BREAKTHROUGH IN DEVELOPMENT OF SUPERCONDUCTING CABLES

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ABSTRACT

The subject of this paper is a breakthrough in the development of long-length high-temperature superconducting (HTS) cables with integrated fault-current limitation (FCL) property, made in the Dutch 6 km FCL Triax HTS cable project.

The increase of electricity consumption and the rising penetration of dispersed generation together with the extension of large-scale renewable energy sources lead to numerous technical bottlenecks in electrical grids such as overloading, high level of fault currents, unstable voltage levels and high electromagnetic fields. New solutions and technologies to respond to these challenges are needed. Superconducting cables technology, in its mature state, can play a significant role in solving grid bottlenecks and making energy supply reliable, consistent and sustainable.

INTRODUCTION

The HTS cable technology demonstrates a great potential in solving of grid congestion issues.

An important characteristic of HTS cables is their high transport capacity. HTS cables can transport up to 10 times more power than conventional cables of comparable radial dimension. This feature is supported by the fact that nowadays a long-length commercial HTS tape conductor of the latest generation (see Figure 1) can carry 300 A/mm2 when cooled to 77 Kelvin.

Figure 1 A sample of HTS tape with FCL properties

In addition to their large power transport capacity and low losses, modern-generation HTS cables also have an integrated fault-current limiting (FCL) property. The HTS cables with an improved non linear voltage-current characteristic behave intelligently, adapting their impedance to the actual need of the network, see Figure 2.

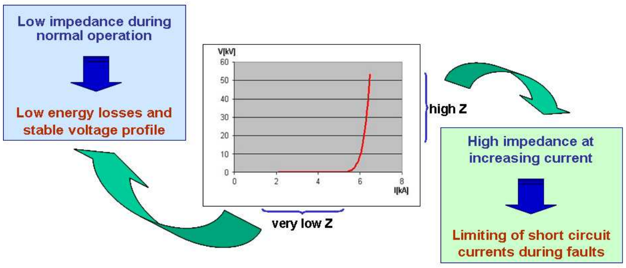

Figure 2 A schematic of the non-linear voltage vs. current characteristics of HTS cables

In this way, this new generation of HTS cables also contributes to a stable voltage profile in a grid, while reducing short circuit currents. Moreover HTS cables have a very small footprint, which makes them suitable for dense and urban areas with expanded underground infrastructures.

Despite its large potential benefits, the HTS cables technology is not yet widespread. In-field demonstrations have been made with lengths of 100-600 m, meaning this technology is still in its immature state. The currently inefficient cooling technology limits the length of the cables up to 1-2 km. The new functionality of integrated FCL capability adds requirements on the cooling due to additional heat production. Therefore an advanced heat management of HTS cable is needed.

6 KM HTS TRIAX® FCL CABLE PROJECT

The Dutch DSO Alliander, in partnership with Ultera™ (a Southwire/nkt cables Joint Venture) and the Delft University of Technology (TUD), has developed an intensive R&D program with intention to develop and install in Alliander's grid a 6 km FCL Triax HTS® cable to demonstrate high performances of the HTS cables technology in a real network.

The consortium works in its project in three directions:

- Considerable improving of thermal insulation of the cryostat. Also cooling channels will be optimized for more efficient flow of the cooling liquid nitrogen;
- Significant reduction of AC loss;
- Optimisation of FCL capability of long HTS cable.

A number of significant breakthroughs in the development of 6 km FCL Triax HTS® cable are presented in this paper.

BREAKTHROUGH IN DEVELOPING A LONG LENGTH FCL TRIAX HTS® CABLE

Reduced heat leakage

Performed calculations and tests of several cryostat models demonstrate reduction of the heat leakage and improvement of the thermal and hydraulic behaviour of the cryostat. Namely, the heat leak into the cryostat is down to 0.5 W/m.

Low flow friction

In a 45 m-long cryostat, containing a full-size cable model (Figure 4), measured pressure drop at the mass flow rate of 0.3 kg/s, temperature 80 K amounts 5 mbar. For a 6 km-long HTS cables this gives a pressure drop below 6 bar (at 1 kg/s and 80 K), which is acceptable as a target.

In order to achieve this result, a 45 m long cryostat was manufactured, consisting of alternatively straight rigid sections and corrugated flexible sections. A dummy cable was inserted into this cryostat and liquid nitrogen was circulated in the annulus between the dummy cable surface, and the inner cryostat surface.

The pressure-drop was measured to be only a few mbar at a flow of 300 g/s of LN2. This indicates a friction coefficient, that is sufficiently low to realize long-length HTS cable systems by using a large fraction of straight, rigid thermal insulation ducts. This is realistic in the cases, where there is access through an open cable trench, and in the cases, where the cable route consists largely of long straight sections of rigid steel ducts.

Figure 3
Cross-sectional view of improved cryostat sample

Figure 4
A 45 m long cryostat with cable model during hydraulic testing

Considerable AC loss reduction

In order to increase the possible length between cooling stations in HTS cable systems, single-phase HTS cable models were made, that show a drastically reduced AC loss. Losses of 0.11 W/m at the transport current of 3 kArms were measured at 60 Hz and at a temperature of 77 K.

The low loss was achieved by using appropriate pitch angles in the two-layer cable conductor, by minimizing the gaps between the HTS tapes, and by using narrow HTS tapes that conform well to the roundness of the underlying former, this feature is explained in Figure 5.

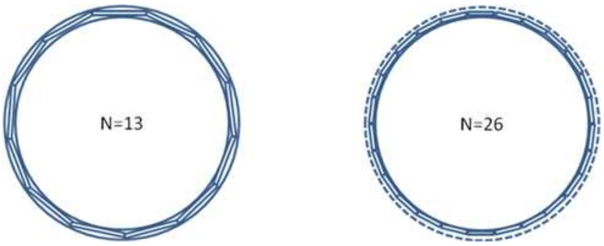

Figure 5 Narrower HTS tapes fit better, than wider ones on the same cable former

The issues to achieve low AC loss in cable conductors, made from multiple HTS tapes, were reviewed in detail.

Historically, it has been expected, that the use of thin-film second-generation (2G) conductors would automatically lead to a reduction of the AC losses in cable conductors by a factor of 10-100. However, this reduction has until recently failed to materialize in cable conductors.

The explanation for this is manifold:

- Firstly the effects of gaps between the HTS tapes results in local magnetic field geometries that induces losses in the HTS tapes.
- Secondly, the application of rather stiff and wide laminated HTS tapes in relatively small cylindrical conductor geometries result in a certain "edginess" of the conductor which also results in higher losses than expected, Figure 5.

- Thirdly, until recently it has been difficult to obtain larger quantities of sufficiently high-quality 2G HTS tapes to demonstrate these low losses.

In the project, we have worked together with SuperPower Inc to realize cable models with reduced losses. SuperPower supplied 6 mm wide and 3 mm wide un-laminated HTS 2G tapes of very high and even quality. These were assembled into HTS cable models of 3-4 m length, each with two layers of HTS tapes.

TParameter	Sample 1	Sample 2	Sample 3
Diameter [mm]	60	42	42
Former	Stainless steel	Glass-fiber	Glass-fiber
ΣI_c(tape, 77 K)	5500	9100	7600
HTS tape width, w [mm]	4	6	3
Gap size, g_m [mm]	1.40	0.05	0.05

Table 1
Specification of the cable models for AC loss tests

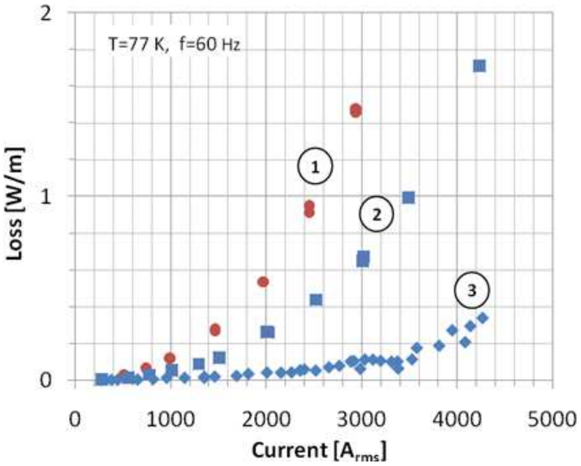

Figure 6
Measured AC losses vs, transport current in three different cable samples made from 2G HTS tapes

The focus with these cable models was to minimize the gaps between the HTS tapes, while keeping adequate pitch lengths and sufficient layer-insulation between the HTS tape layers. The AC loss was reduced to below 0.2 W/m at 3 kA_{rm} in the cable model, using 3 mm wide tapes and very small gaps.

Measured AC losses as function of the transport current in three different cable samples, made from 2G HTS tapes, are shown in Figure 6. The samples are different in terms of cable former diameter, tape-width, and gap size, see Table 1. At the transport current of 3 kA_{rm} a factor 15 reduction of AC loss is achieved in sample 3 as compared to the reference sample 1.

FCL property

The developed FCL modelling shows that the targets for fault current limiting properties will be achieved in the project. The resulting time-durations, temperatures and post-fault load capability will need to be coordinated with the protection management of the grid. Examples of calculated currents during a fault and the resulting temperature profile are shown in Fig 7 and 8, respectively. A 4000 Arms current is let through without limitation or significant heat up for multiple 100’s ms.

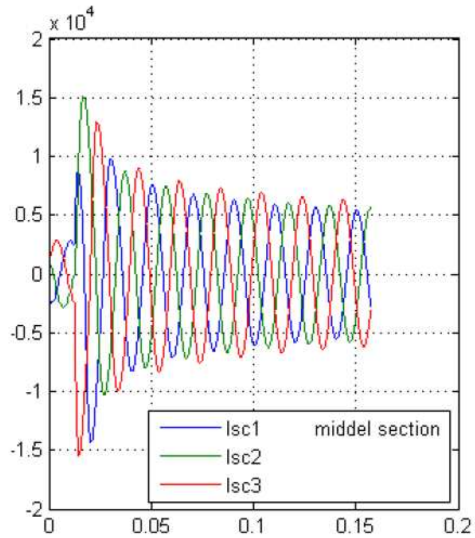

Figure 7
Three-phase fault to earth with a FCL HTS cable (x-axis: time in s; y-axis: current in A)

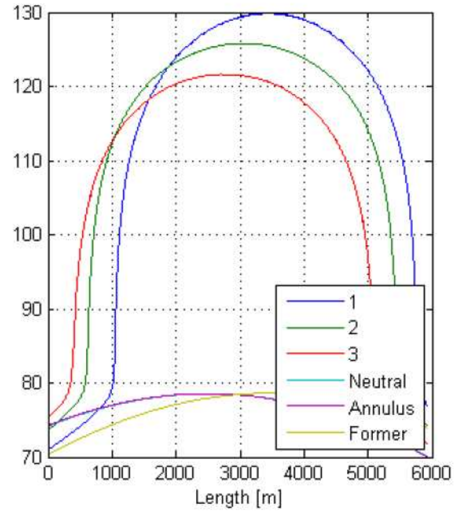

Figure 8 Temperature profile along the FCL cable after a three-phase fault to earth
(x-axis: cable length in m; y-axis: in K)

The developed temperature in the tape is briefly high. Further studies should be aimed to solving of this issue, particularly to faster switching off fault. This will prevent further warmth developing in the cable.

CONCLUSIONS

Tests of the cryostat models demonstrate reduction of the heat leakage and improvement of the thermal and hydraulic behaviour of the cryostat to the desired level.

Reduction of AC losses to the target level of a 6 km cable is demonstrated experimentally, using single-phase cable models.

Fault current modelling of the HTS cable proves that the stated targets for fault current limiting will be reached in the project.

The achievements, already made in the Dutch project, confirm that the stated ambitious targets to develop a 6 km FCL Triax HTS® cable will be reached. This is a large step to maturing the HTS technology towards it's large-scale use.

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