Available online at www.sciencedirect.com

SciVerse ScienceDirect

Physics Procedia 36 (2012) 1285 – 1289

Physics Procedia

Superconductivity Centennial Conference

Low AC loss in a 3 kA HTS cable of the Dutch project

Oleg Chevtchenko[a*], Roy Zuijderduin[a], Johan Smit[a],
Dag Willén[b], Heidi Lentge[b], Carsten Thidemann[b], Chresten Traeholt[c],
Irina Melnik[d] and Alex Geschiere[d]

[a]*Technical University of Delft, 2600 GA, The Netherlands*
[b]*nkt cables group, Priorparken 560, 2605 Brondby, Denmark*
[c]*Department of Electrical Engineering, Technical University of Denmark, DTU, 2800 Lyngby, Denmark*
[d]*Alliander, The Netherlands*

Abstract

Requirements for a 6 km long high temperature superconducting (HTS) AC power cable of the Amsterdam project are: a cable has to fit in an annulus of 160 mm, with two cooling stations at the cable ends only. Existing solutions for HTS cables would lead to excessively high coolant pressure drop in the cable, potentially affecting public acceptance of the project. A way out would be to substantially reduce AC losses from 1 down to about 0.1 W/m per phase at rated current of 3 kA_{rms}, frequency of 50 Hz and temperature of 77 K. In this paper we discuss a strategy towards this ambitious goal, a concept design of the single phase cable 3 kA conductor made of YBCO tapes and present corresponding experimental and simulation data supporting the developed approach leading directly to this goal. HTS cable model was made that show a drastically reduced AC loss. The low loss was achieved by using appropriate pitch angles for two-layer cable conductor of relatively large diameter, by minimizing the gaps between the HTS tapes, and by using narrow HTS tapes that conform well to the roundness of the underlying former. AC loss of 0.12 W/m at 3 kA_{rms} was measured at a frequency of 60 Hz and at a temperature of 77 K.

Keywords: long HTS AC power cable, Dutch project, 3 kA class YBCO cable conductor, single phase model, very low AC losses at 60 Hz and 77 K; concept, experiment, simulation

1. Introduction

Low AC losses are essential for a success of long HTS cables. The requirements for a 6 km-long HTS AC power cable of the Amsterdam project are such that the cable has to fit in an annulus of 160 mm, with two cooling stations at the cable ends only [1]. For an YBCO single phase cable at the transport current of 3 kA_{rms}, frequency of 50 Hz and bath temperature of 69 K relatively low AC loss of 0.235 W/m were measured [2].

* Corresponding author.
E-mail address: o.chevtchenko@tudelft.nl

1875-3892 © 2012 Published by Elsevier B.V. Selection and/or peer-review under responsibility of the Guest Editors.
doi:10.1016/j.phpro.2012.06.291

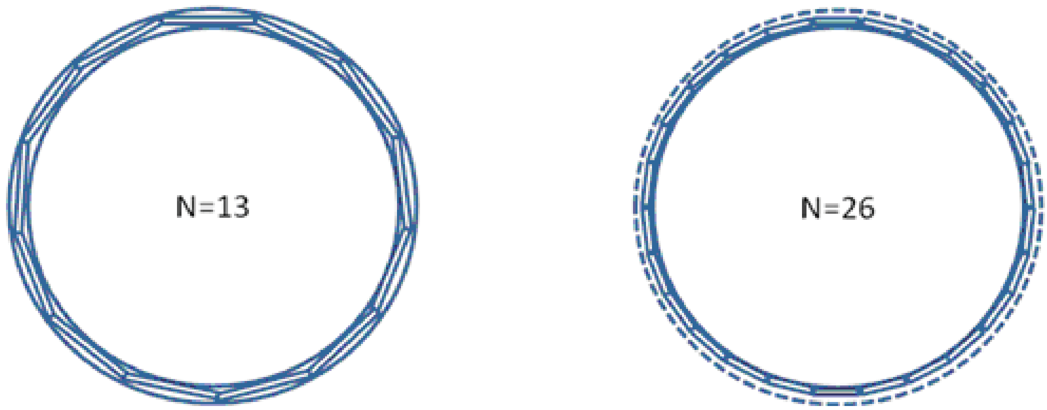

Figure 1 Example of how narrow tapes fit better than wide ones to the same cable former.

In this paper we study possibilities to reduce the AC losses down to about 0.1 W/m at 3 kA_{rms}, 50 Hz and 77 K in a full-size, single phase conductor as required for the triaxial cable of Amsterdam project [1].

2. The sample

In an effort to reduce AC loss in YBCO cable conductor, several full-size single-phase cable models were prepared and tested [1, 3]. In this paper we describe the HTS cable model sample made of commercial YBCO tapes SCS3050 from Superpower. Each tape was 3 mm wide and 0.1 mm thick and had 1 μm thick (RE)BCO layer; 2 μm thick silver over-layer; 20 μm thick surround copper stabilizer and 50 micron Hastelloy substrate [4]. Since the tape width is in fact fixed, special care was taken to match diameter of the cable former to it. The tapes were arranged in two layers around the plastic cable former of relatively large diameter. Care was taken to diminish gaps between adjacent tapes. In order to reduce the loss, pitch angles in each layer of the cable conductor were properly selected, the layers were sufficiently insulated from each other, the gaps between adjacent HTS tapes in the same layer were minimized, and narrow tapes used that conform well to the roundness of the underlying former, this feature is explained in Fig. 1.

Table 1 Specification of YBCO cable conductor

Parameter	[this paper]	[4]
YBCO tape width, mm	3	3
Number of layers	2	2
Nr of tapes in inner layer	42	23
Nr of tapes in outer layer	42	23
Average gap between two tapes, mm	0.1	-
Outer diameter former, mm	42	23.7
Material former	Glass fiber	Cu strands

3. The measurement and the modeling

In the measurement, a low-noise sinusoidal current of 100-4000 A_{rms} through the cable samples at a frequency of 59-61 Hz was produced by using an electromechanical source [3]. The current leads from the current transformer to the two ends of the cable were arranged with two symmetrically placed return copper cables. The measurement circuit was grounded only at one point near a cable end. The current through cable sample was measured using a set of Rogowski coils. The voltage measurement leads had a contact distance of 2.6 m and were placed at a distance of 3 mm from the cable sample outer surface. The voltage over the cable sample was measured using a lock-in amplifier. The AC loss was obtained by accurately determining the component of the voltage over the sample that was precisely in phase with the current through the sample and multiplying the RMS amplitude of this in-phase voltage component with the RMS amplitude of the current going through the cable sample. Liquid nitrogen bath cooling of the cable model at atmospheric pressure was used.

The AC loss as function of the transport current of the single phase YBCO cable model was calculated using the COMSOL model of a HTS cable validated previously [5] and adjusted for this case, see Table 1.

4. Measurement and calculation results

The measurement results are summarized in Table 2 and Figure 2. The measured AC loss amounts 0.115 W/m at the transport current of 3 kA_{rms}, frequency of 60.2 Hz and temperature 77.3 K. This gives a value for the AC loss of 0.096 W/m at the frequency of 50 Hz. The measured AC loss as function of the transport current amplitude is presented in Fig. 2.

Calculated for the same conditions AC losses using COMSOL model are in good agreement with the measurement. Furthermore, as expected at higher than measured transport current amplitudes i>0.8, the calculated using COMSOL model AC loss curve approaches the static losses curve calculated independently from the COMSOL model [6] (the static losses account only for the contribution to the AC losses of DC *I-V* characteristic of the cable conductor at a sinusoidal transport current and the index n=26 in this case, with all magnetization currents suppressed).

Table 2. Comparison of measured AC losses for a 3 kA-class YBCO cable conductor

Parameter	[this paper]	[4]
AC loss at 3 kA_{rms}, 77 K and 50 Hz		
Measured AC loss, W/m	0.096♣	1.3
I_c, kA of the conductor (77K, self-field)*	7.5*	4.7
Index n for the DC I-V curve of the cable	26*	-
Scaled transport current amplitude i	0.57	0.90
Lowest measured AC loss at 3 kA_{rms} and 50 Hz		
Measured lowest AC loss, W/m	0.096♣(77 K)	0.235 (68.7K)
I_c, kA of the conductor (self field)	7.5* (77 K)	9.2 (68.7K)
Scaled transport current amplitude i	0.57	0.46

*Estimated from the measured I_c and n of all individual tapes

♣The loss of 0.115 W/m measured at 60.2 Hz, gives 0.096 W/m at 50 Hz

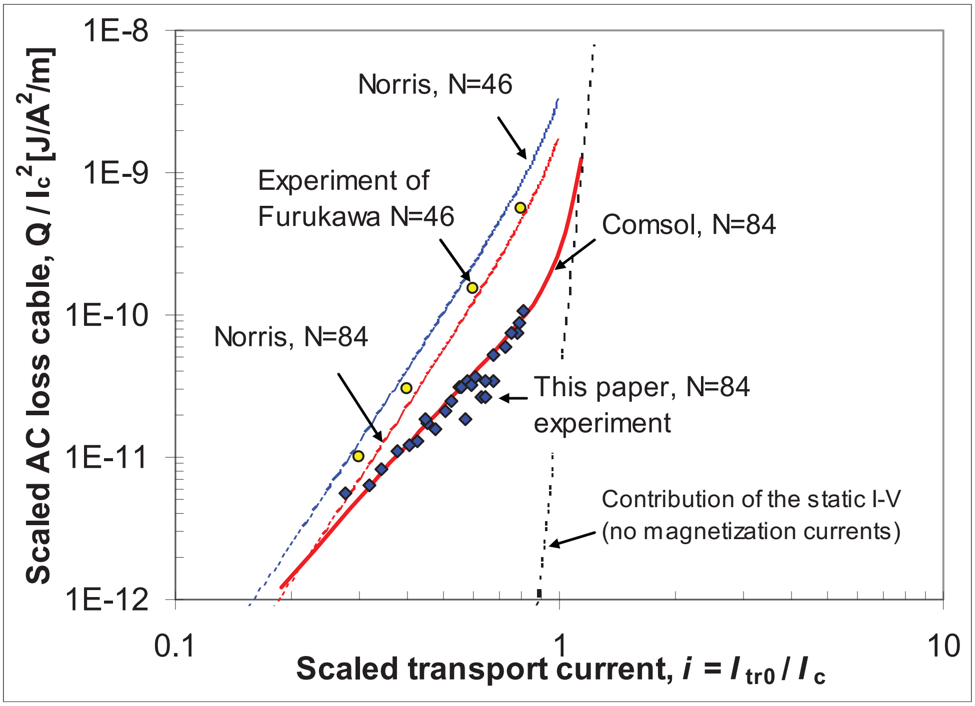

Figure 2 Measured dependence of the cable AC loss on the transport current (the rhombs indicate the measured points at the temperature 77.3 K and the frequency 60.2 Hz); the solid red line is the AC loss calculated using COMSOL model for the same conditions; the circles indicate the other cable AC loss measured in [5]; the solid lines "Norris, N=84" and "Norris, N=46" are the cable's AC losses calculated using Norris formula for a thin strip [5]. Calculated contribution of the I-V characteristic of the cable to the AC losses is also shown as a reference (in this case all magnetization currents in tapes are suppressed).

5. Discussion

It is generally accepted that for the same cable core diameter lower losses can be obtained when narrow YBCO tapes are used [2]. However, for practical reasons at present it is difficult maintaining the tape quality to make commercial YBCO tape with less width than 3 mm and therefore the tape width is in fact fixed. Clearly, the tapes of a fixed width used on a cable former of larger diameter conform better to its roundness, Fig. 1. Furthermore, a cable former of larger diameter allows for larger number of HTS tapes in parallel, for higher critical current of the cable phase at 77 K and for lower amplitude of magnetic field in the conductor area and therefore for lower AC losses at the same transport current, see Tables 1 and 2.

Direct comparison of our result with the AC losses measured on Furukawa cable [5] is done in Fig 2, where both the measured AC loss and the transport current amplitude are scaled by the critical currents of both cables at 77 K, see Table 2. From Fig 2, Tables 1-2 it is clear that we measure lower AC losses at the same conditions because the diameter of the cable former is larger in our case, more 3 mm wide tapes work in parallel, the critical current of our cable is higher at the same temperature, small gaps between the tapes possibly also play a role. Therefore, by using high quality, spatially uniform and relatively narrow 3 mm wide YBCO tapes with high critical current, by matching the cable former diameter to the tape width, by minimizing gaps between adjacent tapes, by selecting a proper value of the conductor critical current in respect to the value of the transport current, by optimizing the twist pitches in both layers, by proper selection of the former diameter in respect to the tape width, etc. it is possible to reduce the AC loss down to 0.1 W/m per single phase as requested for Amsterdam project.

6. Conclusion

Using a full-size single phase model of a HTS triax cable we demonstrated experimentally that it is possible to reduce AC loss in two-layer YBCO conductor to 0.1 W/m at the transport current of 3 kA_{rms}, frequency of 50 Hz and temperature of 77 K. The reduction of AC loss is achieved by optimizing many of tape and cable conductor parameters: by using high quality, spatially uniform and relatively narrow (3 mm wide) YBCO tapes with high critical current, by minimizing gaps between adjacent tapes, by selecting a proper value of the conductor critical current in respect to the value of the transport current, by optimizing the twist pitches in both layers, by proper selection of the former diameter in respect to the tape width, etc.

References

[1] A. Geschiere, e.a., „Breakthrough in development of superconducting cables“, paper 1256, CIRED, 21st International Conference on Electricity Distribution, Frankfurt, 6-9 June 2011

[2] Sh. Mukoyama, e.a., “Model cable tests for a 275 kV 3 kA HTS power cable”, IEEE Trans, on Appled Superconductivity, v. 21, nr. 3, 2011, pp. 976-979

[3] D. Willén e.a., “Measurement of Record-Low AC loss in a 2G (REBCO) Cable Model with Small Tape Gaps”, paper submitted to Superconductor Science and Technology

[4] www.superpower-inc.com

[5] O. Chevtchenko, “Modeling of high temperature superconducting tapes, arrays and AC cables using COMSOL”, COMSOL Conference 2010, November 17-19, Paris, available at: http://www.comsol.com/papers/8770/

[6] O. A. Chevtchenko “On the application of high-T_c superconductors in power coils and transformers”, p. 83, available at: http://doc.utwente.nl/38632/1/t000001e.pdf