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Published in:
I E E E Transactions on Applied Superconductivity

Link to article, DOI:
10.1109/77.614605

Publication date:
1997

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Østergaard, J. (1997). Superconducting power cables in Denmark - a case study. *I E E E Transactions on Applied Superconductivity*, *7*(2), 719-722. https://doi.org/10.1109/77.614605

Superconducting Power Cables in Denmark - A Case Study

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***Abstract*—A case study of a 450 MVA, 132 kV high temperature superconducting (HTS) power transmission cable has been carried out. In the study, a superconducting cable system is compared to a conventional cable system which is under construction for an actual transmission line in the Danish grid. The study considers the design and development of a calculation model for an HTS cable system including auxiliary facilities. From calculations of the selected transmission line, conclusions on the feasibility of HTS cables in Denmark are made. HTS cables appear to be feasible in Denmark. Calculations indicate that HTS cables will be less expensive for high power ratings, have lower losses for lines with a high load, and have a reduced reactive power production. The use of superconducting cables in Denmark accommodate plans by the Danish utility to make a substantial conversion of overhead lines to underground cables.**

I. Introduction

Many experiments of superconducting multistrand conductors have been reported in recent years, and currents in the kiloampere range required for the commercial application of HTS power transmission cables have been demonstrated [1]-[3]. Hence the possibility of constructing a feasible power transmission cable seems within reach. However, it is not clear that a superconducting power transmission cable can fit into a conventional electric power transmission system. A superconducting cable will have characteristics which are different from a conventional cable.

This paper deals with aspects of using an HTS power transmission cable as an integrated part of the transmission system. In particular the study has focused on the cable design, the technical properties of the HTS cable system, the energy saving aspect and the costs of the HTS cable system.

The results presented are based on a project carried out in cooperation between the Danish electric utilities and the Technical University of Denmark [4].

II. Case Study and Cable Design

A. Conventional Solution

The first step in the project was to locate a transmission line in the Danish network feasible for a case study. A 450 MVA, 132 kV (2.0 kA) AC transmission cable system under construction in the Danish electric transmission system south of Copenhagen was selected. The cable system connects a 132 kV sub-station and a 400 kV sub-station. The length of the cable system was 4,050 m.

The conventional cable system, which was laid during the project period is constructed as two parallel conventional cross-linked polyethylene (XLPE) aluminum cable systems, i.e. 6 single-core cables, due to a limited current capacity in conventional cables. Each of the single-core cables have a cross-section of 2,000 mm^2.

The selected line for the study was expected to be a suitable length for an HTS cable system with cryogenic refrigerators at the ends of the cable only. Furthermore, it was expected to have a power rating high enough to be feasible for an HTS cable system as well as being representative for Danish transmission lines with a high load and power rating.

B. HTS Cable System

There are basically two design concepts for an HTS power transmission cable: the cryogenic dielectric (CD) design concept and the room temperature dielectric (RTD) design concept (Fig. 1) [5]. The CD design has an electric insulation and a superconducting shield directly around the HTS multistrand conductor and an overall cryostat applied either over each phase or all three phases. In the CD design the electric insulation has to operate at liquid nitrogen temperature. This is an

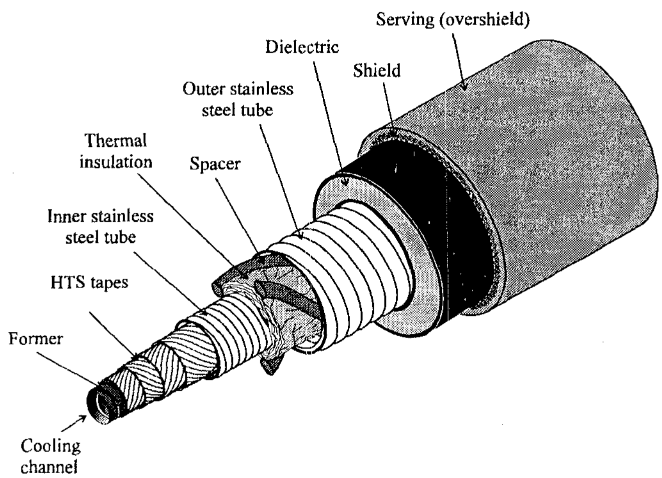

Fig. 1. Conceptual design of an HTS single-core power transmission cable used for the case study (room temperature dielectric design concept).

Manuscript received August 27, 1996.

1051-8223/97$10.00

additional complexity of the cable that has to be overcome. In the RTD design the thermal insulation is applied over the multistrand HTS conductor followed by a conventional electric insulation, shield and serving. The RTD design is similar to a conventional power cable design except that the conventional conductor is replaced with an HTS conductor and thermal insulation.

The case study focuses on the RTD design, which seems to involve fewer technical difficulties [5]. The RTD design concept is feasible for moderate currents only (below about 2.5 kA because of induced currents in the shield and tubes), which however, are sufficient. The design concept is less expensive but also has slightly higher losses due to induced eddy currents in the steel tubes and the shield.

The HTS cable system consists of three single-core cables, each single-core cable being constructed as shown in Fig. 1. The cables are laid direct in a flat formation, which is a common technique in Denmark. Each cable consists of a conductor of multiple Bi-2223 Ag-sheathed tapes helically wound on a flexible former. Liquid nitrogen for cooling, flows through the centre of the conductor and circulates in the three phases (one go-duct and two return-ducts). The thermal insulation system consists of a superinsulation between two corrugated stainless steel tubes. A conventional polyethylene electric insulation, a shield of wound copper wires and a polyethylene serving is applied over the thermal insulation. The entire construction is flexible, allowing the cable to be manufactured in long lengths and wound on cable drums.

C. Calculation Model

For the calculation of the properties of the cable system a model has been developed. The principle of the calculation is illustrated in the flow diagram below (Fig. 2). On the basis of electric specifications, properties of the materials etc. the physical, thermal and electrical properties of the cable are calculated.

Bean's model [6] is used for the calculation of losses in the conductor. It is assumed that hysteresis loss is the major conductor loss compared to viscous resistance loss, coupling loss,

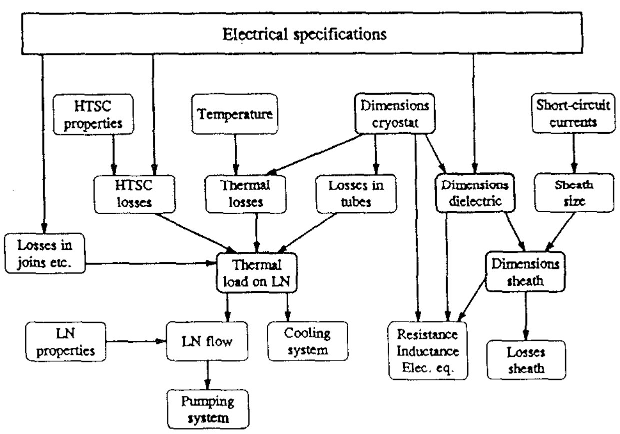

Fig. 2. Flow chart of calculation procedure of HTS cable.

and eddy-current loss. A critical current density, J_c, of 300 A/mm^2 is assumed and a maximum peak operating current density of the conductor is fixed at 75 % of J_c. Losses in the inner tube, the outer tube and the shield are calculated according to the IEC Standard 287 [7]. The shield of the cable is cross-bonded which does not result in any circulating current losses and only eddy current losses exist in the shield.

The liquid nitrogen flow is calculated using a standard flow model [8]. The maximum allowed pressure in the system is fixed to 15 bar, determined by the inner stainless steel tube. The temperature of the liquid nitrogen is determined by a working area between the melting curve and the evaporation curve (plus a 5 K safety temperature margin) in a pressure-temperature diagram of nitrogen. This results in an acceptable maximum temperature of 80 K at the outlet and an acceptable minimum temperature of 65 K at the inlet.

For the cryostat, a thermal conductivity, λ, of 0.25 mW/m·K is assumed [9].

III. Results

A. Calculation Results

The calculation results are shown in Table I and Table II. A single-core HTS cable has an overall diameter and weight comparable to a single-core conventional cable. A maximum pressure drop from 15 bar to 5 bar occurs in the go-duct,

TABLE I
PHYSICAL AND THERMAL CHARACTERISTICS OF A 450 MVA, 132 KV HTS CABLE

		Value
Conductor cross-section (Bi-2223/Ag)		50 mm^2
Number of tapes		138 tapes/phase
Outer diameter of cooling channel		22 mm
Outer diameter of thermal insulation		70 mm
Outer diameter of dielectric		103 mm
Outer diameter of single-core cable		116 mm
Center distance between single-core cables		186 mm
Weight of single-core cable		8.5 kg/m
LN-flow (go/return)	0.26 kg/s	0.13 kg/s
Thermal load on LN at 2.0 kA (go/return)	1.0W/m	0.94 W/m
Pressure drop (go/return)	10 bar	3 bar
Inlet temperature at 2.0 kA (go/return)	68.5 K	65 K
Outlet temperature at 2.0 kA (go/return)	76.5 K	80 K
Nominal power of cooling machines		2 x 6.1 kW
Estimated cool down time from ambient temp.		9 hours

TABLE II
COMPARISON OF AN HTS AND A CONVENTIONAL 4 KM, 450 MVA, 132 KV CABLE SYSTEM

	HTS	XLPE-AL
Conductor cross-section	50 mm^2	2 x 2,000 mm^2
Outer diameter of cable	116 mm	2 x 107 mm
Weight of cable	8.5 kg/m	2 x 12.4 kg/m
Equivalent series resistance	1.1 mΩ/km	12 mΩ/km
Equivalent series reactance	580 µF/km	280 µF/km
Equivalent shunt capacity	0.48 µF/km	0.52 µF/km
Estimated cost of cable system incl. auxiliary equipment and laying	72.7 mill. DKK	70.4 mill. DKK
Capitalized losses	4.7 mill. DKK	7.9 mill. DKK

whereas the maximum temperature drop from 80 K to 65 K occurs in the two return-ducts.

HTS as well as conventional power cables produce reactive power. In long lengths and high voltages, the reactive power production reduces the active current capacity, results in additional losses and has to be compensated by shunt reactors. The shunt reactors can cause resonance problems in the network, and hence set an upper limit for an acceptable length of cables in the network at high voltage levels. The reactive power production by a three phase cable, Q, in MVAr/km can be calculated by using:

$$Q = 2\pi f C U^2 \tag{1}$$

where f is the frequency in Hz, C is the capacitance of the cable, and U is the voltage level. In the case study with the 50 Hz frequency of the Danish network, the reactive power production of the HTS cable system and the conventional cable system is calculated to 10.6 MVAr and 11.5 MVAr respectively. Hence there is a small reduction in the reactive power production. A substantial reduction of the reactive power production is possible by using a lower operating voltage of an HTS cable (and a corresponding higher current) and by using the CD design concept which has a lower capacitance.

Power transmission cables in Denmark are normally required to withstand a short-circuit current of 40 kA in 1 second. Without any additional thermal stabilizer in the HTS cable, calculations show that a current of 13 kA can be allowed over 1 second without damaging the HTS tapes. It is necessary to solve this problem in order to use HTS cables. A fault current limiter (FCL) may be necessary as a protection against high short circuit currents.

B. Losses and Energy Savings

The full-load losses (at a nominal current of 2,000 A) in the 450 MVA HTS cables system are 17.2 W/m·phase, and the no-load losses are 6.2 W/m·phase. In the conventional cable system with two parallel single-core cables per phase the losses are 47.7 W/m·phase (full-load) and 1.0 W/m·phase (no-load). It is clear that the HTS cable system has smaller losses at high loads and higher losses at low loads (see Fig. 3). The high no-load losses of an HTS cable system is due to load independent thermal leaks through the thermal insulation (Fig. 4).

The load of a cable can be described by the annual load factor, T_b, defined as:

$$T_b = \frac{\int_{0h}^{8,760h} P(t)\mathrm{d}t}{P_{max}} \tag{1}$$

where $P(t)$ is the load as a function of the time and P_{max} is the nominal load. The load factor can be between zero and 8,760 hours. To obtain an energy saving by using an HTS cable, it is necessary to have a high load factor.

The annual load factor of lines in the Danish transmission network do normally not exceed 4,500 hours. The lines are operated well below their nominal load most of the time. If an annual load corresponding to a load factor of 4,500 hours is expected for the line, the losses are computed to be 990 MWh/year for the HTS cable system and 1,860 MWh/year for the conventional cable system. These losses can be capitalized to 4.7 mill. DKK (1 USD ≈ 6 DKK) and 7.9 mill. DKK respectively. The loss reduction using the HTS cable instead of the conventional cable system for the 4 km line is therefore 870 MWh (3.2 mill. DKK) or 40 %.

For lines with a low load factor, the loss reduction will be small or negative. Losses due to thermal leaks through the thermal insulation are of major importance to the energy savings. The thermal leak is responsible for more than 50 % of the energy loss in the cable system. Improvements to thermal efficiency are imperative in order to further reduce the losses.

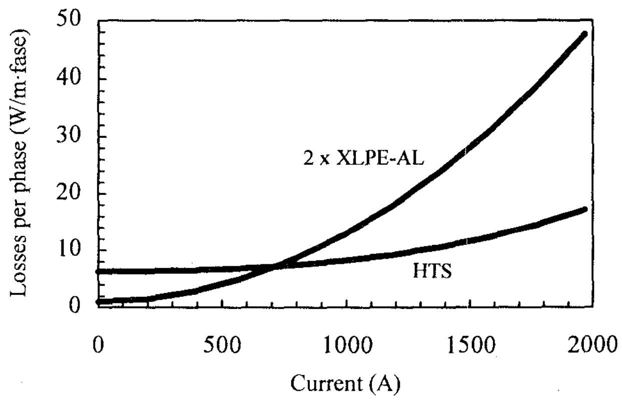

Fig. 3. Losses in 450 MVA HTS and conventional cable systems. The losses in the HTS cable system are smaller than the losses in the conventional cable system at high currents only.

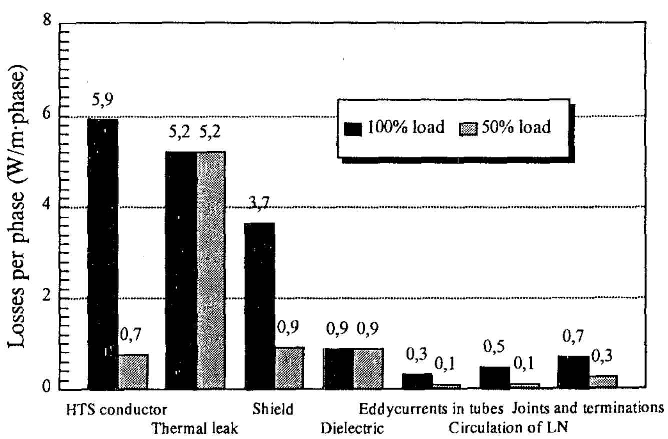

Fig. 4. Distribution of losses in a single-core HTS cable at 100% load and 50 % load. The losses are distributed according to the components origin and the efficiency of the cooling machines is included in the values.

C. Costs

The costs of the HTS cable system and the conventional cable system, including laying and auxiliary facilities such as switchgear, protection equipment, refrigerators etc., is estimated at 72.7 mill. DKK and 70.4 mill. DKK respectively. The cost of the BSCCO/Ag tapes is estimated at 2,200 DKK/kg. Hence the conductor costs are 1/5 of the cost of the entire HTS cable system. The capitalized costs of the losses have little influence on the total costs.

The cost of an HTS cable system is less sensitive to the nominal power of the system than a conventional cable system. Because of this, HTS cable systems can be expected to be less expensive at high power ratings.

IV. Discussion and Conclusion

The study shows that a saving of 40 % of the losses in a 450 MVA transmission line is realistic by using a RTD HTS cable system instead of a conventional one.

The total costs of a 450 MVA HTS cable system is estimated to be comparable to the total costs of a corresponding conventional cable system with two parallel systems.

In 1995 the Danish electric utilities and the Danish government worked out recommendations for converting high-voltage overhead lines to cables [10]. The recommendations include the following guidelines: New lines below 100 kV should always be cables. 150/132 kV overhead lines near urban areas and important nature areas should be removed or replaced by cables. Cables should be preferred for 400 kV infeeds to cities and across national nature areas. In the plan even more drastic scenarios are investigated. In the light of an increased demand for avoiding overhead lines, HTS cables can be a useful alternative to conventional cables in the future.

Massive converting to cables can cause problems with reactive power compensation and limit the total amount of cables in the system. Due to the lower reactive power production of HTS cables by the use of higher currents and lower voltages these problems can be reduced.

In the study the voltage level is given by the existing network. When using HTS cables a reduction of voltage level (and corresponding increase of current) could be preferable. Further studies on this subject are planned.

Reasons for introducing HTS cables in the Danish transmission network include:

- The opportunity of converting parts of the 400 kV network to 150 or 132 kV HTS cables.
- Reduced problems with reactive power compensation.
- No disadvantages of crossing heat sources such as district heating pipes because of a "cold" cable. (Conventional cables will have a reduced current capacity if the cable crosses one or more heat sources.)
- Energy saving of up to 40 % is possible for lines with a high load factor.
- The opportunity of less expensive cable systems for bulk power transmission.

There are also major challenges which have to be overcome before HTS cables can be put into commercial service. A reliable HTS power cable has to be demonstrated, a short-circuit protection of the HTS cables has to be developed, interaction between the existing overcurrent protection in the network and HTS cables should be considered, and new short-circuit calculation methods for networks with several HTS components must be developed.

Acknowledgment

The author wish to thank Prof. Ole Tønnesen, Department of Electric Power Engineering, Technical University of Denmark and Ph.D. Preben Jørgensen, DEFU, Research Institute of Danish Electric Utilities for assistance and encouragement received while conducting this work.

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