INTEGRATING HTS COMPONENTS INTO THE FUTURE TRANSMISSION GRID OF THE NETHERLANDS

Roy Zuijderduin[1*], Oleg Chevchenko[1], Johan Smit[1], Gert Aanhaanen[2], Irina Melnik[3], and Alex Geschiere[3]
[1]Delft University of Technology, Mekelweg 4 2628CD Delft, The Netherlands
[2]TenneT, Utrechtseweg 310 6800 AS Arnhem, The Netherlands
[3]Liandon, 6920 AB Duiven, Duiven, The Netherlands
*Email: R. Zuijderduin@tudelft.nl

Abstract: High temperature superconductors (HTS) can play an important role in solving future power grid problems, such as increasing power demand and decentralized generation. The main obstacle for wide application of HTS components is the price of HTS. As the price of HTS goes down, a much wider integration of HTS components in the grid is expected. The advantages of this are: increased power capacity, intrinsic ability to limit fault currents, increased lifetime of the electrical insulation, increased grid stability, higher efficiency, better control of power flow and improved environmental impact: less electromagnetic emissions, no soil heating. In the future more decentralized power will be generated, with the use of more sustainable sources and more interconnections will be made to increase the grid stability and for easier export and import of electricity. The power grid with decentralized generation can have numerous bottlenecks, e.g.: high level of fault currents and unstable voltages. In this study we assume that the transmission grid of the Netherlands in year 2030 will use AC, make an inventory of the potential bottlenecks in the future grid, propose to solve the bottlenecks by integrating HTS AC cables, illustrate this approach with an example and discuss related issues of such integration.

1 INTRODUCTION

Throughout the years electricity grids are changing to have more capacity for power produced in a more sustainable way. To assure a reliable and efficient high-voltage transmission grid, it is important to identify timely potential bottlenecks since it often takes over 10 years to develop and construct high voltage long lines and substations.
Today HTS components using coated conductor tapes begin to demonstrate their advantages. Many successful tests and demonstrations have shown their technical capability, e.g., HTS power cables and fault current limiters. Since the Dutch electricity grid needs to adapt for the future power demands, the practicability ща integrating HTS equipment is to be studied.
For this a clear picture is needed to predict the potential future developments and difficulties that may arise in the Dutch grid. In a study of the Dutch transmission system operator (TSO) TenneT the future grid development is estimated using four most likely scenarios [1]. In this paper potential places of integrating HTS transmission cables are mapped using the TenneT approach. Integration of HTS cables into Dutch HV-grid and distribution networks will be dealt with in a separate paper.

2 GENERAL DEVELOPMENTS IN DUTCH TRANSMISSION GRID

Voltage structure of the Dutch grid is shown in fig. 1. This paper focuses on the extra high voltage (EHV: 380 kV). EHV of 220 kV, high voltage (HV: 110 and 150 kV), intermediate voltage (50 kV), and medium to

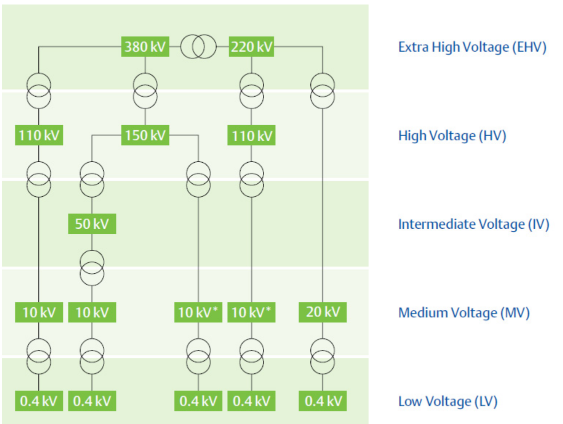


Figure 1 Voltage structure of the Dutch grid

low voltages (10 and 20 kV to 0.4 kV) will be treated elsewhere. The main function of the Dutch EHV-grid is to transmit the electricity over relatively long distances. The higher voltage allows reducing transmission losses per km length. The transmission grid serves the need of supply, transmits electricity from production to end users and connects the North West European electricity market. At first the transmission grid was used to couple large-scale production units and to connect with other countries to receive energy in case of an emergency. Nowadays the EHV-grid is used also for transporting electrical energy between neighbour counties, while the HV-grid guarantees the energy supply at the national and regional levels.
In figure 2 (left) the existing Dutch grid is shown. The grid has one EHV ring made for reliability reasons. Interconnections are made with the production sites and the neighbour countries. It is expected that more interconnections will be built in the future due to the liberalised market. By energy trading the cheapest electricity can be obtained.

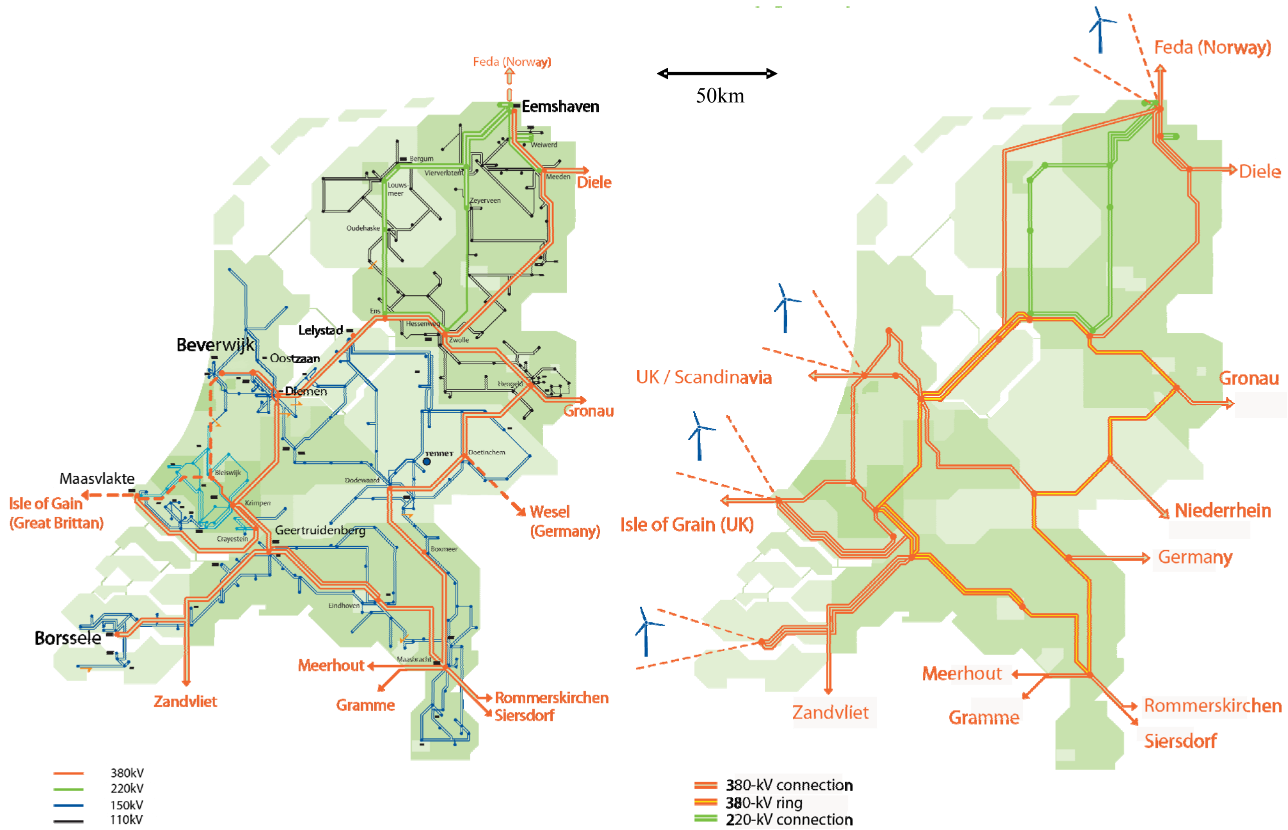


Figure 2: Dutch electricity network in year 2007 (left) and transmission grid in year 2030 (right).

Connected to the EHV ring is the HV-grid which has several smaller rings and connections over shorter distances. Black rectangles indicate production units. In 2006, the 380-kV grid input from the four coastal production sites was as follows: Eemshaven 2.4 GW; Maasvlakte 1.1 GW, Borssele 0.9 GW and IJmuiden (Beverwijk) 0 GW [1].

The increase in energy consumption follows the increase in economic growth. Other factors are changing production processes, computerisation, new communication and entertainment technologies increased electrical applications, air conditioners, heat pumps, electric transport and the growth of service and care sectors [1]. The yearly load growth in Europe is on average 2% to 2015, thereafter 1.5% predicted by UCTE. In the Netherlands the load concentrates mainly in the western and central parts of the country and the yearly growth will depend on which of the four scenarios is implemented.

The EU member states plan to have 20% of the energy supply from sustainable energy sources by 2020 [2]. The available wind energy will be increased to 300 GW, where 150 GW onshore and 150 GW offshore [2]. The goal of the Netherlands is to integrate 6 GW offshore and 4 GW onshore by 2020. It is known that produced renewable energy is less controllable and maintaining the energy balance between generation and demand becomes harder. This is directly applicable to the generation of wind power. In the long run, energy storage is seen as one of possible solutions.

3 TENNET SCENARIOS FOR 2030

TenneT has developed four possible scenarios of how the Dutch electricity grid could change in the coming decades [1], see Fig. 3. The scenarios reflect on the environmental and market dimensions and include four key connections with the outer world: Borssele, Maasvlakte, Ijmuiden (Beverwijk) and Eemshaven.

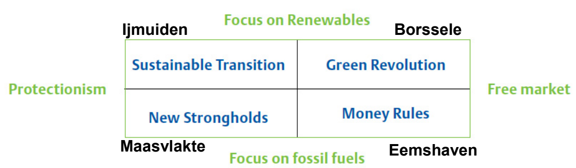


Figure 3: TenneT scenarios and market developments, scenario 1: Green Revolution; scenario 2: Sustainable Transition; scenario 3: New Strongholds; scenario 4: Money Rules [1].

Scenarios 1and 2 assume a society committed to sustainability; while scenarios 3 and 4 envisage a society that remains largely dependent on fossil fuels. Scenarios 1 and 4 are characterized by a free global market, whereas scenarios 2 and 3 foresee a world in which markets are regulated.

The assumed annual growth of electricity consumption for scenarios 1, 2, 3 and 4 is respectively: 2, 1, 0 and 3%. The four scenarios are detailed in [1].

4 POTENTIAL BOTTLENECKS IN 2030-GRID

For each scenario a set of major potential capacity bottlenecks for the EHV-grid (380 kV) in year 2030 is derived using the network analysis and assumptions further explained in [1]. Corresponding production capacity in year 2030 for each key location and for each scenario is listed in Table 1 [1]. The resulting overloading of the EHV-grid is shown in black in Figs. 4-5 for each scenario.

Table 1: Production capacity, GW at key locations

Scenario / Key location	1	2	3	4
Borssele	6.7	0.9	1.5	4.7
Maasvlakte	5.4	4.0	8.6	5.1
IJmuiden-Beverwijk	2.5	6.5	0.0	1.5
Eemshaven	0.0	0.9	1.4	5.0
Total, GW	**14.6**	**12.3**	**11.5**	**16.3**

4.1 Scenario 1: Green Revolution

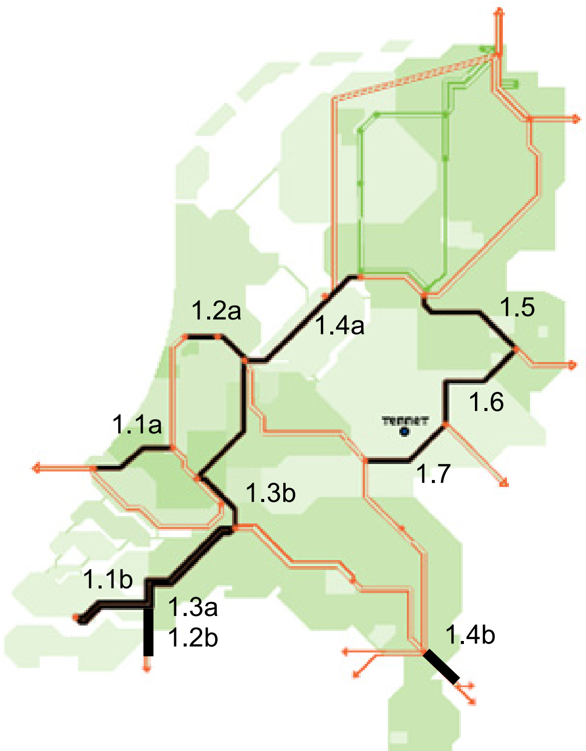
In fig. 4, left the potential transmission capacity bottlenecks are shown for a windy winter day (1.1a-1.4a) and for a sunny windless day (1.1b-1.4b). As explained in [1], the overload 1.3a is due to uneven distribution of transmission power, and the other three bottlenecks (1.1a, 1.2a and 1.4a) are due to the excessive amount of power produced. The solution proposed by TenneT for these potential bottlenecks is: coordination of maintenance for n-1 criteria situations, limiting power production in particular locations, where the power reduction is taken over by other generation locations. A more intense solution is to upgrade the power connection or even the whole EHV ring, or to control the power input flow for instance by phase shifters. In the situation of a windless summer day, power is imported through Eemshaven and production at Borssele is overloading the transmission lines (1.1b). At two interconnections (1.2b, 1.4b) too much power is imported overloading the EHV-lines, which can be solved by phase shifters. Overload 1.3b is due to insufficient transmission capacity of the EHV ring.

4.2 Scenario 2: Sustainable Transition

For this scenario, in the case of a windless day there would not be any bottlenecks in the grid. The potential bottlenecks in case of a windy cold winter day are shown in fig. 4, right. Due to the excessive energy production, the connection 2.1 from Ijmuiden (Beverwijk) is overloaded. One solution is to limit the production capacity of Ijmuiden to 3.5 GW. Another solution is to install a new connection from Beverwijk (to the 380 kV ring between Diemen en Lelystad, see fig. 1). This would also be necessary as the energy demand of the Northern part will grow in the future.

4.3 Scenario 3: New Strongholds

This scenario is based on electricity export to Belgium and Germany due to coal-fired and nuclear plants production at Maasvlakte, see Table 1. There is almost no wind power connected to the grid due to less attention to renewable energy sources. For this scenario, the overloads 3.1 and 3.2 are due to excessive power produced at Maasvlakte, fig. 5, left. The overloaded connection 3.1 is caused by uneven power distributions during n-2 condition. Solutions can be to reduce the power input at Maasvlakte, or to make parallel connections to 3.1 and 3.2.



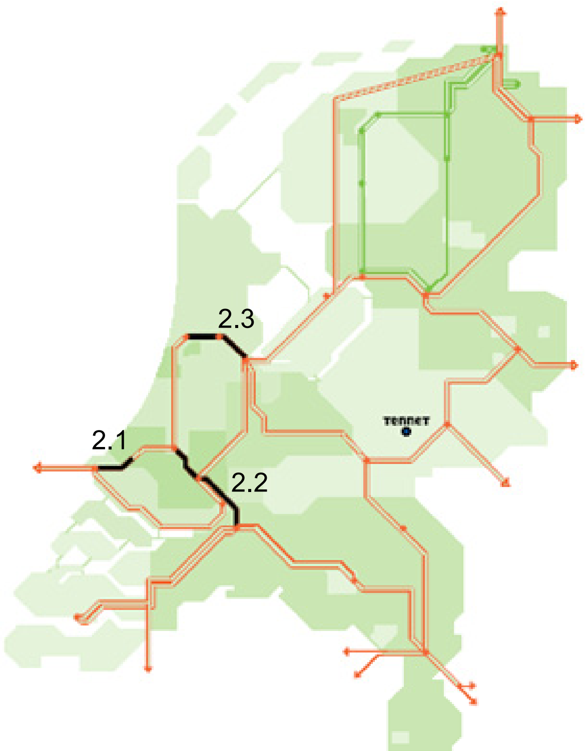


Figure 4 Potential bottlenecks in the grid of 2030: scenario 1 (left), cases of a windy winter day (a) and of a windless summer day (b); scenario 2 (right), case of a cold windy winter day

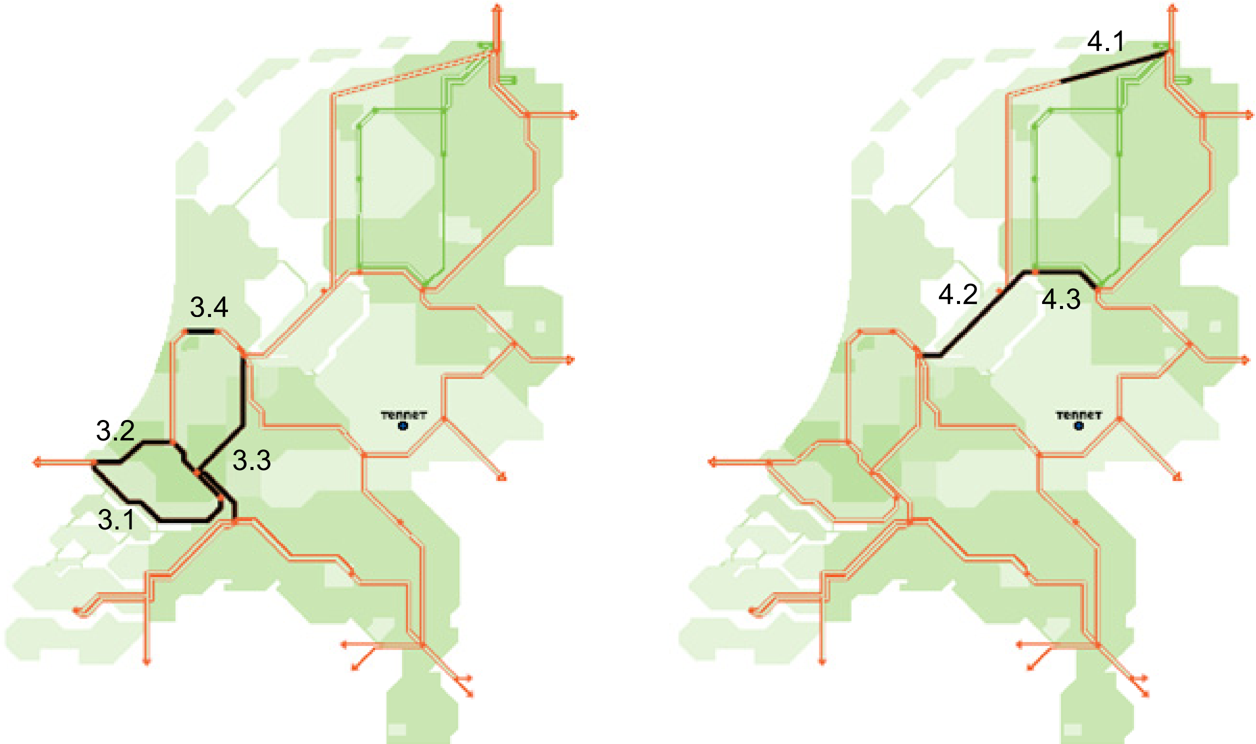


Figure 5 Potential bottlenecks in the grid of 2030: scenario 3 (left), cases of a windy winter day (a) and a windless summer day (b); scenario 4 (right), case of a windy or windless day

4.4 Scenario 4: Money Rules

In this scenario, the power production does not depend on the wind. At Eemshaven production capacity is increased from current 2.4 to 5 GW, Table 1. Connections 4.1 (Zwolle-Ens) and 4.2 (Eemshaven-Bergum) are overloaded, see fig. 5, right. The bottlenecks can be eliminated by either an upgrade of the connections or by limiting the incoming power at Eemshaven.

Comparing the four scenarios (figs. 4-5) one can conclude that depending on the scenario, different parts of the existing grid need to be strengthened in order to have a reliable transmission grid in 2030, as reflected in fig. 2, right.

5 NATIONAL PROJECT SUPERNET

In the framework of the project Supernet, which recently started in the Netherlands, it is estimated that, if the future national grid will be developed using only copper conductors, then in year 2030 the losses will amount to about 10 TWh/year, an amount comparable to the amount of energy produced by all Dutch wind parks in this year. Therefore, a transition to sustainable power will be substantially delayed. Alternatively, more efficient HTS superconducting components can be used for replacing copper-based aging grid components that have to be replaced anyway (e.g. cables, transformers). This way the grid losses can be reduced to about 4 TWh/year and thus additional 6 TWh/year of clean energy can be delivered to customers. The Supernet project studies the possibilities of making the future Dutch grid more sustainable by integrating HTS components primarily at potential bottlenecks. In the framework set by the project, we assume that the price of commercial HTS coated conductor tapes becomes comparable to the price of copper (in Euro/kA/m) and that HTS power cable technology is sufficiently mature.

6 AREAS TO INTEGRATE HTS CABLES

The advantages of HTS cables as compared to overhead lines (OHL) are: savings on land and rights of way; higher transmission capacity; lower AC loss; and better environment. The advantages of HTS cables as compared to conventional cables are: lower losses; longer length between compensation stations; ability to limit fault currents. It can be seen from Section 4 that location of potential bottlenecks in the grid is scenario dependent. Thus, to cover all possibilities, for every TenneT scenario we indicate likely areas to integrate HTS cables.

6.1 The EHV-connections

Scenario 1: in both situations the interconnections 1.3a to Belgium (Borssele-Zandvliet, <50 km) and 1.4b to Germany (Maasbracht-Rommerskirchen, <80 km), see fig. 4, left, can be strengthened by HTS cables with high power capacity. For a windy winter day, three additional HTS connections can be made: 1.1a, 1.2a and 1.4a. For a windless summer day, a connection 1.1b can be made with HTS cables.
Scenario 2: the abovementioned new connection (Beverwijk-North Holland) can be made with HTS

cables, and the power capacity of this new connection can be increased. Even in the distant future the voltage level of this connection can be kept constant by periodic upgrading the cable core with newer HTS tapes.

Scenario 3: due to the increased power production at Maasvlakte, the overloaded connections 3.1, 3.2 (Maasvlakte-Krimpen) and 3.4 (Beverwijk-Oostzaan) can be strengthened by HTS cables. Because of the large capacity at Maasvlakte, part 3.3 of the EHV ring needs to be strengthened by HTS cables.

Scenario 4: in order to solve the overloading connections 4.1 near Eemshaven, the connections can be strengthened with a HTS cable placed in parallel to existing OHL. Hereby the power capacity of the EHV-ring parts 4.2 and 4.3 will be enlarged.

6.2 The EHV-ring

TenneT vision of the grid concept 2030 is one EHV ring with sufficient power capacity together with strong connections to the large power production locations, see fig. 2, right.

To achieve this goal, in case of **scenario 1** substantial parts of the transmission ring have to be strengthened (see marked 1.3b, 1.4a, 1.5, 1.6 and 1.7 in fig. 4, left). This can be done by connecting HTS cables parallel to existing OHL both operated at the same voltage as explained in fig. 6 and Tables 2, 3. An advantage of this solution is that the level of transmission voltage in the ring can be kept indefinitely by a periodic upgrade of HTS tapes in HTS cable core.

6.3 Example of the future grid study

At present 0.9 GW is and in the future 6.7 GW will be transmitted between Borssele and the EHV-ring with the connection length of about 100 km, see Table 1 and fig. 2, right. For this currently two and in the future five OHL (with redundancy) would be required with transmission parameters as listed in Table 2. However, the Dutch regulations currently state that total OHL length will not increase in the future due to the opposition of society and the occupation of land. Therefore, placing underground cables instead of the three additional OHL is an option.

In this paper we present an example when HTS cables are used for this purpose. The grid structure in this case is shown in fig. 6 and results of the grid study for *n*-1 criterion are listed in Table 3. Due to the *n*-1 criterion, five OHL are needed in parallel (fig. 6, top), whereas two OHL are needed in parallel to two HTS cables (fig. 6, bottom). An intermediate case with 4 OHL and 1 HTS cable in parallel is also included into the analysis (fig. 6, middle). In Table 3 the columns (starting from left) are: transmitted power flow *P*; reactive power flows *Q1* and *Q2* at respectively Borssele and Geertruidenberg; total nominal current *I*; voltage drop ΔU, electric loss per circuit, kW; total loss per circuit, MWh; and total loss per connection, MWh. The total loss is calculated with the annual time of 3000 h for the power load and 8760 h for the terminations and cryostat. For the HTS transmission cables the following additional assumptions are made: heat loss in three cryostats is 3 kW/km; cooling penalty is 15; 3-phase termination loss is 1 kW/termination with 4, 8 and 18 terminations respectively for 10, 50 and 100 km length; and ac loss is respectively 1.6 and 2x0.3 kW/km at the current of 5.5 and 2x4.1 kA. The study is performed for different connection length (10, 50 and 100 km) in order to include a case when HTS cable(s) covers part of the connection length between Borssele and the EHV-ring.

It is clear from Tables 2 and 3 that regardless the connection length, HTS cable(s) operated in parallel

Table 2: Transmission parameters at 380 KV

Parameter (380kV)	OHL [3]	XLPE cable [4]	HTS cable [3]
Resistance (mΩ/km)	0.233	10.9	0.05
Inductance (mΩ/km)	0.879	0.47	0.175
Capacitance (μF/km)	0.132	0.202	0.16
Nominal current (A)	2500	1800	6900
Z_0 (Ω) ($\sqrt{L/C}$)	258	48	32
SIL (MW) (U^2/Z_0)	559	2994	4553

Table 3 Example of the grid study to strengthen the connection at Borssele with OHL and HTS cables

L km	Type	Inom A	P MW	Q1 MVAr	Q2 MVAr	I A	ΔU kV	Loss kW	Tot. Loss kW	Loss GWh	Tot. Loss GWh
10	5 x Overhead line	5 x 2500	6579	1457	1333	9725	2.7	13242	13242	66	66
	4 x Overhead line	4 x 2500	2864	468	458	4188	1.2	4087	4837	12	
	1 x HTS Cable	1 x 6900	3705	915	875	5507		750		7	19
	2 x Overhead line	3 x 2500	1062	146	149	1546	0.8	838	1951	3	12
	2 x HTS Cable	2 x 6900	5505	1220	1184	8136		1113		10	
50	5 x Overhead line	5 x 2500	6637	2009	1333	10005	15.7	70521	70521	212	212
	4 x Overhead line	4 x 2500	2876	536	480	5563	6.5	15715	19285	47	78
	1 x HTS Cable	1 x 6900	3708	1057	853	5563		3570		31	
	2 x Overhead line	3 x 2500	1065	151	166	1552	4.3	4251	9456	13	58
	2 x HTS Cable	2 x 6900	5507	1350	1167	8182		5205		46	
100	5 x Overhead line	5 x 2500	6726	2921	1333	10580	39.2	159517	159517	479	479
	4 x Overhead line	4 x 2500	2891	635	506	4272	14.4	32582	39752	98	161
	1 x HTS Cable	1 x 6900	3711	1255	828	5653		7170		63	
	2 x Overhead line	3 x 2500	1069	159	186	1558	9.2	8683	19153	26	118
	2 x HTS Cable	2 x 6900	5510	1526	1148	8250		10470		92	

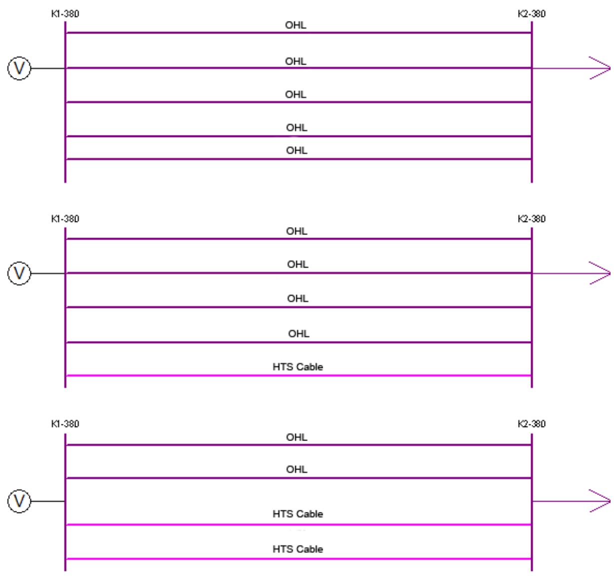


Figure 6 Possible future structures for the connection of Borssele site to the EHV-ring

to OHL, transmit most of the power due to their much lower impedance. For example, at 100 km length two OHL transmit 1.1 GW and two HTS cables transmit 5.5 GW. As a result, annual AC loss of the connection as whole is greatly reduced: from 479 GWh for five OHL to 118 GWh (or x4), Table 3, with annual savings of about 24 MEuro. Another important consequence is that magnetic emission of existing OHL (and hence of the connection) is significantly reduced (x7). Also the voltage drop ΔU is much lower: 39.2 kV for five OHL and 9.2 kV for two OHL and two HTS cables (or x4).

Remarkably, the use of the two HTS cables (fig. 6, bottom) makes it possible to eliminate one OHL connection and yet comply with *n*-1 criterion, which saves in occupation of land and investment. For the connection Borssele this means no additional OHL will be needed (compared to the existing situation), which in turn complies with the national regulations.

As more connections have to be placed underground, reactive power compensation becomes an issue. For compensation, coils and capacitors are usually connected to the cable. Installing these components brings higher investment costs and additional copper loss, therefore alternative solutions should be considered. Operation close to the cable surge impedance loading (SIL) needs the smallest amount of compensation. As shown in Table 2, at 380 kV HTS cable has the characteristic impedance Z_0 of 32 Ω, which is 1.5 and 5 times smaller then for XLPE cable and for OHL respectively. As a result, the HTS cables operate closer to SIL (Table 3) and need substantially less compensation. The power can be transmitted with less reactive content as illustrated in fig. 7 (in order to match to existing switchgear, the case of 3.5 kA HTS cable is also shown).

6.4 Availability of HTS components

At present pilot HTS cables exist or under development for transmission voltages of 138 kV

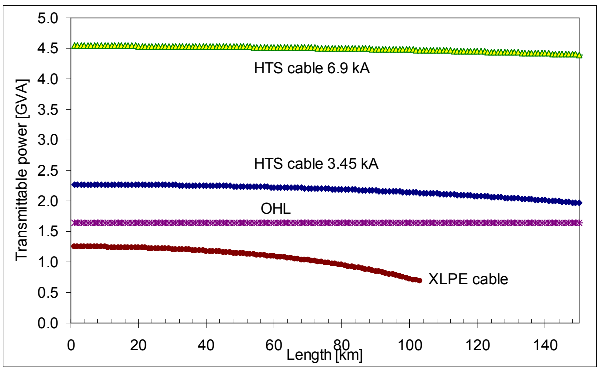


Figure 7 Transmittable power as function of the length for the 380 kV components listed in Table 2

[5] and 275 kV [6]. We assume in this study that sufficiently long HTS cables for 380 kV will be developed within the required time frame.

7 CONCLUSION

In the framework of the national project Supernet, using the vision of TenneT for year 2030, major potential bottlenecks are identified in the future Dutch transmission grid. It is shown that EHV HTS cables in parallel to OHL is a favourable solution to the identified bottlenecks due to the smaller footprint and less permits, higher power capability, less AC loss, reduced magnetic emissions and a possibility to maintain the transmission voltage at 380 kV even in a distant future.

References

[1]. TenneT: "Vision 2030 national electricity transmission grid", May 2010 and February 2008, Arnhem, the Netherlands url:http://www.tennet.org/english/tennet/publications/technical_publications/visie2030/visie2030.aspx

[2] EWEA's reports: "Powering Europe: Wind energy and the electricity grid", Nov. 2010 and "Pure Power: Wind energy targets for 2020 and 2030", Dec. 2009, url: http://www.ewea.org; last accessed: May 14, 2011

[3] Private communication

[4] NKT Brochure 400kV Single Core XLPE cable with copper wire screen and APL sheath

[5] J. F. Maguire, e. a.: "Progress and status of a 2G HTS power cable to be installed in the Long Island power authority (LIPA) grid", IEEE Transactions on applied superconductivity, 2010

[6] S. MukoYama, e. a.: "Development of 275 3kA HTS power cable", 8th International conference on insulated power cables, C.6.2