Power applications for superconducting cables in Denmark

S. Krüger Olsen and O. Tønnesen
Department of Electric Power Engineering, Technical University of Denmark, Building 325, 2800 Lyngby, Denmark

J. Østergaard
DEFU, Research Institute of Danish Electric Utilities, P.O.Box 259,
DK-2800 Lyngby, Denmark

Abstract—**In Denmark a growing concern for environmental protection has lead to wishes that the number of overhead lines is reduced as much as possible and that the energy supply should be shifted to renewable energy sources, e.g. windmills.**

Superconducting cables represent an interesting alternative to conventional cables, as they have other characteristics then conventional cables and will be able to transmit two or more times the current.

Superconducting cables are especially interesting as a target for replacing overhead lines. Superconducting cables in the overall network are of interest in cases such as transmission of energy into cities and through areas of special beauty. The planned large groups of off-shore windmills in Denmark generating up to 400 MVA or more will be an obvious case for the application of superconducting AC or DC cables. These opportunities can be combined with other new technologies such as high voltage DC (HVDC) based on isolated gate bipolar transistors (IGBTs). The network needed in a system with a substantial wind power generation has to be quite stiff in order to handle energy fluctuations. Such a network may be possible, e.g. using superconducting cables.

I. INTRODUCTION

In the sixties and early seventies much work was done around the world on development of low temperature superconducting (LTSC) transmission cables. It was at that time expected that the growing demand for energy would result in the need for larger transmission capacities than possible with conventional high voltage cables and overhead lines.

Because of the near zero Kelvin operating temperature, economically viable applications for LTSC cables were in the range of 5000 MVA and the cables were never adopted by the utility industry. The last research programme concerning LTSC cables ended in 1985 [1].

In 1986, Bednorz and Müller discovered high temperature superconducting (HTS) materials. This incited a renewed interest in superconducting power transmission [2].

HTS cables are developed to constitute an interesting alternative to the conventional cable systems in power transmission. It is expected that the superconducting cables will be commercially available within the next one or two decades.

It is not anticipated that superconducting energy transmission systems will be able to compete economically with conventional overhead lines. However, superconducting cables could be a realistic alternative to conventional high voltage cables [3].

For this reason it is here chosen to compare the characteristics of superconducting cables with the characteristics of conventional cables. The advantages of two designs of superconducting cables are described and the possible applications in the Danish and European network are discussed.

II. HIGH TEMPERATURE SUPERCONDUCTING CABLES

A schematic view of a superconducting cable system is illustrated in Fig. 1. Liquid nitrogen, at temperatures near 77K, is planned to be pumped through the cable. In each end cooling stations are installed, which removes the various losses dissipated in the system. It is expected that such cooling stations will be necessary along the cable length with 4-6 km spacing [3].

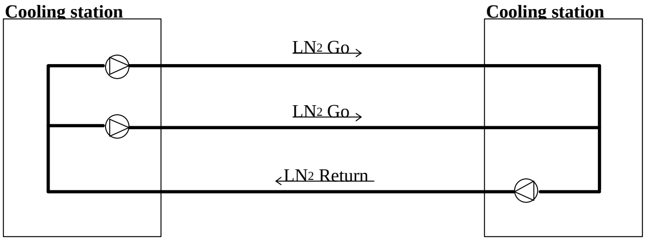

Fig. 1. Schematic view of a cable system with superconducting room temperature dielectric cables.

The basic design principles for high temperature superconducting cables are adopted from the early design studies regarding LTSC cables. Schematic designs are described in various papers e.g. Engelhardt et al. [4].

A. Current/energy carrying capabilities

The two basic designs of superconducting cables have different current carrying capabilities. It is estimated that a room temperature dielectric (RTD) cable will have a maximum current carrying capacity of 2.5 kA/phase [1],[3], which roughly is twice the amount achievable with conventional cables. The limit for this value is determined by

Manuscript received September 14, 1998.

This work was carried out within the programme *Superconductors in the Danish Energy Sector* and was sponsored by the Danish Energy Agency and ELKRAFT.

the eddy current losses in the cryogenic enclosing and the shield. If the cryostat is made of a non-metallic material the current carrying capability will be higher.

The nominal power level on transmission voltages (132/150 kV - 400 kV) is in the regime of 500 - 2000 MVA per system with 2.5 kA for a RTD cable.

Cables designed with cryogenic dielectric design (CD) have a superior current carrying capability compared with the room temperature dielectric design. The estimated limit for this type of cable is in the order of 8 kA per phase [5]. This value might be somewhat uncertain as it is based on the maximum losses acceptable compared with losses in conventional cables and the losses depend on tape quality.

The estimated nominal power level at transmission voltage for a CD cable is in the regime of 1500 - 5500 MVA per system.

It is assumed that a DC superconducting cable will be able to carry as much as 15 kA or more [5]. At 400 kV DC level the expected power transmission level is 6000 MVA.

Furthermore HTS cables can be designed to have electric characteristics (resistance, capacitance and reactance) which is not achievable with conventional cables. This fact combined with a superior current carrying capacity, which is in the order of 2-6 times a conventional cable give new possibility for designing the electric network.

III. APPLICATIONS FOR HTS CABLES IN DENMARK - FUTURE NETWORK CONSIDERATIONS

Overhead lines are generally getting more unpopular. There is in principle two ways to proceed if the length of the overhead lines in the network is to be reduced. The first one is to move transmission from 132/150 kV to 400 kV and then replace the large number of 132/150 kV overhead lines with only a smaller additional length of 400 kV overhead lines as a penalty. The second way is to replace transmission lines with underground cables. Superconducting AC cables are in the latter case interesting as an alternative to conventional cables.

A. The Danish Power Grid

The Danish power grid is divided into separate systems. One system is Jutland and Funen (handled by ELSAM), who is connected through AC overhead lines to the continental western European power system. The other system is Zealand (handled by ELKRAFT), that is connected to the Nordic power system (NORDEL) through AC submarine cables.

In addition to the AC connections DC connections exists through submarine cables between Jutland and Norway, Jutland and Sweden, and between Zealand and Germany.

Two important transmission corridors are the 400 kV backbone of Jutland and the connection between Sweden and Germany on Zealand.

In the Jutland-Funen power system it is planned to alter the net structure by implementation of a 400 kV ring structure in Jutland. This will decrease the overall length of overhead lines and result in a more reliable network. The backbone in this new ring structure is planned to be expanded to a 400 kV two-system connection. This connection is used for distribution of energy in Jutland and as a corridor for energy transmission between Norway and Germany.

A similar ring structure in the 400 kV network is planned for Zealand.

There is at transmission level in Denmark a total of 4000 km of overhead lines and cables (1994 figures) [6].

280 km of 3100 km 132/150 kV transmission lines is made as underground cables, while the rest are overhead lines. A conventional underground cable at 132/150 kV is roughly 3-8 times more expensive than the corresponding overhead line [7]. In the future, a growing part of the lines on this voltage level will be laid down as cables, as cables are getting cheaper and more technically attractive.

At 400 kV level only a minor part of the 900 km transmission lines is laid as cables. The 10 km connection between Zealand and Sweden is implemented as an AC submarine cable, and as something new the transmission into Copenhagen is made through a newly developed 400 kV XLPE cable.

400 kV underground cables are not widely used because a 400 kV underground cable system is 10-20 times more expensive than a system with overhead lines [7]. Furthermore underground cables at 400 kV need a relatively large number of shunt reactors. Also, the required shunt reactors can cause instability in the network and they are expensive.

B. Applications for HTS cables in the overall network

There are in the overall network several possible applications for superconducting cables. The most obvious are of course all situations where overhead lines are unwanted, such as in the cities and in areas of special beauty.

1) Supplying energy into major cities and through areas of special beauty: In order to get fewer overhead lines or to upgrade power supply in urban areas, there is a possibility of moving transmission into superconducting cables. This of course is only interesting in densely populated areas like Copenhagen, Århus, Odense or Ålborg.

The use of superconducting cables for power supply into densely populated areas would probably be in the form of strategically placed and relatively short lengths of cable. Depending on the circumstances, both RTD cables and CD cables are of interest in this case.

Superconducting cables are interesting as a possibility for moving overhead transmission into the ground. It will be possible to move transmission from a one system 400 kV overhead line into the ground with the use of only one system 400 kV RTD cable.

2) Free trade with energy: Since the late eighties the European Union has been working with plans for a liberal energy market. The objective of these considerations is an energy market where energy can move freely. The consequence could be that big companies could go on the energy market and find the cheapest energy supplier, even though this supplier is located far away.

In the European network such a scenario is not practically possible, as the overall network is not strong enough. There is at this moment not clear how a liberal energy market will work in reality.

A possibility for getting the network ready for a liberal energy market is to make strategic energy corridors throughout Europe by using powerful superconducting cables. The superconducting cables for a network like this would probably be of the cryogenic dielectric design, as the transmitted energy would be of substantial quantity. The Danish part of such energy corridors could be the backbones in the Jutland and on Zealand.

A final proposed network could be a ring network with strategic parts of the ring implemented as high-level energy transmission corridors.

A powerful conventional high voltage DC (HVDC) connection between Norway and Holland in the North Sea is actually already under development for the purpose of trading electric energy [8].

3) Applications for HTS cables with groups of windmills: In order to decrease the production of CO_2 by the year 2030 to about half the 1988 level, it is planned to expand the exploitation of renewable energy sources to 35% of the total Danish energy supply [9]. 25% of the total energy supply is planned to come from windmills corresponding to 5500 MW installed wind power. 4000 MW is planned to come from offshore based groups of windmills located 7-40 km from the coast on a water depth of 0-15 m.

The consequence is that up to 50% of the total electric energy production must be supplied by windmills [9].

On dry land it is hard to find suitable locations where large groups of windmills can be widely accepted. This is the reason for considering offshore based groups of windmills. The advantages are numerous:

-Possibility for increased wind-based energy production.

-Better wind conditions. The energy production per windmill is increased by an estimated 50%.

Offshore wind power offers the best opportunity for reduction of CO_2 emission.

The number of windmills considered is substantial as the windmills are expected to have a power rating of 1.5 MW/unit (4000 MW/1.5 MW = 2700 units).

There are numerous disadvantages by the large-scale use of windmills. The main disadvantage is the variation of energy produced from windmills, which the power plants have to be able to counteract. This is a non-trivial task when the installed power of windmills is getting as high as intended. In order to utilise the fuel in the best way; the power plants are designed to produce both electricity and heat. This is a concern if windmills produce half of the electric power. How do we produce the heat needed, without using the power plant in an inefficient and polluting way?

4) Connecting groups of windmills to the overall network: Connecting groups of windmills to the overall network can be done either as AC or DC.

In the DC case there are several aspects that are special in the use of windmills. The HVDC technology is a field where a lot of R&D effort is spent. A new approach is the HVDC concept based on a series connection of many insulated gate bipolar transistors (IGBTs) [10]. The most obvious advantages of the technology are, that it is expected to be relatively cheap, and that it is possible to control the reactive power production/consumption by the use of pulse width modulation (PWM). Control of the reactive power is necessary for connecting windmills with asynchronous generators to the network. While conventional HVDC converters in conjunction with windmills demand a quite stiff network, this is not a problem with the new technology.

Economical considerations will decide whether conventional cables AC/DC or superconducting cables AC/DC are chosen for the purpose of connecting wind power to the network. DC superconducting cables together with IGBT based HVDC converters are however a possibility that has to be considered.

5) The need for back-up power in conjunction with windmills: With the planned goal of supplying half the Danish electric power demand with energy from windmills, several problems arise. One of these problems is the need for fast acting back-up power. The energy delivered from windmills is not all ways constant. For this reason, the system has to be ready at all times to supply the amount of power needed and to consume excess power. This may be done in several ways:

① By using very big energy buffers.
② By having very fast reacting power plants, which do not pollute when not active.
③ By the retrieval of energy from the neighbouring countries and power systems.

The first solution could be implemented by the use of flywheels, superconducting magnetic energy storage devices

(SMES) or devices. An alternative way is to use water reservoirs, which are filled when surplus energy is produced. This method is used in Norway and other locations, where excess power is used for lifting water, with the use of big pumping systems.

The second solution can be implemented by the use of gas or diesel turbines. However these turbines are normally not very big (normally in sizes of up to 100 MW).

Another solution is an extension of the energy exchange with Norway, Sweden and Germany, which already is a reality. The connections however have to be stronger than they are today. This is a suggested application for superconducting AC or DC cables.

The total solution will most likely be a combination of the three suggested solutions. The implications are that in a future network there will be a need for transmission links that are substantially stronger than the ones existing today. There will therefore be a need for power cables, which have the qualities of superconducting cables.

CONCLUSION

It can be concluded that superconducting cables represent an interesting alternative to conventional cables, as they are able to transmit more energy and they possess other characteristics than conventional cables.

Superconducting cables are interesting as a possibility for moving overhead transmission into the ground. It will be possible to move transmission from a one system 400 kV overhead line into the ground with the use of only one system 400 kV RTD cable.

Superconducting cables in the overall network are interesting in special cases such as transmission of energy into cities and through areas of special interest.

The planned big groups of windmills both on dry land and offshore, will constitute a possible application for superconducting AC or DC cables. It is planned that windmills will supply 50% of the Danish need for electric power in the year 2030. This gives opportunity to use superconducting cables in conjunction with other new technologies; e.g. IGBT based HVDC converters. The network, in a system with 50% wind power, has to be very stiff in order to handle energy fluctuations. Such a network could be constructed with superconducting power cables.

REFERENCES

[1] D. W. Von Dollen, N. G. Hingorani, R. W. Samm, High temperature superconducting cable technology, Power cables and Accessories 10kV-500kV, 23-25 November 1993, Conference Publication No. 382

[2] J. G. Bednorz, K. Müller, Z. Physik, B64, pp. 189, 1986

[3] J. Østergaard, *Superconducting cables in Denmark - design and application*, Department of Electric Power Engineering, DTU, 1995, Unpublished master thesis in Danish (Title: Superledende Kabler i Danmark - Konstruktion og anvendelsespotentiale), 1995

[4] Engelhardt J S, Von Dollen D, Samm R, Application considerations for HTSC power transmission cables, Fifth Annual Conference on Superconductivity and applications, Buffalo, N.Y., p. 692-711, 1992

[5] Characteristics of superconducting cables - electrical data, economy, cool down and quench, DEFU, Teknisk rapport 372, Report in Danish (Title: "Karakteristika for superledende kabler - elektriske egenskaber, økonomi, nedkøling og quench"), 1996

[6] Principles for establish and reconstruction of high voltage lines, Ministry of Environment and Energy, Denmark, Report in Danish (Title: "Principper for etablering og sanering af højspændingsanlæg"), 1995

[7] Plan for development of the ELSAM network 1995, ELSAM, Report in Danish (Title: "Netudviklingsplan 1995") 1995

[8] T. Kvarts, NKT Cables, Broendby, Denmark, Personal contact July1998

[9] Plan for off-shore based windmills in Denmark, Elselskabernes og Energistyrelsens Arbejdsgruppe for havmøller Juni 1997, Report in Danish (Title: "Havmølle-handlingsplan for de Danske farvande"), 1997

[10] T. Hjort, Direct Current Distribution Line Installed in Sweden, Transmission & Distribution World, September 1997