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DESIGN, INSTALLATION AND OPERATION OF WORLD'S FIRST HIGH TEMPERATURE SUPERCONDUCTING POWER CABLE IN A UTILITY POWER NETWORK

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SUMMARY

High voltage power cables based on high temperature superconductors (HTS) are nearing technical feasibility. During the past years several development projects around the world have focused on bringing the superconducting cable technology into the grid.

For the first time, a high temperature superconducting demonstration cable system has been installed in a utility network supplying electricity to consumers. The cable is a 30-m long, 30 kV_{rms}, 2 kA_{rms} cable, installed in the network of Copenhagen Energy at a substation supplying app. 50,000 customers. The purpose of the cable installation is to obtain installation and operating experience with this type of cable.

The cable system has been in operation since May 28th 2001, and the first operating experiences of the cable have been satisfactory. The cable has been in operation for more than 4,000 hours, and the cable has supplied 29,000 MWh of energy to the customers.

Keywords: Superconducting cable, demonstration project, high temperature superconductor (HTS), cooling, cable termination, monitoring, installation, operating, test site.

1. INTRODUCTION

Superconducting materials have the ability to transport very high currents without electric loss when they are cooled to low temperatures. The current density in a superconductor is 300-10,000 times higher than in copper.

Until the discovery of high temperature superconducting (HTS) materials in 1986, the application of superconductors was limited by a very expensive cooling to liquid helium temperatures at 4 K (-269°C).

The HTS materials overcome this by being superconducting above liquid nitrogen temperature, 77 K (-196°C). Cooling at this temperature is a factor of 1000 less expensive than liquid helium cooling [1]. The discovery thereby opened a possibility for cost effective HTS applications in the electric power network.

Power cables based on the HTS materials can offer several advantages compared to conventional power cable technology due to the unique properties of the HTS material, the needed internal cooling and a perfect magnetic shielding (for some designs). The advantages of an HTS power cable are:

- High current and power rating
- Compact cable dimensions
- Low losses
- No thermal interaction with the surroundings
- No magnetic interaction with the surroundings

Furthermore, HTS power cables have the potential of lower cost per transferred MW compared to conventional technologies. This is due to very low material consumption as well as potential for reducing cost elements like installation cost, transformers etc.

The application of HTS power cables includes short internal substation connections, generator connections and replacement (retrofit) of low capacity power cables in existing ducts. Furthermore – dependent on the

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future development of HTS material cost – HTS cables can be applied for urban feeder cables, bulk power transmission, low voltage high current cables, DC power links etc.

Several projects around the world focus on development of HTS power cables, and several large-scale demonstrators have been made or are under way [2-5]. The first HTS demonstration cable operated in a utility network has been developed by Danish industry, universities and utilities and has been installed in the 30 kV network of Copenhagen Energy.

2. CABLE SYSTEM DESIGN

The main parts of the developed HTS cable system are: 1) The HTS cable, 2) The cable terminations, 3) The cooling system and 4) A monitoring system.

2.1 HTS cable

The cable is designed as a single-core so-called room temperature dielectric (RTD) cable shown in Figure 1.

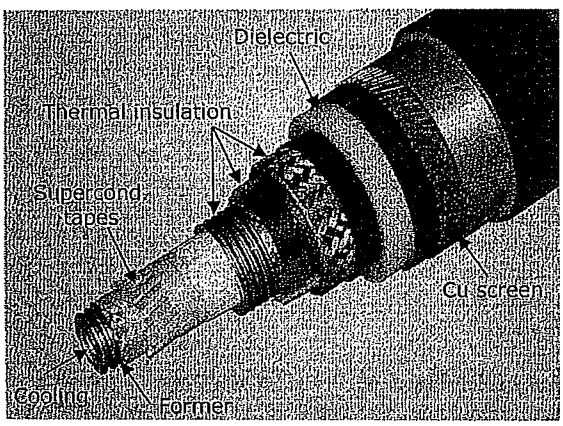

Figure 1 Design of the HTS cable.

In this design, the superconducting tapes are wound in layers with helical patterns around a former. The former is a flexible stainless steel tube, which also functions as a cooling duct for LN_2. With this design the HTS tapes are cooled through conduction through the steel former wall and the bedding material i.e. the HTS tapes are not in direct contact with the liquid nitrogen.

Outside the superconducting layers the thermal insulation (cryostat) is placed. The cryostat consists of an outer and inner cryostat wall made of corrugated stainless steel. Superinsulation layers, in the form of thin plast films with metallic deposited aluminium, are placed between the two walls of the cryostat together with spacers. The vacuum together with the reflecting films in all minimise heat radiation, convection and conduction from the surroundings. With the present design the heat in-leak is 1.5 W/m.

Each end of the cryostat is terminated in Johnston-type couplings, where the female couplings are integrated in the thermal terminations.

The electrical and geometrical data for the HTS cable are summarized in Table 1.

Property	Value	Unit
Nominal voltage	36	kV_{eff}
System voltage	30	kV_{eff}
Nominal current	2,0	kA_{eff}
Rated power	104	MVA
Weight	13	kg/m
Conductor cross section	~ 100	mm^2
HTS tape fill factor	25	%
Cable length	30	m
Former ID/OD	20/30	mm/mm
Conductor ID/OD	32/36	mm/mm
Thermal insul. ID/OD	39/66	mm/mm
Electrical insul. ID/OD	70/90	mm/mm
Elec. Cu-Screen ID/OD	90/95	mm/mm
PE-sheath ID/OD	95/105	mm/mm

Table 1 Electrical and geometrical data for the HTS cable.

The electrical insulation consists of polyethylene (PE) that is triple-extruded onto the cryostat in one length of ~100 m. An electric screen made of semiconductive tapes and 120 mm^2 Cu-wires was wound on the outside of the main insulation together with a water barrier consisting of swelling tapes and aluminium foil with glued waterproof joint. The outer mechanical protection consists of a 5 mm thick double layer extruded polyethylene (PE).

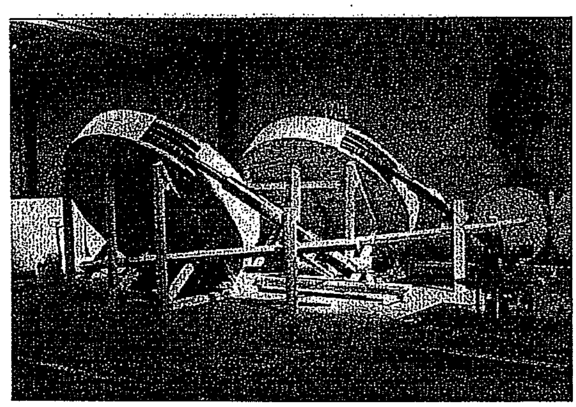

Figure 2 Two of the three single-core 30 m cables wound on drums ready for shipping from the cable manufacture.

2.2 Cable terminations

The cable termination consists of 2 main parts: 1) The electrical termination where the main insulation is terminated (see Figure 3) and 2) the cryostat termination, where the HTS tapes are soldered onto a copper block connected to a flexible Cu-current lead (77 K - 300 K), and an insulating transition for in- or outlet of LN_2 in the cables.

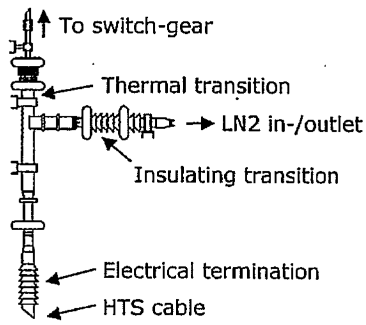

Figure 3 Cable terminations.

The cryostat part of the termination with the current lead and the in-/outlet construction for LN_2 is connected to the cable at the electrical termination by means of a Johnston coupling. Therefore, the cryostat part can be mounted after the cable has been installed.

2.3 Cooling system

A schematic view of the HTS cable cooling system is shown in Figure 4. Liquid nitrogen at 65 K – 77 K is pumped forward through two of the single-core cables and returns through the third single-core cable.

The main cooling system consists of two Stirling-cycle coolers. Each cooling machine has a footprint of app. 1x2 meter, and can remove 1.1 kW at 77 K. A backup cooling system with LN_2 boil-off and a LN_2 reservoir has also been installed.

The passive backup cooling system automatically takes over if the main cooling system fails. No interruption of the cable operation is necessary.

In order to avoid cavitation in the LN_2 and to facilitate start-up, the circulation pump is placed immediately after the heat exchanger in the heat exchanger tank. The storage tank with pressurised nitrogen gas is connected to the system just ahead of the heat exchanger. Thus, any nitrogen gas that enters to compensate for volume changes has time to condensate into liquid nitrogen in the heat exchanger.

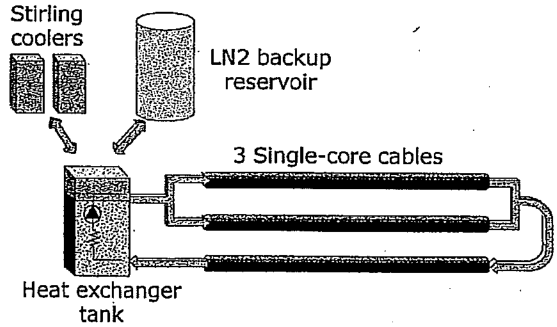

Figure 4 Principle of the cooling circulation system.

2.4 Monitoring system

A monitoring and data collecting system has been established to ensure a sufficient information collection and to facilitate evaluation of the cable system performance.

The monitoring system consists of a PLC and a PC. The PLC measures the values from a number of sensors: temperatures, LN_2 flow, currents etc. The PLC provides the data to the SCADA system at Copenhagen Energy as well as a data logging PC.

The SCADA system provides the operators at the network operating central with alarms from the system. The PC logs the measurements with 1-minute interval (1-second intervals during alarms). This gives a reasonable resolution for analysis of the data. The PC acts as a web server and the actual measured values are accessible online via a web browser. A screen dump is seen in Figure 5.

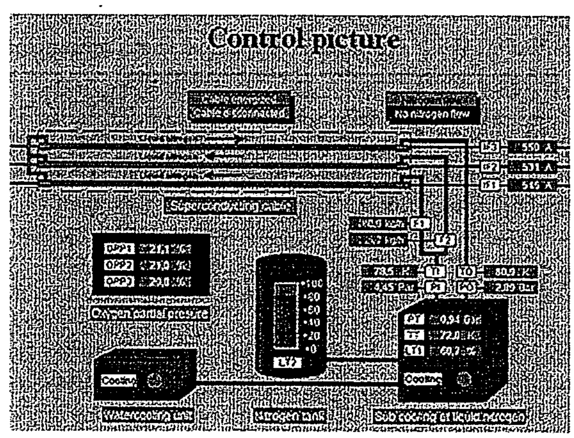

Figure 5 Screen from the cable monitoring and data logging system accessible via www.

3. TEST IN LABORATORY

All the three 30-m cables were tested in the laboratory with non-destructive routine tests and supplementary tests concerning DC-current carrying capability at operating temperature.

Also, a test programme for non-electrical tests (pressure and temperature drop) was elaborated. The terminations were tested separately. All tests were successful.

3.1 Electrical routine tests

The following tests were carried out:

- Measurement of the resistance of the HTS conductors at 15-25°C. (IEC 60502 clause 16.2.)
- Partial discharge test (IEC 60502 clause 16.3, IEC 60885-3); the cable sample is tested without terminations and joints at 36 kV for 10 sec. Max allowable PD level: 10 pC.
- AC voltage withstand test according to IEC 60502 clause 16.4; the test shall be made at room temperature. 63 kV_{eff} is applied for 5 min.

3.2 DC-current carrying capability

The cable conductor is gradually cooled down from room temperature to approximately 85 K by passing cold nitrogen gas through the cooling channel. After about 3½ hour liquid nitrogen is pumped into the system and a final flow rate is adjusted to 700 kg/hour at 4 bars.

A four-point measurement method is used to measure the DC I-V curve for the conductor. The current is raised stepwise with 100A step, and kept constant on each step for 30 sec.

Typically for a single phase a critical current, I_c, at 79 K was measured to 2770 A ± 100 A, and at 66 K to I_c = 5000 A ± 200 A.

3.3 Pressure test of the cryogenic system

The cable and the terminations are pressurised using gaseous nitrogen at room temperature and liquid nitrogen at 77 K, to detect any leakages.

Other parameters such as pressure drop and temperature rise in each cable length, temperature stability at different AC currents, heat removed by the liquid nitrogen for the cable including terminations, and temperature-pressure working ranges were also measured. AC measurements was done both electrically and calorimetrically.

4. DEMONSTRATION IN THE GRID

Feasibility and reliability of HTS cables have to be demonstrated before commercial use can take place.

Thus, the purpose of the installation at Amager has been to demonstrate a superconducting power cable in the electric power network under realistic conditions as well as to collect experience regarding installation and operation of such a system.

It shall be demonstrated whether a complete superconducting cable system consisting of HTS cable, terminations, cooling system etc. can be operated in a realistic environment and with realistic effects. This includes varying load, possibilities for overcurrents and short circuit currents, thermal and mechanical loads from the physical environment, and operation by the utility staff.

4.1 Installation site

The Amager 132/30 kV substation was chosen as site for the installation due to the possibility of a controllable installation with possibility of varying load etc. Furthermore, the installation simulates a commercial high current internal connection in a substation.

The Amager substation is an indoor station with open switchgear. It supplies app. 50,000 customers including private households, offices and light industry at the Amager Island, the southern part of Copenhagen. The maximum load of the station is app. 2,000 A at 30 kV.

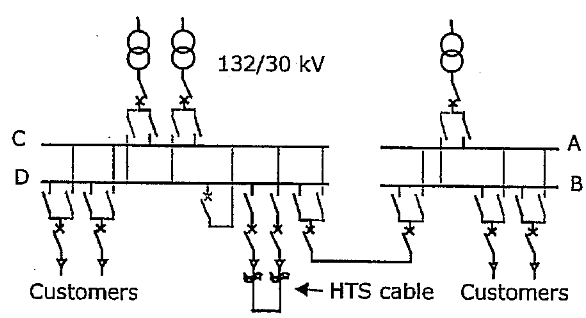

Figure 6 Simplified electrical diagram of the HTS cable system installation.

The cable is installed between two busbars as illustrated in Figure 6. One or two feeding transformers supply power to busbar C and the outgoing cables are connected to busbar D. An existing parallel conventional connection acts as a backup for the HTS cable.

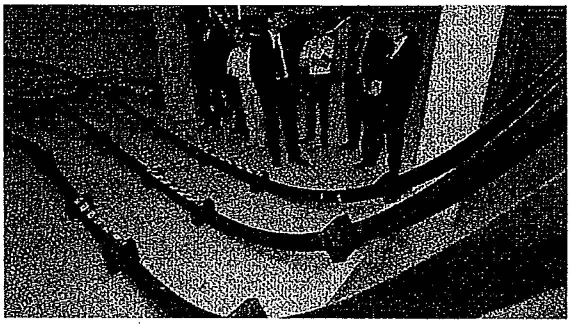

Figure 7. Installation of the HTS power cable in the basement of the Amager substation.

The cable is installed from busbar C in the top of the building, continuing down to the basement in a loop (see Figure 7) and up again through the building to busbar D. Busbars, switchgear, terminations and cooling unit are placed on the different floors in the building.

4.2 Cable system installation

The HTS cable system including cooling was installed during 3 months in the spring 2001. The staff normally hired by Copenhagen Energy for cable installation work installed the HTS cable and monitoring system.

The HTS cable was manually pulled into place due to the short length and restricted free space. The staff experienced that the cable was easily bendable, and due to its low weight (1/3 of a corresponding conventional cable) the installation was done in 3 hours per phase.

After installation pre-operating test was performed. This included:

- Test of cooling machine
- Test of liquid nitrogen circulation
- 24-h voltage test without load

The HTS cable was inaugurated and energized May 28th 2001.

5. OPRATIONAL PERFORMANCE

The operational phase started with a no-load operation for control of stable cooling etc. (done with both cooling machines and backup boil-off system) and succeeding stepwise load increasing of the cable during several weeks. The load was increased stepwise by switching outgoing cables from busbar C to busbar D. In the first steps, the HTS cable was operated in parallel with the conventional connection. Later, the conventional connection was opened, and the HTS cable alone supplied power to the customers. The HTS cable presently (December 2001) supplies ~50% of all outgoing cables of the substation.

Until mid December 2001 the cable has been cooled and in operation for more than 4,000 hours. The cable has supplied 29,000 MWh in this period.

5.1 HTS cable performance

The HTS cable has performed as expected. No degradation of the superconductor or the thermal insulation due to installation etc. has been observed.

Currents up to app. 700 A have been flowing in the cable. In Figure 8, an example of the load in a one-week period is shown.

Due to a failure in the 30 kV network the cable has been exposed to a 6 kA, 142 ms short circuit current. No degradation or temperature rise was observed after the short circuit.

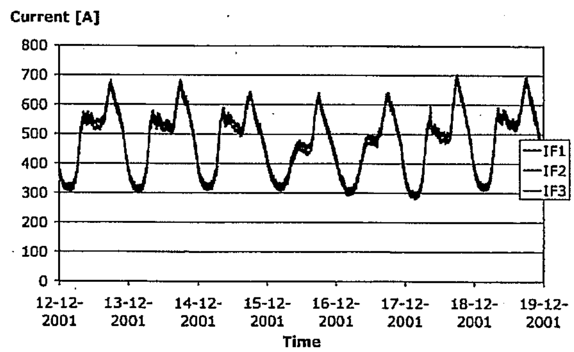

Figure 8 Current flowing in the HTS cable for a 7 day period December 12th-19th, 2001.

5.2 Cooling system

The cooling system has proven to provide the necessary cooling of the cable both when it was operated with cooling machine and backup boil-off cooling.

As seen in Figure 9, the LN_2 temperature is stable and independent of load etc. The outlet temperature from the cable for the period in Figure 9 is app. 81 K. By regulating the pressure in the liquid nitrogen heat exchanger tank the temperature can be decreased below this level.

As seen in Figure 10, the LN_2 in- and outlet pressures are stable during operation. The system is pressurised by the external LN_2 tank, and the pressure drop is determined by the flow.

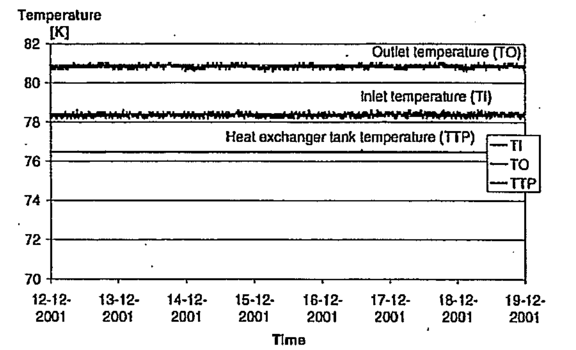

Figure 9 Temperature of liquid nitrogen in heat exchanger tank (TTP), inlet to cable (TI) and outlet from cable (TO) during operation of main cooling system.

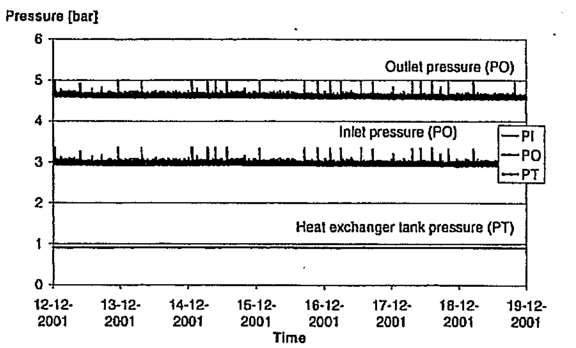

Figure 10 Pressure in heat exchanger tank (PT), at inlet to cable (PI), and at outlet from cable (PO).

The flow is divided between two phases in the forward direction. No oscillations or instability between the two flows has been observed during operation.

A problem related to a misaligned LN_2 pump emerged during the initial operation. The pump has been remounted, and the initial test program was extended.

Furthermore, there have been non-critical problems concerning the conventional water-cooling unit for the cooling machines. Some design changes have been implemented to the water-cooling unit.

6. CONCLUSION

A 30-m 3-phase RTD HTS cable system has been designed, developed and manufactured. The cable has a nominal rating of 30 kV_{rms} and 2,0 kA_{rms}.

After a comprehensive successful test programme performed in the laboratories, the cable system was installed and inaugurated on May 28th, 2001 as the world's first HTS cable in the public network.

The installation was performed with success during 3 months. Due to high flexibility and low weight of the cable the cable installation was unproblematic.

The cable system has been in operation for more than 4,000 hours, and it has been operated by the utility staff. The cable has supplied 29,000 MWh of energy to the customers. Due to a short circuit in the MV network the cable has been exposed to a 6 kA short circuit current. No degradation of the cable has been observed. The LN_2 cooling system successfully provides a stable temperature needed for operating the cable.

The test programme for the HTS cable system will continue until the end of 2003.

7. ACKNOWLEDGEMENTS

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