MINISTERIE VAN ECONOMISCHE ZAKEN

GENERAL COST COMPARISON BETWEEN UNDERGROUND CABLES AND O.H. LINE SYSTEMS FOR H.V. TRANSMISSION

FINAL REPORT

APRIL 2008 (REVISED MAY 2007)

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1. BASIC ASUMPTIONS

→ **Number of circuits**

2

→ **Power to transmit (per circuit)**

- 1740 MVA - normal condition
- 2635 MVA (N - 1)

→ **Thermal conditions (for cable) for AC/DC links**

- Soil temperature at 1.5 m depth

  15 °C
- Soil thermal resistivity
  - . 0.5 Km/W
  - . 0.75 Km/W
- Laying conditions
  - . Flatbed formation
  - . With screen cross bonding
  - . No soil drying up

→ **Thermal conditions for drilling laying - flat formation**

- Soil temperature at
  - . 2 m depth : 13 °C
  - . 7 m depth : 10 °C
  - . 20 m depth : 8 °C
- Soil thermal resistivity at
  - . 2 m depth : 0.8 Km/W
  - . 7 m depth : 0.7 Km/W
  - . 20 m depth : 0.5 Km/W

→ **Dimensioning characteristics - with AC**

- Rated Voltage : 380 kV
- Rated current per circuit : 2640 A/4000 A (N-1)

→ **Dimensioning characteristics - with DC**

- Rated Voltage : ± 500 kV
- Power : 2400 MW

2. AMPACITY CALCULATIONS

2.1. ALTERNATIVE WITH AC VOLTAGE

"Laying conditions"

2.1.1. In trenches - Flat configuration (see figure 1)

	2000 mm^2 copper	2000 mm^2 copper enamelled	2500 mm^2 copper	2500 mm^2 copper enamelled
For soil resistivity of 0.5 Km/W	2030 A	2260 A	2200 A	2550 A
For soil resistivity of 0.75 Km/W	1810 A	2030 A	1950 A	2260 A
Minimum requirement in normal condition	**1320 A**			
Minimum requirement in N-1 condition	**2000 A**			

Typical arrangement of cables in flat configuration (2 cables/phase)

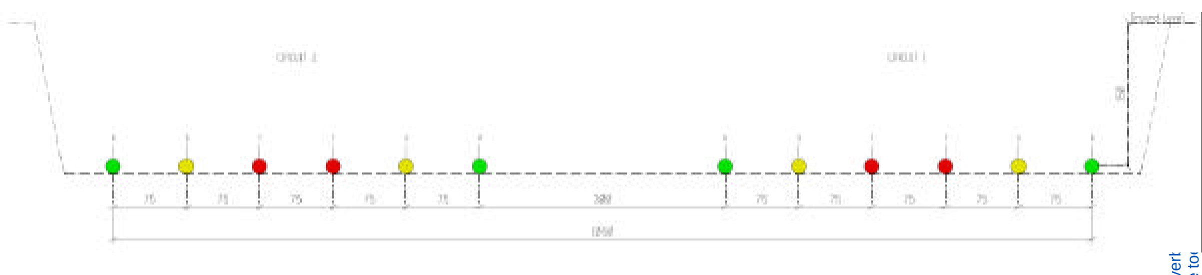

Figure 1

2.1.2. Flat configuration - Depth of 2.5 m

Basic assumptions:

- soil resistivity of 0.5 and 0.7 Km/W;
- no soil drying;
- soil temperature: 13 °C.

	2000 mm^2 copper enamelled	2500 mm^2 copper enamelled
For soil resistivity of 0.5 Km/W	2280 A	2553 A
For soil resistivity of 0.75 Km/W	2007 A	2289 A
Minimum requirement in normal condition	**1320 A**	
Minimum requirement in N-1 condition	**2000 A**	

2.1.3. In trenches - Trefoil configuration (see figure 2)

	2000 mm² copper	**2000 mm² copper enamelled**	**2500 mm² copper**	**2500 mm² copper enamelled**
For soil resistivity of 0.5 Km/W	1664 A	1836 A	1792 A	2034 A
For soil resistivity of 0.75 Km/W	1438 A	1584 A	1546 A	1749 A
Minimum requirement in normal condition	1320 A			
Minimum requirement in N-1 condition	**2000 Z**			

Typical arrangement of cables in trefoil configuration (2 cables/phase)

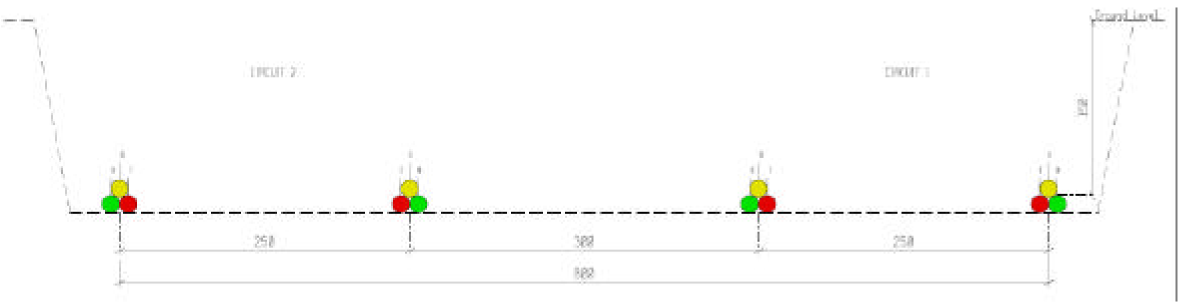

Figure 2

2.1.4. Flat configuration in PE tubes with concrete bloc - Depth of 1.5 m

See figure 3.

In this case we have assumed:

- soil resistivity of 0.5 and 0.7 Km/W;
- no soil drying;
- soil temperature: 15 °C.

	2000 mm^2 copper enamelled	2500 mm^2 copper enamelled
For soil resistivity of 0.5 Km/W	2143 A	2407 A
For soil resistivity of 0.75 Km/W	2002 A	2243 A
Minimum requirement in normal condition	**1320 A**	
Minimum requirement in N-1 condition	**2000 A**	

Typical arrangement of cables in flat configuration in tubes with concrete (2 cables/phase)

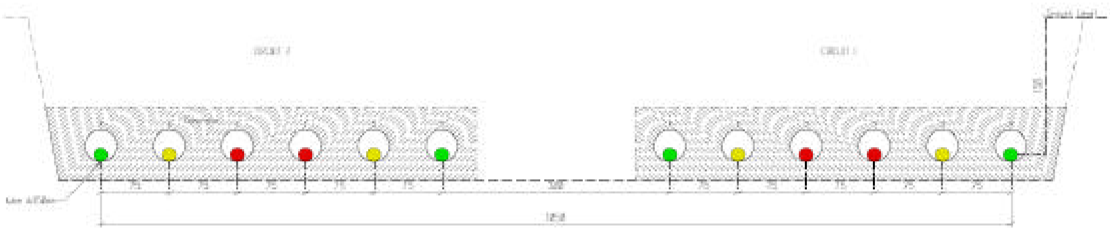

Figure 3

2.1.5. In drilling conditions

	2000 mm² copper	2000 mm² copper enamelled	2500 mm² copper	2500 mm² copper enamelled
2 m depth (10 m distance between drillings)	1520 A	1695 A	1631 A	1874 A
7 m depth (10 m distance between drillings)	1440 A	1600 A	1540 A	1767 A
20 m depth (10 m distance between drillings)	1500 A	1680 A	1610 A	1850 A
Minimum requirement in normal condition	1320 A			
Minimum requirement in N-1 condition	**2000 A**			

Typical arrangement of cables in drilling condition (2 cables/phase)

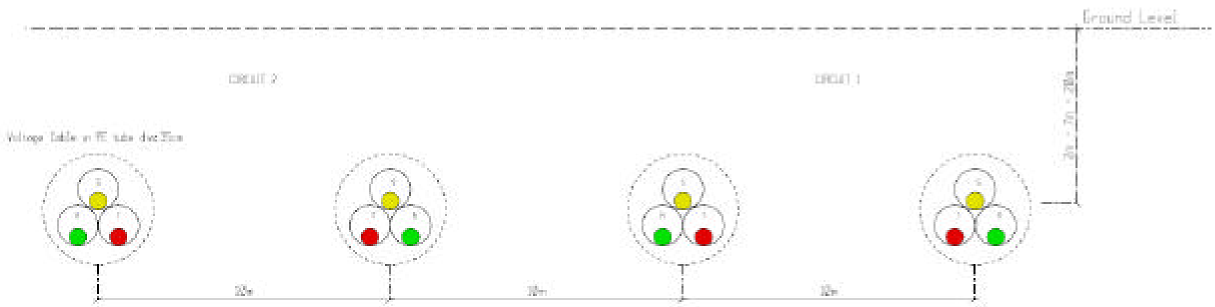

Figure 4

The results reveal that laying in directional drillings remains the delicate point in the underground links.

In our case we found that even with a section of 2500 sq. mm copper, with 2 cables per phase, whereas the normal operating conditions can be maintained, it is impossible to ensure the N-1 condition.

In this case we could examine what would happen with I max. as the cable's temperature delta, and check whether it would be acceptable and for how much time.

Also bear in mind that an N-1 situation that lasts 30 days is extremely exceptional.

Also, before we can give a firm opinion, we should know the exact nature of the soil at those locations.

Increasing the tube diameter would also slightly improve the situation.

The calculations were made with PE tubes having 250 mm outside diameter.

2.1.6. In drilling conditions; PE tubes with increased diameter

- Calculations made
  - With PE tubes of 350 mm outer diameter/320 mm inside diameter.
  - For 250 mm² copper and 250 mm² copper enamelled.

Depth (m)	Soil resistivity (km/W)	2500 mm² copper	2500 mm² copper enamelled
2	0.8	1738 A	2271 A
7	0.7	1627 A	2085 A
20	0.5	1698 A	1957 A
Minimum requirement in normal condition		1320 A	
Minimum requirement in N-1 condition		**2000 A**	

- The maximum temperature of the conduction in N-1 condition reaches the following values:

Depth (m)	Soil resistivity (km/W)	2500 mm² copper	2500 mm² copper enamelled
2	0.8	116 °C	< 90 °C
7	0.7	134 °C	< 90 °C
20	0.5	124 °C	94 °C

- Results

  Only **2500 mm² copper enamelled** could withstand the N-1 condition during 30 days. Maximum allowable temperature during 30 days one or two times during live time of the links should be around 95 °C.

2.2. ALTERNATIVE WITH DC VOLTAGE

Two types of cable exist:

a) cable with a mass impregnated paper insulation;

b) cable with a polyethylene alloy insulation (dry insulation).

The first one is a well experimented technology (more than 30 years).

The second one is new technology (type tests are just finished).

Cable data required:

• Voltage	:	± 500 kV	± 500 kV
• Type of insulation	:	Mass impregnated paper insulation	Polyethylene alloy insulation
• Section for normal condition	:	1200 mm^2 copper	800 mm^2 copper
• Metallic screen	:	Lead alloy sheath	Aluminum welded laminated sheath
• Number of cables per circuit	:	4	4
• Power to transmit	:	2400 MW	2400 MW

3. MAIN CHARACTERISTICS OF OVERHEAD LINE

3.1. ALTERNATIVE WITH AC VOLTAGE

Based on the terms of the contract, we have assumed that the design already made with new tubular poles is the final design.

3.2. ALTERNATIVE WITH DC VOLTAGE

Based on the terms of the contract, we have assumed that this alternative is not considered although technically feasible.

4. CONSIDERATIONS IN THE CHOICE AC/DC

4.1. FUNCTIONALITY OF THE LINK

The functionality of the link is in essence:

- To complete a mesh in the already elaborate 380 kV network of The Netherlands in order to increase its loadability, given new productions and loads planned.
- To provide additional in feed points from 380 kV into the lower voltage levels 220 kV and 150 kV.
- The extremities and intermediate take-off points are at a synchronous AC voltage level: there is NO INTRINSIC NEED for an asynchronous link.
- We have no knowledge of particular load flow control needs in the 380 kV grid, there is NO INTRINSIC NEED for a highly flexible and controllable link at the location in question.
- As far as we know the 380 kV grid of The Netherlands, the additional 380 kV link is not expected to increase the short-circuit levels in such a way that "decoupling" by DC links would be a necessity.

4.2. CONSIDERATIONS ON THE CHOICE

Following considerations should be kept in mind:

- The functionality can be perfectly assured with AC, there is NO functional gain with DC in this particular application.
- AC is overall more reliable than DC.
- AC is (both CAPEX and OPEX) far more economical as DC, mainly due to the impact of the conversion stations. This fact is more and more aggravated if multi-terminal systems are considered (the case here).
- DC creates additional interference in the adjacent AC grids (reactive power management, harmonics) as well as in the environment (DC ground return spill currents in certain conditions, with possible corrosion of buried metal structures and potentially ecological side effects on soil organisms).
- DC has substantially more spatial, visual and noise impact at the interfaces with the existing network (converting stations).

4.3. CONCLUSION ON THE CHOICE AC/DC

Considering all the above:

- On technical and economical grounds AC is the preferential choice.
- Any marginal advantages of DC from the ecological point of view should be outweighed against the additional ecological disturbance of DC with respect to AC.

5. COST COMPARISON

5.1. GENERAL COMMENTS

For OHL, and due to the fact that we are not involved in this new design, we have assumed that the cost overview given is considered reasonable.

For underground AC cable links we assumed that the final technical solution could be of 2000 or 2500 sqmm copper.

Prices are given for 2500 sqmm copper with a ratio between drilling and trenches of 16 %.

As an alternative, price is given with 2500 sqmm copper enamelled.

For underground DC cable links, the prices for DC links are depending mainly on the price of the AC/DC convectors.

5.2. PRICES

5.2.1. OHL

→ Unit price/Km

Bi-pole 2 x 380 kV	**2,3 M€/Km**

5.2.2. Underground links

→ AC links (2 x 380 kV) - 2500 sqmm copper, laying depth of 1.5 m (flat configuration)

- Cables, accessories and tests [1]	7,4 M€/Km
- Laying (trenches and drillings including junction pits)	3,7 M€/Km
Total [2]	**11,1 M€/Km**

→ AC links (2 x 380 kV) - 2500 sqmm copper enamelled

- Cables, accessories and tests [1]	8,5 M€/Km
- Laying (trenches and drillings including junction pits)	3,8 M€/Km

1 *Unit price of Copper is 6.6 €/kg.*

2 *This price does not include the prices for a right of way and different access required and no unforeseen costs.*

Total [2] **12,3 M€/Km**

→ AC links 2500 sqmm copper,
laying depth of 2,5 m (flat configuration)

Assumptions

We have assumed that the cost of the execution of the trenches should be multiplied by a coefficient of min. 5 and the unit price of laying the cable should be multiplied by 2. Based on those assumptions, prices are:

- Cables, accessories and tests [1] 8,8 M€/Km
- Laying (trenches and drillings including junction pits) 9,5 M€/Km [2]

Total [3] **18,3 M€/Km**

→ DC links

- Cable (roughly estimation) **6 M€/Km**

- Convertor

  . The roughly estimated price of an AC/DC - DC/AC convertor is 0,18 M €/MW.

  . For 2400 MW the total price should be of: **423 M€/circuit**

5.2.3. OHL/AC underground station

A roughly estimated price should be of: **1 M€/station**

1 *Unit price of Copper is 6.6 €/kg.*

2 *To be confirmed due to "exceptional depth".*

3 *This price does not include the prices for a right of way and different access required and no unforeseen costs.*

6. MAGNETIC FIELD OF AC CABLES

A calculation of the magnetic field in flat configuration has been done for I = 1320 A per cable (normal condition) (see figures 5 and 6).

- At 1,5 m depth the maximum value is 51 µT (measured at 1 m above ground). The value of 0,4 µT should be at distance of 18 m from the main axis of the link.
- At 3 m depth, the maximum value is 16 µT (measured at 1 m above ground). The value of 0,4 µT should be at a distance of 17,7 m from the main axis of the link.

In trefoil configuration for I = 1320 A per cable (normal condition).

- At 1,5 m depth, the maximum value is 16,74 µT (measured at 1 m above ground). The value of 0,4 µT should be at a distance of 20 m from the main axis of the link (see figure 7).

If the reference is the limit value of 0.4 µT, increasing the depth from 1.5 m to 3 m is not useful (the distance with respect to the axis of the link remains some 18 m). Same conclusion for the trefoil configuration.

However, if it is the maximum value that is important, increasing the depth from 1.5 m to 3 m permits to reduce the maximum value by 70 %.

Also the cost related to laying at 3 m depth becomes seriously prohibitive.

In this case, the better option would be to lay the cables in a trefoil configuration at 1.5 m depth. The maximum value will be of 16,74 µT instead of 51 µT in flat configuration with the same depth (1,5 m).

In this option the transit capacity will decrease of 18% to 20% compare to the flat configuration.

Magnetic field with a depth of 1.5 m flat configuration

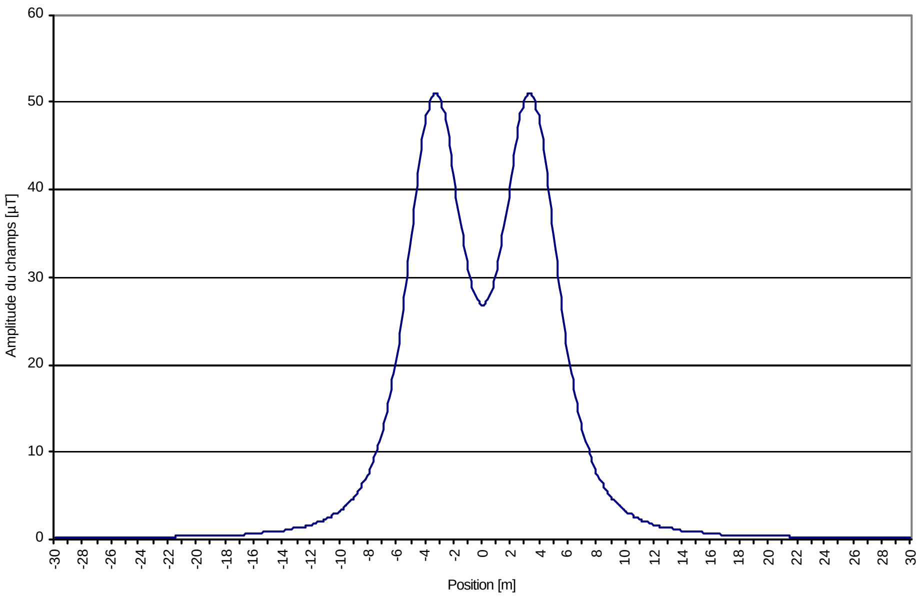

Figure 5

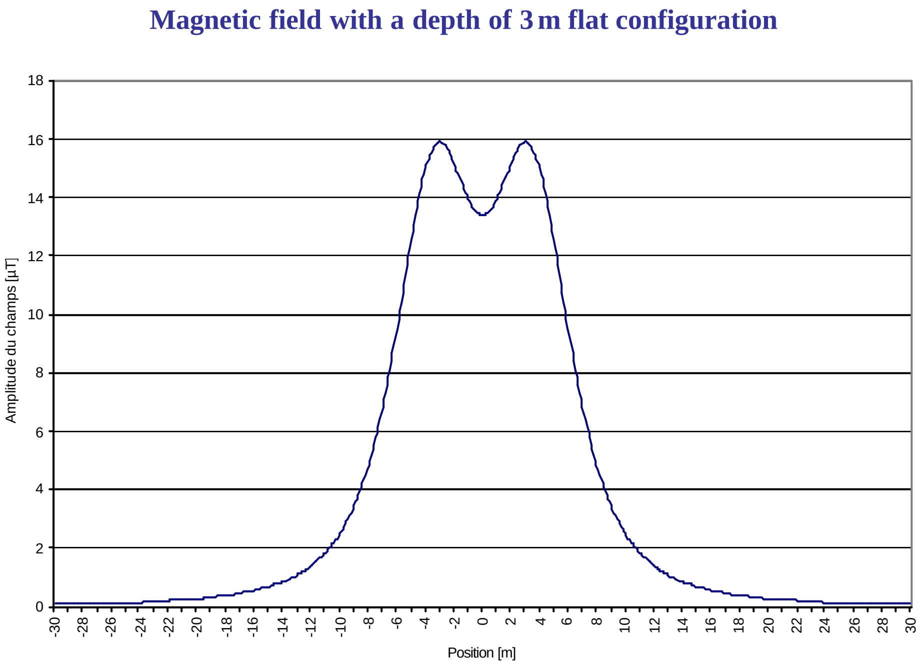

Figure 6

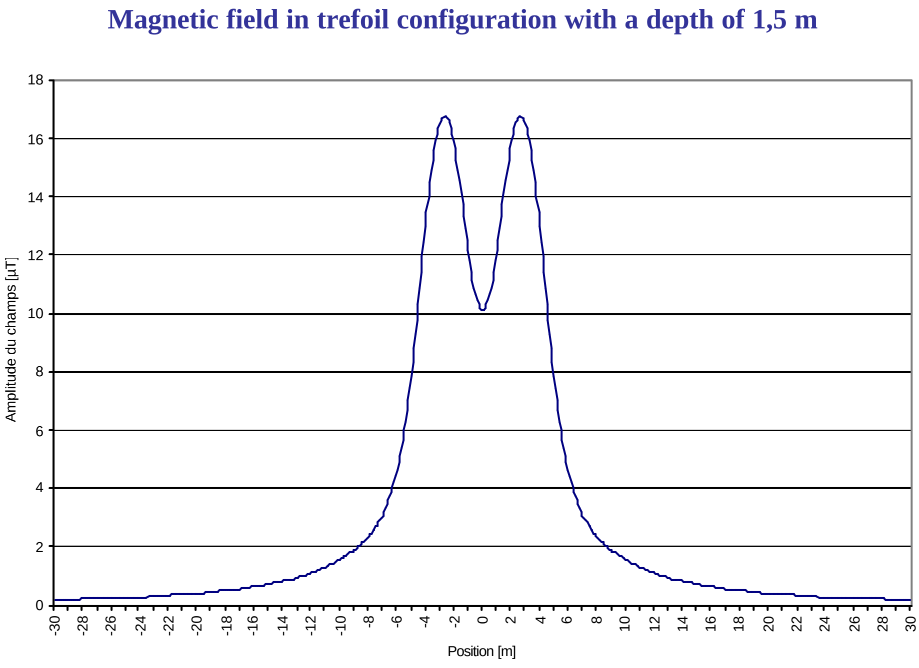

Figure 7

7. REACTIVE POWER MANAGEMENT IN AC

7.1. GENERAL

AC circuits operate by principle under alternating current and are thus subject to series inductive voltage drops and shunt capacitive "loading" currents i.e. production of Mvars.

OH lines have less shunt capacitance and the production of Mvar is moderate.

Cable circuits have considerable capacitance and generate thus substantial Mvars which:

- have to be transported on the cable itself, i.e. they occupy part of the load carrying capacity;
- have to be absorbed at the cable extremities by the overall AC system either as inductive load Mvars, as underexited Mvars on the generators or as explicit compensation inductive Mvars by dedicated shunt reactors;
- may create substantial switching transients when energizing a cable due to sudden closing on the high capacitive Mvar load.

7.2. SHORT CABLE STRETCHES (PART OF LINK)

The proposed circuits 400 kV (each two cables in parallel) represent a shunt Mvar generation of some 24 Mvar/circuit x km.

A 5 km circuit (120 Mvar) should not represent a switching problem, and the absorption of 120 Mvar in the overall grid (which is interconnected all over Western Europe) seems at first sight possible without any special compensation measure.

❖ *Note*

The Belgian Elia grid comprises numerous 85 Mvar capacitor banks. Switching of such a 85 Mvar bank on 150 kV is comparably much more severe than switching of 120 Mvar capacitive cable on 400 kV.

7.3. LONG STRETCHES (LINK OF 17 KM)

A 17 km circuit brings 410 Mvar at no load switching.

The possibility to absorb these depends on local network conditions.

Only the network planner has sufficient elements to judge this.

Probably some shunt Mvar absorption is to be foreseen. To maximize the effect on switching operations, these reactors should preferably be permanently connected to the HV link extremities and switched together with the cable itself.

Shunt reactors 400 kV 200 Mvar are quite normal ratings, available from different manufacturers. Delivery times range from 18 to 24 months.

No extra switchgear bays 400 kV are needed.

8. LOSSES

8.1. LOSSES IN OHL

- Basic assumptions for losses calculation:

- Cross section of the conductors	:	AAAC 620 mm^2
- Bundle	:	4 cables/phase
- Ambient air temperature assumed	:	35 °C
- Ampacity in one conductor (normal condition)	:	660 A (2640 A/phase)
- Assumed wind speed	:	0.6 m/sec
- Date	:	21st of June at noon

In those conditions, the maximum conductor temperature should be of 63.6 °C.

❖ *Note*

In case of an ambient air temperature of 30 °C instead of 35 °C, the maximum conductor temperature should be of 58.8 °C.

- Losses

- Per cable	:	27.78 W/m	(27.38 W/m)
- Per phase	:	111.12 W/m	
- Per circuit	:	333.36 W/m	

8.2. LOSSES IN AC UNDERGROUND CABLE

- Ampacity per cable (2 cables/phase): 1320 A (normal condition)
- Electric data of cable - Conductor temperature
  - Ground temperature: 15 °C
  - Flat configuration

- Conductor temperature for I = 1320 A
  - 2000 mm^2 copper : 53 °C
  - 2000 mm^2 copper enamelled : 44 °C
  - 2500 mm^2 copper : 48 °C
  - 2500 mm^2 copper enamelled : 39 °C

- Losses
  - 2000 mm^2 copper : 160.7 W/m/circuit
  - 2000 mm^2 copper enamelled : 132.6 W/m/circuit
  - 2500 mm^2 copper : 142.2 W/m/circuit
  - 2500 mm^2 copper enamelled : 103.4 W/m/circuit

9. LIVE CYCLE COSTS

9.1. BASIC ASSUMPTIONS

- OHL length : 17 km
- Underground cables length (route length) : 5 km

1. Live duration

30 and 50 years

2. Load assumption

- Load at the beginning (compare to 2640 A = normal load) : 1500 A
- % of increase : 2 %/year
- Maximum nominal load : 2640 A

3. Occupation of the circuit per year

- 8700 H at normal load (1500 A + 2 %/year)
- 60 H at N-1 condition (4000 A)

4. Price of kWh

We have assumed a unit price of 0.060 €/kWh (60 €/MW/h).

5. Maintenance

- OHL : each 10 years - 1 month interruption (important maintenance)
- XLPE cables : each year - 1 week oversheath tests + partial discharges measurements at junctions

6. Dismantling

- OHL

  We assume a total cost of 15 % of the initial investment taking into account that the pile foundation will be demolished - 1,5 m max.

- XLPE cables

  We assume a total price of 1.3 of the cost of the trenches + laying of cable. For drilling: impossible to dismantle the cables as well as tubes inside the borings.

9.2. RESULTS

The results for 30 and 50 years are given in figures 8 and 9.

LIVE CYCLE COSTS (30 YEARS)

Assumptions	**OHL lenght**	**17**	**km**
	Underground cables (route lenght)	**5**	**km**

Live duration	**30**	Years

	OHL (17 km)	Underground Links (5 km)
	k€	k€
Initial Investment	39100.0	61500.0
Maintenance	972.5	1750.1
Losses	66267.3	9684.6
Dismanteling	14235.9	29108.9
TOTAL	120575.7	102043.6
Per km		
TOTAL	*5480.71*	*20408.73*
Ratio	1	3.7

Unit prices in k€

OHL	XLPE cables	
2300	12300	
1	5.35	**Ratio**

0.06 €/kWh

Figure 8

LIVE CYCLE COSTS (50 YEARS)

Assumptions	**OHL lenght**	**17**	**km**
	Underground cables (route lenght)	**5**	**km**

Live duration	**50**	Years

	OHL (22 km)	**Underground Links (5km)**
	k€	**k€**
Initial Investment	**39100.0**	**61500.0**
Maintenance	**2497.7**	**4101.3**
Losses	**103617.8**	**14909.2**
Dismanteling	**25711.6**	**52574.0**
TOTAL	**170927.1**	**133084.5**
Per km		
TOTAL	***7769.41***	***26616.90***
Cost Ratio	**1**	**3.4**

Unit prices in k€		
OHL	XLPE cables	
2300	**12300**	
1	**5.35**	**Ratio**

0.06 €/kWh

Figure 9

❖ **Important remarks**

Above calculations are based on a OHL length of **17 km** and an underground cable links length of 5 km.

It means that based on ref. 7.2. for 5 km circuit (120 MVar) **no compensation** equipment should be necessary.

Longer underground cable links will require, depending on the local network condition, some shunt MVar which bring supplementary losses (not negligible)!!

If 100% of shunt reactance compensation is foreseen, some 240 Mvar (2 x 120 Mvar) is to be installed. At an estimated initial investment (no prices received yet from the manufacturer consulted for this purpose) of 20 k€ / Mvar installed, this adds 4 800,-k€ to the initial investment for the 5 km cable.

Shunt reactance compensation increases losses (for 240 Mvar) on a permanent basis by some 1.2 MW (for 5 km and two circuits) or some 120 W / m / circuit. Typically the cable losses per m and circuit rise from (2500 mm^2 copper enamel) 103.4 W / m / circuit to 223.4 W / m / circuit.

The lifetime loss cost is almost proportional to the W / m / circuit loss value.and becomes :

For 30 years	20 924 k€	instead of	9 684.8 k€	and
For 50 years	30 222 k€	instead of	14 909.2 k€.	

The total life cycle cost/ km for cable becomes:

For 30 years	23 616.6 k€	instead of	20 408.7 k€	and
For 50 years	30 639.5 k€	instead of	26 616.9 k€..	

The total life cycle cost ratio cable / line becomes:

For 30 years	4.31	instead of	3.70	and
For 50 years	3.94	instead of	3.40.	

10. RELIABILITY OF EHV CABLES - STATE OF THE ARTS

- Producers guarantee homogeneous cable quality according to international standard (IEC 62067).
- Repairs caused by damage:
  - Quick and precise location of errors with modern monitoring technology.
  - Reparation time 2 - 3 weeks (if, as recommended, spare parts are kept in stock).
- Careful long-term testing has been conducted and life expectancy of XLPE-insulated cables is approximately 30 - 40 years.
- Prequalification tests have been performed on 400 kV and 500 kV cable systems with different conductor sizes up to 2500 mm^2 and type tests on almost the whole range of conductors.

  Lower conductor sizes have higher stresses at the conductor and lower stresses at insulation surface: see figure 10 below.

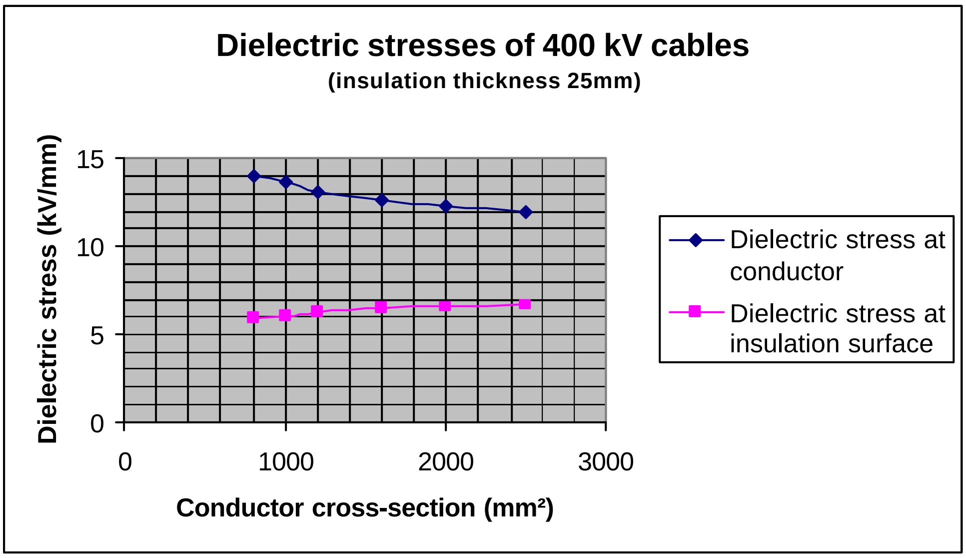

Figure 10

The dielectric stresses at insulation surface are not very different from each other from the whole range of conductor sizes. From a dielectrical point of view this means that test and field experience with a medium sized cable conductor gives confidence in the whole range of sizes for the dielectric behavior of accessories.

Experience has shown that long term tests distinguish between good and bad accessories: e.g. prequalification tests for the Bewag project in Berlin have led to breakdown on bad designs of terminations and joints. These tests allowed cable manufacturers involved in these tests to improve the designs of their accessories and pass the tests correctly during a second long term test.

- Higher over voltage

  The over-voltages have noting to do with cables; it is related to network design and conditions. But anyway the security factor for cables is good as shown by type tests at 2 Uo and long term pre-qualification tests at 1.7 Uo and by long term development tests, which did not show any ageing on cable insulation.

- Number of EHV cable installing globally 1994-2005 (Document issued of Europacable - session 2008 - "Overview of underground power cables at high/extra high voltage levels").

Number of EHV cable installations globally 1994-2005

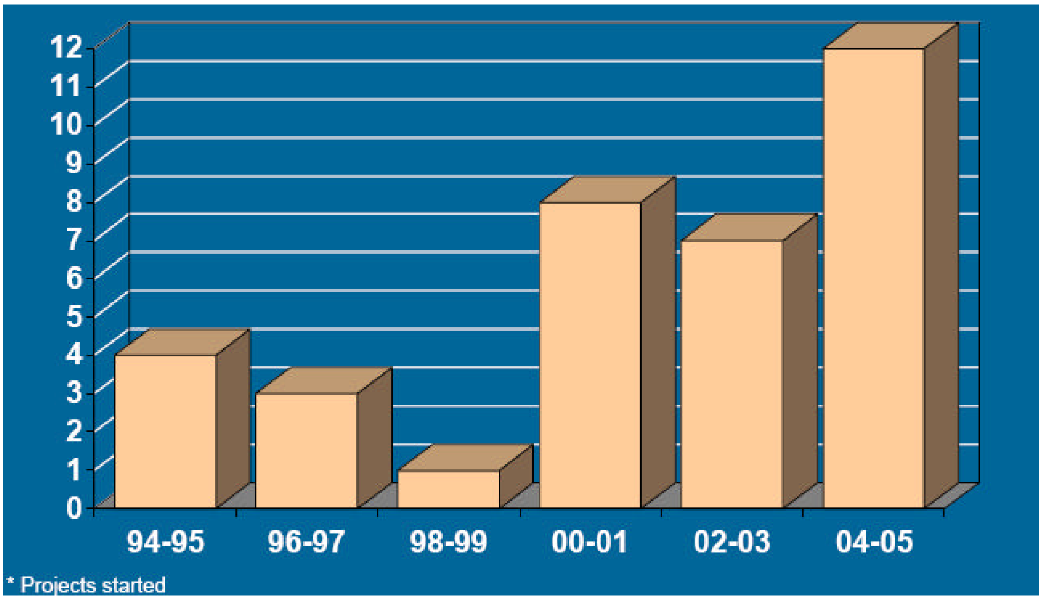

Figure 11

Length of km of EHV underground cable 220-400 kV: 1996-2006

	1996	2006	Change %
Austria	48	59	23
Denmark	31	52	68
France	600	914	52
Germany	99	110	11
Ireland	64	106	66
Italy	130	231	78
Netherlands	6	12.5	108
Spain	31	558	1700
UK	553	662	20

Source: CIGRE 338 December 2007

Figure 12

Examples of major 400 kV projects in Europe

Location	Project	Cable circuits x Length (km)	Time period
Copenhagen	Elimination of OHLs in urban area	1x12, 1x22	1996/9
Berlin	Connect West/East systems	2x12	1996-00
Vale of York (UK)	Area of outstanding beauty	4x6	2000/1
Madrid	Barajas Airport expansion	2x13	2002/3
Jutland, DK	Area of outstanding beauty, waterway & semi urban areas	2x14	2002/3
London	London Ring	1x20	2002/5
Rotterdam	Randstad "ring" waterway crossings	2x2.1	2004/5
Vienna	Provide power to centre of city	2x5.5	2004/5
Milan	Section of Turbigo-Rho line	2x8.5	2005/6

Figure 13

- Stockholm has decided to dismantle overhead HV lines in the city and the suburbs and put cables in multipurpose tunnels. The valorization of land covers almost the cost of the new installations.

- Conclusion

  As it is mentioned in the report CIGRE 21-104-2002:

  > "*The successful performance of tests confirmed that 400 and 500 kV XLPE cable systems using properly selected materials and technologies and installed by skilled personnel using suitable techniques exhibit a high degree of reliability and considerable safety margins*".