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Energy losses of superconducting power transmission cables in the grid

Jacob Oestergaard, Jan Okholm, Karin Lomholt, Ole Toennesen

***Abstract*—One of the obvious motives for development of superconducting power transmission cables is reduction of transmission losses. Loss components in superconducting cables as well as in conventional cables have been examined. These losses are used for calculating the total energy losses of conventional as well as superconducting cables when they are placed in the electric power transmission network. It is concluded that high load connections are necessary to obtain energy saving by the use of HTS cables. For selected high load connections energy saving of 40% is expected. It is shown that the thermal insulation and cooling machine efficiency are the most important loss element in a superconducting cable system.**

***Index Terms*— losses, simulation, superconducting transmission lines.**

I. INTRODUCTION

SUPERCONDUCTING power transmission cables based on high temperature superconductors (HTS) are under development these years, and a number of cable development projects have emerged since the development of long length BSCCO/Ag power-in-tube conductors [1]-[5]. It is expected that superconducting cables can provide a new type of cable with new properties like higher current carrying capability, energy loss reduction, more compact construction and new electrical properties resulting in a wider application range. In this paper the energy loss will be treated.

Despite the term superconductivity there will be losses in a practical ac cable used in the electric power transmission system. When ac current or magnetic field is applied to a superconductor loss will occur due to hysteresis in the material. But also other loss components like induced currents in metallic parts, thermal leaks etc. will occur in a practical cable. In this paper an overview of the loss components is given, and the importance of the different components is evaluated.

The energy losses in a HTS cable are dependent on the load and thereby on where the cable is placed in the power transmission grid. In this paper different representative locations in the grid are examined regarding losses and the use of HTS cables.

II. LOSS COMPONENTS IN CABLES

A. Conventional cables

The theory for losses in conventional copper or aluminum power transmission cables for ac is well established and international standards exist on the field [6]. The losses consist of the following four elements: conductor losses, induced losses in sheath, induced losses in steel pipes (in pipe-type cables), and dielectric losses.

The *conductor losses* arise due to the resistivity of the conductor material. The losses W_c can be calculated by the equation:

$$W_c = R_c I^2 \tag{1}$$

where R_c is the ac resistance and I is the rms current. By use of the standards it is possible to determine the ac resistance R_c [6].

The *induced losses in sheath* in room temperature dielectric design cables arise due to an alternating magnetic field in and around the metallic sheath in the cable. The losses can be reduced by transposition of the sheaths or by bond the sheath in only one end. Transposition is common for high power transmission cables. The induced losses are proportional to I^2, and the losses can be calculated as described in the standards [6].

Induced losses in the pipe will occur in pipe-type cables. The nature of these losses is the same as for induced currents in the sheath. Pipe-type cables are most common in the U.S.

The *dielectric losses* are losses in the electric insulation material of the cable and they arise due to a non-ideal electric insulation material. The dielectric losses, W_d, can be calculated as:

$$W_d = \omega C U_0^2 \tan\delta \qquad C = \frac{2\pi\varepsilon_r\varepsilon_0}{\ln(D_o/D_i)} \tag{2}$$

where $\omega = 2\pi f$, C is the capacitance per unit length, U_0 is the rms phase voltage, and $\tan\delta$ is the loss factor for the actual type of insulation material. The capacitance C is determined by the dielectric constant ε and the outer and inner diameter D_o and D_i of the insulation. It is seen that the dielectic loss is independent of the current and therefore a no-load loss component. For a 132 kV single-core cable the dielectric losses will usually be below 1 W/m·phase (typical values are $\tan\delta=0.001$ $\varepsilon_r=2.5$).

The maximum loss in conventional cables is primarily

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determined by maximum allowed temperature in the cable (depends on the type of dielectric) and the thermal resistance from the cable to its ambient. This means that the full-load losses per unit length (W/m·phase) in conventional cables are quite independent on voltage level and rated current.

For a typical direct laid 3-phase single-core cable which is a typical cable in Europe, the full-load losses are in the order of 30-40 W/m·phase.

B. HTS cables

Losses in HTS cables are fundamentally different from losses in conventional cables. The losses itself are very small, but they have to be removed by the internal liquid nitrogen (LN) cooling which has a low efficiency η. Typical values for the cooling efficiency for large cooling machines are in the range 7%-14%. In the following the efficiency is assumed to be 9%.

HTS cables can be divided into two groups with different basic design and slightly different loss characteristic. The two basic designs are cryogen dielectric (CD) design and room temperature dielectric (RTD) design (see Fig. 1).

Losses in a HTS cable system can be divided into the following components due to the origin of the losses: conductor ac loss, thermal leak through thermal insulation, induced losses in shield (only RTD), induced losses in thermal insulation (only RTD), hydraulic losses in LN, pumping losses, and losses in joints and terminations.

Conductor ac losses have been a major subject for measurements and modeling. High precision and reliable measurement of ac loss is a nontrivial task [7], and no widely accepted physical based model taking account the complicated geometrical properties exist. 50% errors or more between measurements and models are not unusual. In spite of this, several models are often used to estimate the losses. This includes the monobloc model [8], UCD-model [9], and the network model [10]. In this paper the UCD-model is used for ac loss estimation. For a 3-phase RTD cable system with no or little separation of phases additional ac losses will occur due to additional magnetic field from neighboring phases. This effect is here neglected because sufficient phase separation is expected.

Performed measurements and calculations indicate that by proper design, losses at 2 kA_{rms} can be reduced to 0.2-0.6 W/m·phase [7]. Both models and measurements predict a linear dependence to the cubic of the current.

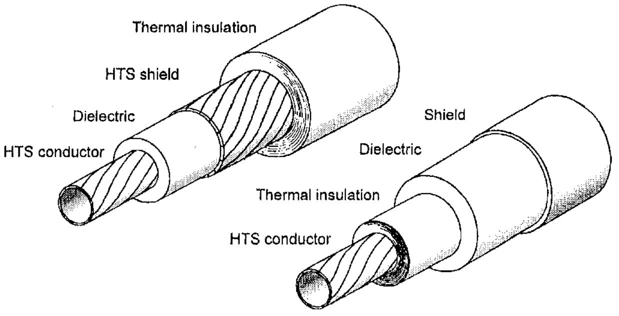

Fig. 1. Schematic illustration of room temperature dielectric design cable and cryogen dielectric design cable, respectively. The cryogen dielectric design cable can be made as a 3-core cable with common thermal insulation.

In a HTS cable there will exist a *thermal leak* through the thermal insulation due to a non-ideal insulation and the substantial temperature difference ΔT between the surroundings (~300K) and the liquid nitrogen (~77K). The thermal losses can be calculated by:

$$W_{th} = \frac{2\pi\lambda\Delta T}{\ln(D_o/D_i)} \tag{3}$$

where λ is the thermal conductivity of the thermal insulation and D_o and D_i is the outer and inner diameter of the thermal insulation.

The insulation has to be made as a vacuum insulation to sufficiently reduce the thermal leak. Depending on the outer and inner diameter of the thermal insulation thermal conductivity of 0.1-0.2 mW/(m·K) can be obtained. This results in losses in order of 0.5 W/m·phase - 1.5 W/m·phase. The losses are independent of current rating of the cable.

Induced losses in the shield occur in a RTD cable, as it does in conventional cables, and the models used for conventional cables can be used for calculating these losses. For CD cables the induced currents will result in ac loss as in the HTS cable conductor and the same models can be used.

Dielectric losses occur in HTS cables as in conventional cables. For CD design cables the dielectric losses has to be removed by the LN.

Circulation of liquid nitrogen results in *hydraulic losses* due to flow friction. The losses can be calculated by:

$$W_{hyd} = \frac{\dot{m}\Delta p}{\gamma_{LN}} \tag{4}$$

where $\dot{m}$ is the mass flow rate, Δp is the pressure drop of the flow and γ_{LN} is the mass density of LN (809 kg/m^3). For a long length cable pressure drop of 2-5 bar/km can be expected. The losses will occur in the flow and they have to be removed by the LN.

The pressure difference has to be applied by an external pumping system which will consume energy corresponding to the flow losses plus losses in the pump system itself. The energy consumption of the pumping system is denoted *pumping losses*.

For a complete cable system there will be *losses in joints and terminations*. There will be terminations in both ends of the cable and for long cables joints will exist for each cable section. Losses in termination come from thermal conduction through the metallic current lead from ambient temperature to LN temperature as well as resistive losses in the current lead. An optimal current lead design results in the following minimal power load to the LN [11]:

$$W_{t,min} = I\left(2\rho\int_{77K}^{300K}\kappa(T)dT\right)^{0.5} \tag{5}$$

where ρ is the conductivity of the current lead material and $\kappa(T)$ is the thermal conductivity of the current lead material. If the current lead is made of brass (which is one of the best alternatives) the minimal loss per kA in the termination is 43 W/kA. Minor losses will occur in joints due to connections etc.

Some loss components only occur in the RTD cables, but losses in CD cables can be as large as in RTD cables due to larger thermal insulation and thereby larger thermal leak. On the other side if cable dimension is not a problem a very efficient thermal insulation can be made for the CD cable.

III. TOTAL LOSSES IN HTS CABLES

A complete HTS cable system can be designed by the use of a previous developed calculation model [12], and the loss components can be found for different loads.

The results of a calculation of a 4 km 450 MVA 132 kV 3-phase single-core cable system with RTD design is shown in Fig. 3. The losses in the cooling machine are distributed at the components, e.g. the cold losses have been divided by the cooling machine efficiency. At full load three major loss components exist: thermal leak, ac conductor loss, and induced loss in shield.

At 50% load only the thermal leak is left as a major loss component. In Fig. 3 the total losses for the same cable system is shown as function of load current, and the result is compared with the losses in a comparable conventional cable system with 450 MVA rated power. The conventional cable system consist of two parallel systems (6 parallel single-core cables) to provide the same power transmission.

The losses in the HTS cable at 2 kA_{rms} are ~25% of the losses in the conventional cable system, but at no-load the losses in the HTS cable are larger than the losses in the conventional cable. The break-even point is around 650 A corresponding to 33% load of the cable system.

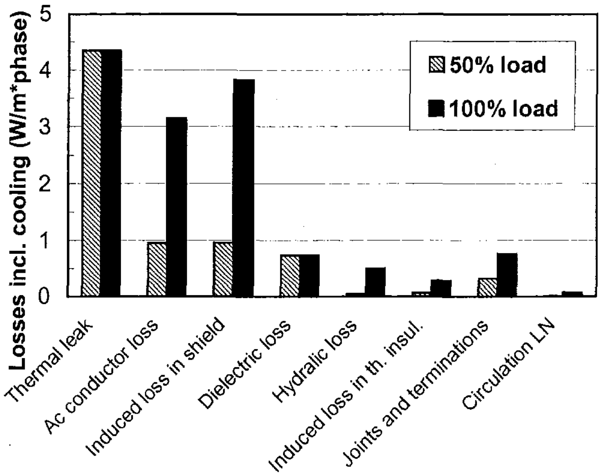

Fig. 3. Distribution of losses on primary components in a 450 MVA 132 kV HTS cable system with room temperature dielectric design at 50% and 100% load. The efficiency of the cooling machine is included in the loss components. At full load there is tree major contribution to the loss, and at half load only one major loss component exist namely the thermal leak loss.

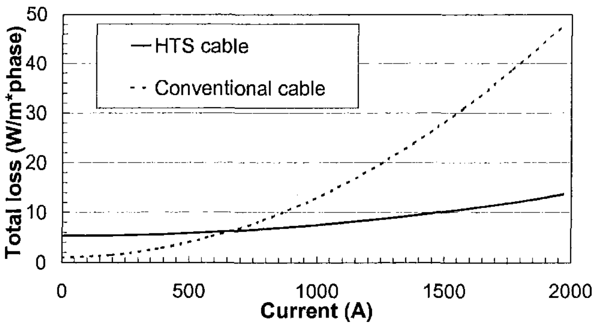

Fig. 3. Losses in HTS cable system and conventional cable system, respectively. Both systems have a rated power of 450 MVA at 132 kV and the conventional cable system consist of two parallel cables.

IV. ENERGY LOSSES FOR CABLES IN THE ELECTRIC POWER GRID

Several representative cable connections in the Danish electric power network have been analyzed with respect to annual losses by use of HTS cables and conventional cables, respectively.

A. Cable to combined heat-power plant

Combined heat-power plants are usually connected to the grid via a cable roughly fitting the maximum power production of the power plant. The production units are characterized by a on-off production cycle – either no production or full production. The production is typically maximum during the daytime with high energy prices and zero at nighttime. The production scheme gives a favorable energy flow for a HTS cable with respect to losses. A typical Danish combined heat-power plant has 4000 hours - 5000 hours of full-load per year. The calculations on a 50 kV cable connection for a combined heat-power production unit shows that the losses can be reduced by 40% by the use of a HTS cable instead of a conventional cable (see Fig. 4).

B. Cable in the 132 kV meshed network

Cables in the meshed transmission system normally have a

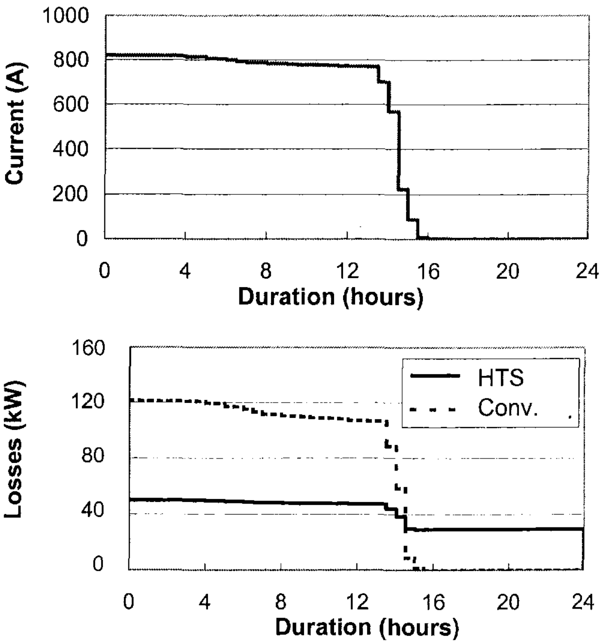

Fig. 4. Load profile and loss in HTS and conventional cable system for a 2.5 km connection between a combined heat-power plant and the network. The data covers a representative 24 hour period.

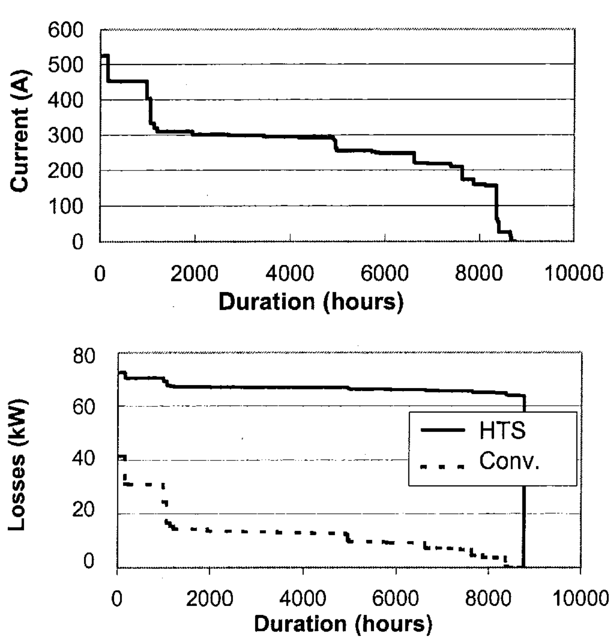

Fig. 5. Load profile and loss in HTS and conventional cable system in the meshed grid for a 4 km connection. Data covers a year (8760 hours).

low load factor. The rated power of the cable is much higher than the normal load. This is illustrated in Fig. 5 with a 450 MVA (2000 A) cable connection. The maximum actual current is around 500 A corresponding to ~25% load. The result is much higher energy losses per year in the HTS cable due to the high no-load losses.

C. Cable to offshore windmill park

Offshore windmill parks will in the future play an increasing role in the transmission network, and HTS cables can be utilized for this application [13]. In Fig. 6 a load profile for a cable connecting an offshore windmill park is shown. This load profile result in 44% loss reduction for a HTS cable system compared to a conventional cable system.

V. CONCLUSIONS

HTS cables are dominated by no-load losses due to a non-ideal thermal insulation. The load dependent losses due to ac conductor loss and induced losses are relative small.

From a loss point of view HTS cables are most feasible in connections with high load current in a large part of the time. HTS cables are therefore most feasible in connections between networks and at connections of production units or load areas (like a city) to the network.

At connections of productions units like offshore windmill parks the energy losses can be reduced by ~40% by use of RTD design HTS cables. When HTS cables are placed centrally in a meshed network the load factor of the cable is low and no energy savings are possible.

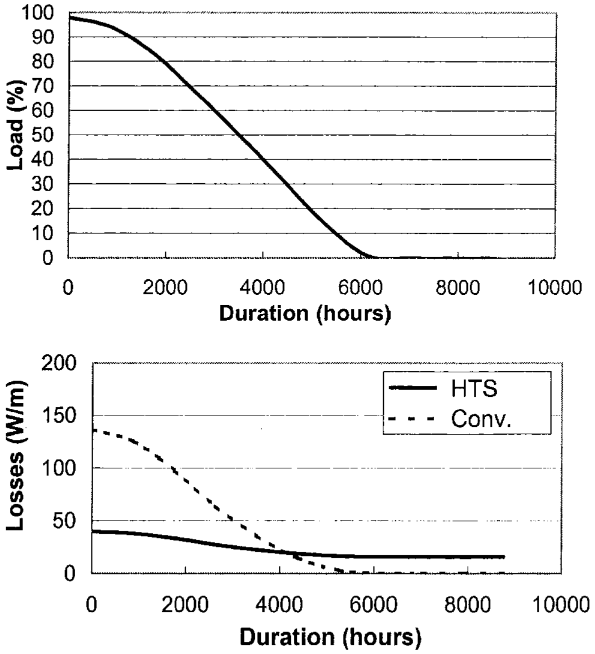

Fig. 6. Load profile and loss in HTS and conventional cable system for a connection between a offshore windmill park and the network. Data covers a year (8760 hours).

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