns
- Structure of electricity supply
Collect statistics for the lengths of underground and OHL

Analyse as function of voltage/power

Submarine and DC circuits excluded

Only include projects up to 2006

Describe significant underground cable projects

Factors to be considered when comparing costs

Non-cost factors that must be taken into account
**WG B1-07: Membership List**

<table>
<thead>
<tr>
<th>Name</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steve Swingler</td>
<td>UK (Convenor)</td>
</tr>
<tr>
<td>John Daly</td>
<td>Ireland (Secretary)</td>
</tr>
<tr>
<td>Ken Barber</td>
<td>Australia</td>
</tr>
<tr>
<td>Rudolf Woschitz</td>
<td>Austria</td>
</tr>
<tr>
<td>Alain Gille</td>
<td>Belgium</td>
</tr>
<tr>
<td>Ray Awad</td>
<td>Canada</td>
</tr>
<tr>
<td>Josip Antic</td>
<td>Croatia</td>
</tr>
<tr>
<td>Christian Jensen</td>
<td>Denmark</td>
</tr>
<tr>
<td>Anne Chauvancy*</td>
<td>France</td>
</tr>
<tr>
<td>Matthias Kirchner</td>
<td>Germany</td>
</tr>
<tr>
<td>Ernesto Zaccone*</td>
<td>Italy</td>
</tr>
<tr>
<td>Masao Matsumura</td>
<td>Japan</td>
</tr>
<tr>
<td>Gert Aanhaanen</td>
<td>Netherlands</td>
</tr>
<tr>
<td>Christer Akerwall*</td>
<td>Sweden</td>
</tr>
<tr>
<td>Walter Zenger</td>
<td>USA</td>
</tr>
</tbody>
</table>

* The original members of the working group were Monique Le Stum, Marcello Del Brenna and Johan Karlstrand*
WG B1-07: Membership

- Total: 15
- Utilities: 8
- Manufacturers: 4
- Research Institutes: 3
Fundamentals

Report
- Simple, Brief, Factual
- Technical detail in appendices
- Objective
- Avoid government policy/regulatory issues
- Refer to work of other Working Groups

Questionnaire
- Very specific questions of fact
- Concentrate on statistics of circuit
- Analysed in voltage ranges
Target audience

- Utilities
- Manufacturers
- Governments
- Politicians
- Developers
- Environmental campaigners
Target audience

- Utilities
- Manufacturers
- Governments
- Politicians
- Developers
- Environmental campaigners

Authoritative .......an international consensus

Make choosing between cable and overhead line a more transparent process
1 Introduction
2 Statistics of installed lengths
3 Technical Considerations
4 Cost Factors
5 Conclusions
6 References

A Statistics of Installed Lengths
B Thermal Design
C Electrical Design
D Construction and Installation
E Operation
F Cost Estimation
G Significant Cable Projects
23 Significant Cable projects

- Significant - of international interest in engineering, commercial, environmental or social terms

- Basic details of construction of cable, installation methods and reason for these choices

- Technical details (Bonding, forced cooling, monitoring, protection)

- Anything else that is novel either regarding engineering, environmental or commercial/regulatory considerations

- Why was undergrounding chosen

- Photo of construction Collect statistics for the lengths of underground and OHL
## 23 Significant Cable Projects

<table>
<thead>
<tr>
<th>Country</th>
<th>Project name</th>
<th>kV</th>
<th>(mm²)</th>
<th>Installation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denmark</td>
<td>Aarhus-Aalborg</td>
<td>400</td>
<td>1200</td>
<td>Direct buried or duct</td>
</tr>
<tr>
<td>UK</td>
<td>Nunthorpe-Newby</td>
<td>400</td>
<td>2000</td>
<td>Direct buried</td>
</tr>
<tr>
<td>Netherlands</td>
<td>Nieuwe Waterweg &amp; Calandkanaal</td>
<td>380</td>
<td>1600</td>
<td>Direct buried or duct</td>
</tr>
<tr>
<td>Belgium</td>
<td>Tihange - Avernas</td>
<td>150</td>
<td>2000</td>
<td>Direct buried</td>
</tr>
<tr>
<td>Korea</td>
<td>Youngseo-Youngdeungpo</td>
<td>345</td>
<td>2000</td>
<td>Tunnel</td>
</tr>
<tr>
<td>Germany</td>
<td>Berlin Diagonal</td>
<td>380</td>
<td>1600</td>
<td>Tunnel</td>
</tr>
<tr>
<td>Japan</td>
<td>Shinkeiyo-Toyosu</td>
<td>500</td>
<td>2500</td>
<td>Tunnel, Bridge</td>
</tr>
<tr>
<td>Spain</td>
<td>Barajas Airport</td>
<td>400</td>
<td>2500</td>
<td>Tunnel</td>
</tr>
<tr>
<td>USA</td>
<td>Bethel to Norwalk</td>
<td>345</td>
<td></td>
<td>Ducts, direct buried</td>
</tr>
<tr>
<td>USA</td>
<td>Jefferson - Martin</td>
<td>230</td>
<td>1267</td>
<td>Ducts, direct buried</td>
</tr>
</tbody>
</table>
SP05: An underwater 380 kV crossing in the Netherlands

Overview
Part of the 380 kV grid reinforcement project in the Netherlands is to complete the double circuit loop in the province of Zuid-Holland. This means crossing the river Nieuwe Waterweg and the adjacent Calandkanaal. Both waterways connect the Rotterdam harbours with the open sea. Between the Nieuwe Waterweg and the Calandkanaal there is a finger of land approximately 70 m wide.

Because the vertical clearance for the entry to Rotterdam harbour will be approximately 200 m, an overhead crossing of the waterways was not considered suitable. In that case these Eiffel towers in a row would have been constructed. So the grid owner decided to use a double circuit underwater crossing using horizontal directional drilling.

The cable will be spliced into the existing 380 kV overhead line which is in operation at 150 kV. The capacity of the overhead line is 4000 A (2635 MVA). To match this continuous rating, three cables per phase would be necessary. The question was to find a solution that is economically more attractive.

Circuit details
The entire crossing of the two waterways is too long (approximately 1500 m) to cover with one directional drilling and the use of PE tubes. Therefore the drillings will have to be carried out in 2 stages; northwards from the finger of land towards Neussche Waterweg (811 m) and southwards under the Calandkanaal (693 m). On the finger of land joints will be placed and there will be a cable route in a trench connecting the two landing points of the drillings.

After careful evaluation of the possible solutions it was decided to install a forced water circulation system to equalize local hot spots in the directional drilling with cooler sections of the directional drilling. Normally the ground layer with the highest thermal resistance determines the necessary conductor size.

A small layer of ground with a high thermal resistance (3.05 K/mW) could have caused a heat-spot, but water circulation (without active heat exchangers) allowed the desired rating with a copper conductor size of 1600 mm² rather than over 2700 mm².

The land part of the cable connection (to the transition compounds on both banks), is approximately 100 m. The cables are direct buried in a trench, which is filled with a special back-fill material.

Technical Details
The requirements for the final stage of the project are shown in Table 1. Introduction of an overload factor and carrying out the project in stages over a number of years (as the load grows) allows a more economical solution (Table 2).

Table 1: Final requirements

<table>
<thead>
<tr>
<th>Capacity</th>
<th>1500</th>
<th>1654</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration</td>
<td>week</td>
<td>week</td>
</tr>
</tbody>
</table>

Table 2: Staged requirements in the land group

<table>
<thead>
<tr>
<th>Stage (year)</th>
<th>Voltage</th>
<th>Capacity</th>
<th>Load factor</th>
<th>Cable phase</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>380</td>
<td>1000</td>
<td>1.00</td>
<td>1 x 1600 Cu 380 kV</td>
<td>Chilled cable from 1971</td>
</tr>
<tr>
<td>2005-2006</td>
<td>1000</td>
<td>1060</td>
<td>0.58</td>
<td>1 x 1600 Cu 380 kV</td>
<td>In operation under 150 kV</td>
</tr>
<tr>
<td>2006-2007</td>
<td>1000</td>
<td>1060</td>
<td>1.00</td>
<td>1 x 1600 Cu 380 kV</td>
<td>Depends on load growth</td>
</tr>
<tr>
<td>2007-2008</td>
<td>1654</td>
<td>1654</td>
<td>1.00</td>
<td>1 x 1600 Cu 380 kV</td>
<td>Depends on load growth</td>
</tr>
</tbody>
</table>

* Include forced water circulation.

The forced water circulation system is an economically attractive solution because of the lower initial investment cost, even allowing for the higher pipe losses, extra costs of maintenance and electricity for the pumps.

To meet the final requirements 2 cables per phase are required, but the second set can be postponed until necessary. Extra tubes for these cables are already installed in the first run.

To avoid extra joints (22 in the final stage) and because it was not possible to create a balanced cross-section system, the system now has a single bunched earth system and two separate earth cables of 240 mm² Cu.
Questionnaire

- Collect statistics for the lengths of underground and OHL
- Five voltage levels
- Cable divided into extruded or lapped
- Circuit length with no regard to number of cables per phase
- Cross-site cables should not be included
- Typical continuous rating for overhead line
## Data Collected

<table>
<thead>
<tr>
<th>Voltage Range (kV)</th>
<th>Rating Range (MVA)</th>
<th>OHL (cct km)</th>
<th>Cable (Extruded) (cct km)</th>
<th>Cable (Lapped) (cct km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50-109</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>110-219</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>220-314</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>315-500</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>501-764</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
% of Total circuit length that is underground
% Underground 50 - 109 kV
% Underground 110 - 219 kV
% Underground 220 - 314 kV

United Kingdom
Japan
Ireland
France
Spain
Italy
Brazil
Switzerland
Netherlands
Canada
Portugal
Mexico
Sweden
USA
Australia
Germany
% Underground 315 - 500 kV

Denmark
Korea
Austria
United Kingdom
Australia
Brazil
Japan
USA
Spain
Germany
Netherlands
Italy
Canada
Sweden
% of cable with Extruded Insulation

- 50-109 kV: 72%
- 110-219 kV: 47%
- 220-314 kV: 40%
- 315-500 kV: 27%
Summary of Statistics
- HV Networks are predominantly overhead
- Situation more extreme at higher voltages

Main reason
- Underground cable systems generally more expensive
- Situation worse at higher voltages

Why?
- Why is underground cable more expensive
- Why is it worse at higher voltages
Technical differences increase cable costs

- Electrical insulation of the conductor
- Heat transfer to prevent overheating
- Construction work necessary to install the circuit
- Electrical Design
- Operation
- Recent developments to reduce the cost of undergrounding
Electrical insulation of the conductor

1. Insulator
2. Phase conductor - low-power lines often have a single conductor; higher power lines may use multiple sub-conductors.
3. Spacer to hold the two sub-conductors apart
4. Earth wire at the top of the tower or pylon
5. The three phase conductors on one side of the tower make up one electrical circuit. Most lines have two circuits, one on each side.
Electrical insulation of the conductor

- Conductor
- XLPE insulation
- Metallic (aluminium) sheath
- Polyethylene oversheath
Heat transfer to prevent overheating

Sheath loss
Conductor loss
Dielectric loss
## Dimensions and weight

<table>
<thead>
<tr>
<th>Material</th>
<th>Area (mm²)</th>
<th>Diameter (mm)</th>
<th>Mass per unit length (kg/m)</th>
<th>Resistance (Ω/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overhead conductor</td>
<td>Al alloy</td>
<td>821</td>
<td>37.3</td>
<td>2.3</td>
</tr>
<tr>
<td>Underground conductor only</td>
<td>Copper</td>
<td>2500</td>
<td>64</td>
<td>22</td>
</tr>
<tr>
<td>Complete underground cable</td>
<td></td>
<td>149</td>
<td>39</td>
<td></td>
</tr>
</tbody>
</table>
Relative size of a 400 kV XLPE cable and an overhead line conductor of similar rating.
Construction

Construction works are a significant part of the cost.

Cost varies widely depending on:

- ease of access along the route
- amount of power to be transmitted

Urban undergrounding

- large number of crossing services
- trench walls have to be supported in order to work safely
- need to manage the traffic flow
- restrictions often paced on the hours of working
- Deep bored tunnels – practically easy but expensive
Urban undergrounding
Rural undergrounding

In rural areas the costs might be reduced
- Mechanical excavation can often be used
- Trenches with unsupported sloping walls

Additional costs for large-scale rural undergrounding
- Protection of watercourses
- Preserving hedgerows and woodlands
- Archaeological surveys
- Directional drilling under roads, railways and waterways
Unsupported trench
Power transfer – Voltage ranges

- Voltage Range - kV
- Mean power - MVA

50-109
110-219
220-314
315-500
Construction 66-90 kV

Soil

Backfill

1 m
Construction 66-90 kV
Construction 400 kV

- 3m
- 1.6m
- ~20m
- 3m
Transition on tower

90 kV terminations

110 kV terminations
400 kV transition compound
Electrical Design

- Special bonding
- Reactive compensation
- Fault clearance and protection
When both ends of the metallic screen are grounded, there is no induced voltage but a current flows along the metallic screen.
Solid Bonding
Single Point Bonding

Earth continuity conductor

SVL
Transferable power

- 400 kV 1000 MVA
- 132 kV 330 MVA
- 400 kV 330 MVA
- 132 kV 100 MVA
Reactive Compensation
400 kV Shunt Reactor (160 Mvar)
Protection and reclosure

- OHL Circuit may have transient faults e.g. lightning strike
- Automatically reclose circuit-breaker (delay of 1 - 20 s)

- Cable Circuit - almost always permanent faults
- In most cases - no re-closure on cables faults

- Hybrid circuits – zone/unit protection
- Fault in cable section - re-closure inhibited
- Risk assessment based on cable length & fault current
Operation

- Security of supply
- Fault repairs
- Routine maintenance
- Upgrading
- Monitoring
Reducing the cost of undergrounding

- Lean cable design
  - Higher stress/Lighter sheath
  - Longer drum lengths
  - Fewer joints
Reducing the cost of undergrounding

- Lean cable design
  - Higher stress/Lighter sheath
  - Longer drum lengths
  - Fewer joints

- Mechanised Laying
  - Direct laying of cable bundles
  - Pre-burial of ducts
  - Float/flow assisted pulling
Reducing the cost of undergrounding

- Lean cable design
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- Mechanised Laying
  - Direct laying of cable bundles
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  - Float/flow assisted pulling

- Deferring Expenditure
  - install spare ducts/leave space in tunnel
  - install pipes for water cooling
  - DTS and real time ratings
  - novel or bespoke solutions
Mechanised laying – 20 kV cable bundle
Mechanised laying – ducts for 63 kV cable
Comparing Costs

- Like for like?
- Cost Ratios
- Components of cost
Short-term ratings

Continuous rating

Load

Time
Short-term ratings

- Actual load
- Preload
- Continuous rating

Load vs. Time
Short-term ratings

![Graph showing load and time with preload, continuous rating, and actual load.](image)

- **Load**
- **Time**
- **Continuous rating**
- **Actual load**
- **Preload**
Short-term ratings

Short-term load capacity

Load

Time

Short-term load

Continuous rating

Actual load

Preload

57
Short-term ratings

Short-term load capacity

Load

Time

Continuous rating

Actual load

Preload

Short-term load
Short-term ratings

Load

Short-term load capacity

Duration of short-term load

Preload

Time

Continuous rating

Actual load
Short-term rating – 50% preload

- 30 minute rating
- 12 hour rating
- Continuous rating

Relative short-term rating

Cu-conductor Area - mm²

400 800 1200 1600 2000
Cost Ratios

- Often thought of as simple way of comparing costs
- Wide range of values quoted for apparently similar circuits
- 1996 study, cost ratios ranged between 5 and 21
- Leads to confusion and mistrust between the various stakeholders
- Sensitive to small changes in OHL costs
- Commercially irrelevant
## Cost Ratios

<table>
<thead>
<tr>
<th>Case</th>
<th>Cost of underground cable</th>
<th>Cost of overhead line</th>
<th>Cost ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$10 million</td>
<td>$500 thousand</td>
<td>20</td>
</tr>
</tbody>
</table>
## Cost Ratios

<table>
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<tbody>
<tr>
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<td>$10 million</td>
<td>$500 thousand</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>$10 million</td>
<td>$1 million</td>
<td>10</td>
</tr>
</tbody>
</table>
# Cost Ratios

<table>
<thead>
<tr>
<th>Case</th>
<th>Cost of underground cable</th>
<th>Cost of overhead line</th>
<th>Cost ratio</th>
<th>Additional cost of undergrounding</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$10 million</td>
<td>$500 thousand</td>
<td>20</td>
<td>$9.5 million</td>
</tr>
<tr>
<td>2</td>
<td>$10 million</td>
<td>$1 million</td>
<td>10</td>
<td>$9.0 million</td>
</tr>
</tbody>
</table>
Components of cost

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

- Buy land/right to access in order to build/repair the circuit
- Develop purchase and testing specifications
- Cost of procurement process
- Prequalification & type testing costs
- Purchase cable system (including accessories, etc)
- Purchase monitoring and ancillary systems
- Purchase reactive compensation
- Purchase protection/re-closure equipment
Operation

- Compensation for restricting land
- Other on-going land costs
- Likely cost of future expansion/upgrading
- Cost of maintenance
- Cost of planned outage for maintenance
- Cost of spares holdings
- Cost of losses
- Cost of repair
- Cost of outage for repair
Compare on a case by case basis

- Calculate costs of underground option
- Calculate costs of overhead option
- Compare these
- Balance with factors that are difficult to cost:
  - visual intrusion
  - threats to sensitive habitat
  - damage to archaeological heritage
  - land-use issues
Thank you for your attention

Any Questions?