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Strengthening future electricity grid of the Netherlands by integration of HTS transmission cables

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Abstract. The electricity grid of the Netherlands is changing. There is a call of society to use more underground cables, less overhead lines (OHL) and to reduce magnetic emissions. At the same time, parts of the future transmission grid need strengthening depending on the electricity demand in the coming decades [1]. Novel high temperature superconductor (HTS) AC transmission cables can play a role in strengthening the grid. The advantages as compared to alternatives, are: economic, underground, higher power capacity, lower losses, reduced magnetic field emissions in (existing) OHL, compact: less occupation of land and less permits needed, a possibility to keep 380 kV voltage level in the grid for as long as needed. The main obstacles are: the relatively high price of HTS tapes and insufficient maturity of the HTS cable technology. In the paper we focus on a 34 km long connection in the transmission grid (to be strengthened in three of the four of TenneT scenarios [1]), present the network study results, derive the requirements for corresponding HTS transmission cable system and compare HTS system to the alternatives (OHLs and XLPE cables).

1. Introduction

In the year 2030 the losses in the Dutch AC grid will be 10 TWh when only copper conductors are used. The lost amount of electricity is comparable to that generated by all Dutch offshore wind parks in the same year (in the moderate scenario). Many grid components are at the end of their lifetime and a replacement wave is expected. Since a regular replacement can take 10 years, new solutions need to be studied timely. In the framework of the national project SuperNet, we study how to strengthen the Dutch grid of 2030 with HTS cables. The study uses four scenarios of the grid development provided by the Dutch Transmission System Operator (TSO) TenneT.

In [2] general trends of Dutch transmission grid were explained using the scenarios of TenneT illustrated with the example of network study of the future grid strengthening with HTS cables. However, economic (and other) aspects of such step were not considered. These are very important, since many of HTS cable demo-projects stop as soon as a subsidy is off. Instead, one can look for economically sound sustainable areas where HTS cables can be applied (without compromising e.g., system reliability) and a reasonable profit can be made at the same time.

In this paper we present results of the techno-economic study performed in this direction for HTS transmission cables, compare HTS cable to available alternatives (OHL and XLPE cable) focus on one selected connection and define areas in the grid where the sustainable approach is valid. Based on the analysis, two new scenarios for integration of HTS cables in Dutch transmission grid are proposed.

HTS cable economy is sensitive to the price of HTS tape. Our approach is that higher voltage allows using less HTS tapes for the same transmitted power, leading to a competitive HTS cable.

2. Dutch transmission grid and the connection Krimpen-Geertruidenberg

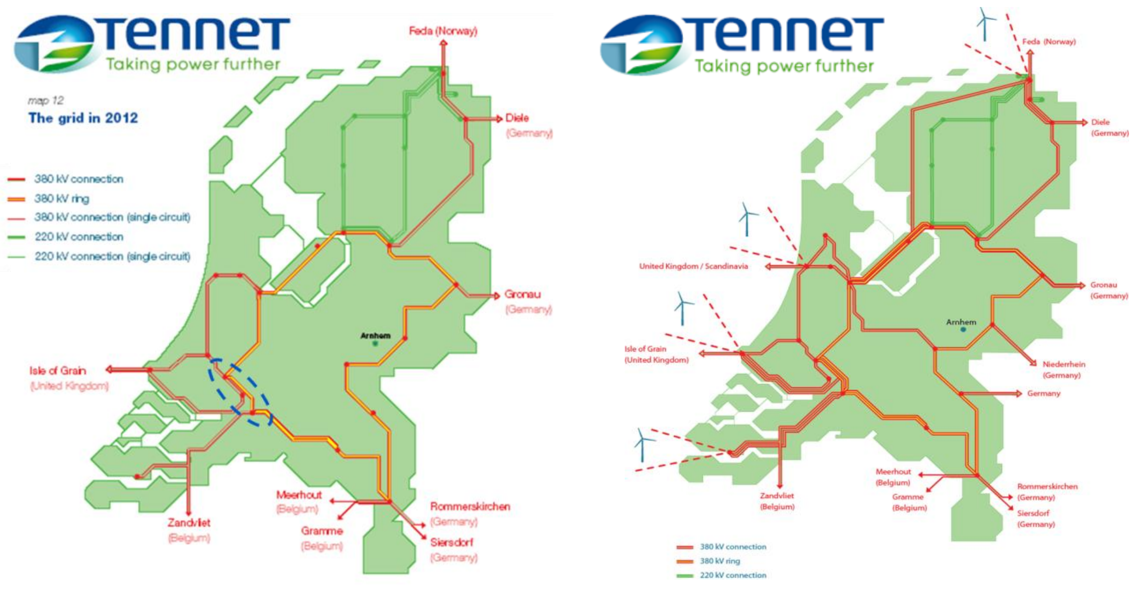
2.1. Dutch grid today and in the year 2030

The Dutch AC grid is shown in figure 1a. It consists of the 380 kV ring and several 380 and 220 kV connections. The total (single circuit, 380 kV) length amounts 2127 km. Even though XLPE cable outperforms OHL in public acceptance, rights of way, efficiency, magnetic fields, visual and acoustic impacts, TV and radio interference, electrocution risk, impact on aviation, on building planning, on flora/fauna, impacts of weather and catastrophic events, over 95% of the AC grid is made of OHLs. The total electrical energy produced (consumed) in year 2010 was 124 (109) TWh respectively. Example of the Dutch transmission grid in year 2030 is shown in figure 1b [1]. In this scenario, according to TenneT, business will be as usual. The grid will be made of OHLs where possible and of XLPE cables (where OHLs are impossible to use), with no HTS cables foreseen. Total electrical energy consumed in year 2030 will be 150 TWh and the losses are 1.5-2 TWh.

Four scenarios of possible grid development in year 2030 are provided by TenneT [1] and further elaborated in [2]. The important conclusion for this study was that in three of the four TenneT scenarios, the connection Krimpen-Geertruidenberg K-G (see figure 1a) will need strengthening.

2.2. Connection Krimpen-Geertruidenberg

A closer look at what this 380 kV connection is today and will be in year 2030, exposes the following. Dutch regulation states that the total length of OHL cannot be increased. At present two 2.5 kA OHLs form this 33.7 km long connection, each OHL will be upgraded to 5 kA later on. This however is not sufficient, and in the year 2030 the following alternatives are considered for *n*-1 redundancy: <u>option 1</u>, one new 5 kA OHL will be added. This would require more rights of way and contradicts with the Dutch regulation; <u>option 2</u>, two 5 kA HTS cables in parallel to the two OHL (using the same rights of way); <u>option 3</u>, one 5 kA HTS cable (in series with a flexible alternating current transmission system FACTS) in parallel to the two OHLs (using the same rights of way); <u>option 4</u>, two 5 kA XLPE cables added in parallel to the two OHLs. XLPE cables will need additional right of way, though less than one additional OHL (in option 1).
Reliable transmission system needs n-2 redundancy (n-1 under maintenance). Corresponding options were included in our study, but are out of scope of this paper.



a b

Figure 1. Dutch transmission grid (380 kV and 220 kV are shown in orange and green respectively): a – existing grid in year 2012 [1], the connection K-G is indicated by the dashed ellipse; b – in year 2030, example scenario - business as usual - of TenneT [1].

2.3. Network study

Example of the study is presented in Table 1. Here (for n-1 redundancy) from left to right column are shown (calculated values of): transmitted power flow P, reactive power Q_1 and Q_2, for respectively the source and the load sites, receiving end current I_2, voltage drop ΔU, the loss per parallel branch and the total loss per connection in GWh/year. The last columns show averaged over the lifetime of 40 years losses (assuming a load growth of 2 % per year). The assumed power load (transport current) in year 2030 and at the end of the lifetime is 7 GW (10 kA) and 10 GW (15 kA), respectively. Under the n-1 redundancy the OHL can carry double rated current for days. Therefore, e.g., for option 1, three (not four) OHLs are needed to transmit the 10 GW. While for option 1 the currents are equally distributed over the OHLs, in option 2 most of the current flows in HTS cables. However, when e.g., one OHL fails, too much current will flow in one HTS cable; this is why namely two HTS cables are needed. In option 3 one of the HTS cables is replaced with FACTS (in series with the HTS cable) distributing the load current properly between the cable and the OHLs in all situations. For more details (including other assumptions of the study) see [2].

2.4. Economics of the available options

For options 1, 4 economics is evaluated using TenneT procedures. For options 2, 3 a model was constructed including the technical specifications, genuine design of all HTS cable components and systems, realistic costs of these (terminations, HTS cable core, electrical insulation, cryostat, cooling system, etc.), laying, dismantling, maintenance and other costs allowing to assess the investment (IC) and the lifetime costs (LTC) of the connection. The YBCO tape price was estimated to decline from present 350 down to 25 €/kAm within next 10 years [3], since just 10 km of such HTS cable would require 5 Mm of such tape.

Performed analysis shows that option 3 as compared to option 1 has the same IC and same LTC at the HTS tape price-performance ratio of 103 and 241 €/kAm respectively. At the tape price of 25 €/kAm the savings on IC and LTC are 227 and 625 M€ respectively. As compared to 4, option 3 has the same IC and the same LTC at the HTS tape price of 283 and 356 €/kAm respectively. At the tape price of 25 €/kAm the savings on IC and LTC are 746 and 957 M€ respectively.

Option 2 as compared to 1 has same IC and same LTC at the HTS tape price of 36 and 135 €/kAm respectively. At the tape price of 25 €/kAm savings on IC and LTC are 63 and 611 M€ respectively. As compared to 4, option 2 has the same IC and LTC at the tape price of 135 and 195 €/kAm respectively. At the price of 25 €/kAm the savings on IC and LTC are 582 and 944 M€.

Notably, a hybrid connection (options 2-4) allows to expand the grid underground, as such connection is more reliable than that made of cables only (since if a cable is out of service, remaining OHLs transmit full load current for as long as needed e.g., to repair a cable). Besides, options 2, 4 reduce magnetic emissions from existing OHLs drastically (see table1), a feature desirable for a TSO. Moreover, when HTS cables are used instead of XLPE, substantial cost savings are expected (see text above), connection is more compact and its length has no practical limit in a country like the Netherlands (25 km for option 4) [2]. Other applications of HTS cables include e.g., replacement of aged OHLs and partial undergrounding.

Table 1. Example of the grid study to strengthen the 380 kV connection K-G with OHLs (5 kA each), XLPE cables (2.5 kA each) and HTS cables (5 kA each).

Option	Nr. of circuits x Type	Nr. of cores x rated current, *kA*	P_1 *MW*	Q_1^{**} MVA_r	Q_2 MVA_r	I_2 *kA*	ΔU *kV*	Loss *GWh/ year*	Total Loss *GWh/year*
1	3xOHL	9 x 5	6644	812	0	10.1	5.7	290	290
2	2xOHL	6 x 5	1436	-65	82	2.1	0.0	32	61
	2xHTS	6 x 5	5366	-50	-82	8.1		29	
3	2xOHL	6 x 5	3631	243	102	5.5	-1.3	108	134
	1xHTS*	3 x 5	3084	255	-282	4.7		26	
4	2xOHL	6 x 5	1799	81	-30	2.7	1.7	52	112
	2xXLPE	12 x 2.5	4962	219	30	7.5		61	

*FACTS in series with HTS cable; ** calculated for cos φ = 1 of the load

3. Future Dutch transmission grid

Therefore, in addition to the scenario(s) of TenneT [1], we propose the following.

Scenario 1 (years 2025-2050, vision of Supernet project): OHLs and HTS cables co-exist, future grid is made of OHLs and HTS cables connected in parallel and using the same rights of way. Expansion of the grid is entirely underground; strengthening of the grid is made with HTS cables. The grid transformation is made at the same or lower IC and LTC. Extrapolating results obtained for connection K-G (option 3 against option 1) on the entire 380 kV grid gives savings of 5 and 13 B€ respectively. Total electrical energy consumed in year 2030 can be as high as 200 TWh and estimated losses are below 0.7 TWh. Almost the same reliability of the grid is expected, the voltage level of 380 kV can be kept forever and there is no need to introduce 750 kV level (as foreseen by ENTSOE).

Scenario 2 (years beyond 2050, vision of Supernet project): HTS cables rule, aged OHLS are replaced with HTS cables, the future grid is made entirely with HTS cables. The cable cores are periodically upgraded with modern HTS tapes, the voltage level is 380 kV and future needs for more electrical energy are met by changing the current capacity of HTS cores.

In order to arrive at scenario 2, HTS cables (as compared to OHLs) have first to show superior behavior in respect to: reliability, power capacity (including circuit breakers and other switching material), maturity, availability, failure rates, maintenance, time of repair, connection length and life expectancy (this requirements are softened in scenario 1 by the presence of the OHLs). A transition from scenario 1 to 2 is achieved by replacing aged OHLs with HTS cables.

4. Conclusions

Our study concludes that reliability of a transmission connection with OHLs alone is the highest, with cables in parallel to OHLs is close to that, and with cables alone is lower. Since reliability, power capacity, maturity, availability, failure rates, maintenance, time of repair, connection length and life expectancy of HTS cables in respect to OHLs are to be demonstrated, until then we propose to use HTS cables in parallel to OHLs. This way the issues of HTS cables can be tolerated in the grid and the cables can be used as soon as their assets are at the level of XLPE cables. HTS cables can be cheaper, more compact and reduce magnetic emissions in OHLs helping TSOs to treat this problem.

From economic point of view it is attractive for connection K-G to replace option 4 with 3 (or 2) at the HTS tape price from 356 to 283 (195 to 135) €/kAm and below. And, it makes sense to replace option 1 with 3 (or 2) at the HTS tape price from 241 to 143 (135 to 36) €/kAm and below. The tape prices and the volumes are within reach in 3-12 years. This allows to start expansion of the Dutch grid underground in a cost competitive way. Results for 220 and 150 kV grids will be treated separately.

Our assessment is based on realistic expectations for HTS cables. New advances can make HTS cables even more attractive: better ReBCO tapes, electrical insulation and cryostats, more efficient cooling using a cold from liquefied natural gas and gas-driven compressors at the cable cooling stations; the latter contributing to a climate in nearby buildings (with heat pumps fed by cable cooling losses), etc.

Acknowledgement

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