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Efficiency of superconducting transmission lines: An analysis with respect to the load factor and capacity rating

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ABSTRACT

Superconducting transmission lines (SCTL) are an innovative option for the future electricity grid and in particular for high-capacity HVDC power transmission. The promise of superconducting electric lines lies principally in their small size, with potential advantages in terms of efficiency, environmental impact and public acceptance. Furthermore, contrary to standard conductors, SCTL do not have any resistive losses, therefore the only remaining power loss is due to the cooling system that is needed to keep the superconductor at its cryogenic operating temperature. In order to obtain a realistic value for the SCTL efficiency, both the actual load factor and the capacity rating have to be taken into account. This paper analyzes the transmission efficiency characteristics for two long-distance SCTL designs developed at the IASS and at EPRI as a function of the load factor for capacities up to 10 GW, and in comparison with established transmission technologies. The focus of this study is the planned expansion of the HVDC transmission system in Germany, which is aimed at achieving the current CO_2 reduction goals by integrating an increased share of intermittent renewable energy (RE) into the grid. The results can be readily extended to other scenarios and can provide complementary information for decision processes directed at planning a sustainable future grid.

1. Introduction

A sustainable electric energy supply is one of the major tasks in the near future, especially in the context of increasing the renewable energy share to reduce greenhouse gas emissions and to meet the steadily growing global energy demand. Any innovative technology that can improve the efficiency of future electric grids will be a welcome and much needed addition to the established transmission- and distribution line options. Superconducting transmission lines (SCTL) have a number of advantages compared to standard technologies, in particular for high capacity HVDC power transmission. Besides their small size, the potential for an improved transmission efficiency is one of the key advantages. Additional benefits of SCTL are related to the easier acceptance by the public (small corridor width, underground, no electric fields) [1] and possibly economic advantages [2]. Due to the absence of electrical resistance, the only remaining loss for DC applications is the constant amount of power per unit length caused by the cooling system that is needed to keep the superconductor at its cryogenic operating temperature. The real efficiency of any transmission line, be it a standard technology or a SCTL, depends strongly on the load factor that in turn depends on the overall scenario the TL is embedded in and the boundary conditions thereof. The actual share of renewables in the electricity mix has a huge impact on the load factor, as for instance wind is an intrinsically intermittent energy source compared to hydro power where electric energy is generated using a water reservoir and the power output can be controlled to a certain degree. The complexity of the electric grid in which the HVDC high capacity TL is embedded plays a significant role too as it becomes more challenging to optimize the power flow for an overall minimization of energy losses between numerous centers of energy generation and demand in a meshed grid including the AC grid.

The aim of this paper is to give a more detailed insight into the efficiency of superconducting transmission lines in a real world application with respect to the load factor in a sustainable future electric transmission grid that integrates high shares of RE. A high-efficiency transmission line translates into low equivalent greenhouse gas emissions, which is one of the main reasons for switching to RE generation in order achieve the 2 °C goal.

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In the following, Germany and its planned HVDC transmission system are chosen as the case study for investigating the efficiency of superconducting lines. This should be merely seen as a convenient example due to the existing availability of concrete plans and detailed information [3,4]. Conclusions can be adapted to other regions or projects with similar load factor and capacity ratings.

The planned HVDC transmission corridors for the year 2025 are displayed in Fig. 1 for scenario B of the most recent German Grid Development Plan (GDP 2025 draft by the Federal Network Agency [3]). The time horizons for the GDPs are 10 and 20 years. The required level of power line route expansion was calculated to be 3200 km for HVDC corridors totaling a transmission capacity of 10 GW. This does not include the German share in the three DC interconnectors between Germany and Belgium, Denmark and Norway. Of particular interest for this paper are corridor A in the far west (and here the northern part A1) and corridor C (also called Südlink in Germany).

2. The load factor in the context of RE integration

Assuming a grid that integrates a high share of renewable energy generations for a future sustainable energy supply it will be hard to achieve a 100% load factor because:

1. The variation of the energy demand over the year and during the day.
2. The intermittent nature of RE – with an RES of the energy mix in Germany of already 25% (2014) and 80% by 2050 [5,6].
3. General considerations tend to match the capacity of transmission lines to the highest possible output of RE sources.

These factors lead to a limitation and reduction of the average load of transmission lines and in particular of HVDC high capacity transmission lines which are considered in this paper.

In contrast to SCTL, standard conductors have an electrical resistance and power losses show a quadratic dependence on the transport current for direct current (DC) applications $P_{\mathrm{Loss}} \sim I^2$. Load factors of less than 100% of the maximum transmission line capacity therefore result in lower relative electric losses and higher efficiencies for standard conductors but in lower efficiencies for SCTL due to the fixed energy consumption of the cryogenic system.

A simulation of the load factors of the planned North-South HVDC TL in Germany was done by the Center for Energy Graz as part of a study on the required German grid extension commissioned by the Federal Network Agency [4]. The average load factors were investigated for various planned HVDC transmission corridors in Germany based on the GDP from 2012. The simulation assumes the forecasted installed RE and conventional generation capacities according to scenario B of the GDP 2012. These capacities are listed in Table 1 for the years 2024 and 2034 taken from the GDP (2014 2nd) and the year 2022 used by [4] (based on the GDP 2012 which has been updated with now slightly different numbers). The study included the forecasted power generation (mix) of adjacent countries and cross border electric energy exchange.

The average load factors are found to be between 54% (corridor C with 4 GW capacity as of GDP 2012) and 86% (corridor A1 with 2 GW capacity) for the year 2022 and to be between 21% (corridor C with 9.2 GW capacity) and 91% (corridor A1 with 6 GW capacity) for the year 2032. These results stem from the calculation B.NEP4K assuming all corridors A, B, C and D to be in place. Please note that the GDP 2014 2nd upgraded the capacity for corridor C to 6 GW in 2024. An improper connection to the AC grid at the southern end of HVDC corridor C is partly responsible for the low average load factor of that corridor. In any case, there are huge differences in the average load factor when comparing all corridors. The efficiency of a hypothetical superconducting TL would therefore vary tremendously depending on the corridor, as would the efficiency of standard conductors. Please note that corridor C actually consist of sub-corridors that have different start and end points where they connect to the AC grid but are located in geographical proximity. DC-AC converter and entry points will be located close to shutdown nuclear power plants to take advantage of existing AC grid infrastructure. Please also note that bulk energy HVDC transmission lines have been realized so far mainly by making point-to-point connections and using Line-Commutated-Converter (LCC) technology that does not allow to build a meshed DC-grid due to their black start inability. The planned HVDC corridors in Germany are in contrast based on Voltage-Source-Converter (VSC) technology that is more flexible and allows to build an HVDC-grid, similar to the existing AC grid, for instance to connect several wind farms to one transmission line or to simply make a 3-fold DC interconnection.

Table 1
Net generation capacities in Germany according to the baseline scenario B in 2022 (used for TU Graz simulations), 2024 and 2034.

Net capacity in GW	B-2022	B-2024	B-2034
Conventional			
Nuclear	0.0	0.0	0.0
Brown coal	18.6	15.4	11.3
Hard coal	25.1	25.8	18.4
Natural gas	31.3	28.2	37.5
Oil	2.9	1.8	1.1
Storage (incl. pump storage)	9.0	10.0	10.7
Others	2.3	3.7	2.7
Sum (conventional)	89.2	84.9	81.7
Renewables			
Hydro	4.7	4.7	5.0
Wind onshore	47.5	55.0	72.0
Wind offshore	13.0	12.7	25.3
Photovoltaics	54.0	56.0	59.5
Biomass	8.4	8.7	9.2
Other renewables	2.2	1.5	2.3
Sum RE	129.8	138.6	173.3
Sum total generation	219.0	223.5	255.0

3. Methods for calculation

3.1. Long-distance superconducting transmission line based on MgB_2 developed at IASS

Results shown are based on a bi-polar long-distance SCTL developed at the Institute for Advanced Sustainability Studies in Potsdam/Germany (IASS) which is based on the affordable superconducting material magnesium diboride (MgB_2) [7]. The underlying idea was to connect remote places of renewable energy generation by a highly efficient transmission technology. An MgB_2 based SCTL can have much lower costs than SCTL projects based on high-temperature superconductors (HTS) primarily due to lower production costs and can therefore facilitate an accelerated adoption of this promising technology. This MgB_2 SCTL was designed to have a capacity rating of 10 GW at a voltage and current rating of ±125 kV and 40 kA with cooling stations located every 300 km. It can either be cooled by liquid hydrogen or gaseous helium plus liquid nitrogen. This voltage is lower than that of state-of-the-art HVDC cables based on standard conductors (525 kV). Reducing the voltage level can lead to lower cost and simpler operation of relevant grid equipment. Superconductors have high current densities, meaning they have the ability to transfer a high current per cross section of the conductor. This allows for lower operating voltages leading to a simplified design with a smaller outer diameter, thus reducing the heat influx. Within a cooperation of CERN and the