DEMO200 – Concept and Design of a Superconducting 200 kA DC Busbar Demonstrator for Application in an Aluminum Smelter

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Abstract—**A number of technical applications such as aluminum smelters, electrolysis plants or large data centers require DC feeding currents of several hundred kA. Within the project DEMO200 we want to show the feasibility of a superconducting single-pole 200 kA DC busbar. To this end, a technology demonstrator of 2 m length will be developed and tested. It is based on REBCO superconducting tapes and will consist of ten identical modules with a current capacity of 20 kA each. These modules are joined in a compact structure fitting in a cryostat with an inner diameter of 30 cm. In contrast to the target application, the ten modules of this demonstrator will be electrically connected in series, thus a 20 kA DC source is sufficient for demonstration. Two different module designs are investigated, either with HTS Cross Conductors (CroCo) or wave-shaped stacks. Except for the additional electrical insulation between the modules, the mechanical structure of the demonstrator, local self-fields and the Lorentz forces will be the same as in the application case. Solutions for key technical challenges, such as current leads, Lorentz forces, low-ohmic soldered joints, and the compensation of the thermal contraction are proposed.**

Index Terms— **DC power transmission, HTS cables, large scale applications, DC power systems, power cables**

I. INTRODUCTION

In a number of applications in electrical engineering, large direct currents (DC) are required. Among them are electrolysis plants, data centers, metal smelters [1] or the feedings of fusion magnets [2] with currents of more than 100 kA over distances of several hundred meters. Today, in general normal conducting air-cooled busbars are deployed, mainly aluminum or copper, with cross sections of up to 1 m². It seems promising to replace these busbars by superconducting devices [1, 2]. With the tremendous progress in the development of high temperature superconducting (HTS-) tapes in the last years an enormous amount of work has been dedicated to power distribution with HTS-cables, but mostly for applications with alternating current (AC) at high voltage and moderate currents.

Comparatively little work has been done with respect to DC applications at high currents [6-8]. However, the superconductors seem especially well adapted for these cases, since the AC-losses vanish or, due to residual voltage or current ripples, are small. Moreover, at high currents, dimensions and weight of an HTS-busbar fall by more than one order of magnitude below its normal conducting counterpart, thus reducing ancillary costs. If the DC-busbar exceeds a certain length (e.g. a few 10 m), the losses of a superconducting version (including losses due to cryostat, current leads, pumps) easily remain below the ohmic losses of a conventional implementation [1, 9]. With the predictable increase of energy prices and considering ecologic aspects, these benefits will probably gain in importance in the future.

The present project was initiated at the request of Trimet, the operating company of a large aluminum smelter in Hamburg, Germany. An oven line of 90 electrolysis cells and a length of 600 m is fed with a DC of 200 kA. Today, the return conductor is realized by a partitioned aluminum busbar with a cross section of 0.5 m² and a weight of 1.3 t/m. The ohmic losses sum up to about 20 GWh per year (~ 1 M€/a). With reasonable assumptions on the thermal losses of the cryostat, the current leads, and the efficiency of the liquefiers, a superconducting alternative would generate energy savings of about 90%. Even including the large investment costs, a return of investment within 6 years is expected [9].

The project aims to show the feasibility of such a busbar. For this purpose, a 2-3 m long demonstrator is designed and will be assembled. It will be based on Rare Earth-Barium-Copper-Oxide (REBCO) HTS-tapes. Since a 200 kA DC current source is hardly available for development purposes, we plan DEMO200 as a series connection of ten modules in a compact, parallel arrangement. All functionalities, as total current, layout of tapes, local self-field, Lorentz forces, cooling conditions, current leads, electric connections and the compensation of thermal length changes are almost the same as in a real-life busbar, but a feeding current of 20 kA will be sufficient.

Partners in the project are: Vision Electric Super Conductors (VESC) for system design, integration, current lead development and operation, KIT for module development and subscale test and Messer SE for the cryogenic design.

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The paper is organized as follows: In chap. II we will describe the 20 kA modules including tape arrangement, Lorentz force compensation and current leads, chap. III presents the overall design including the cryo-concept, and in chap. IV a subscale test is described.

II. SUPERCONDUCTING MODULES

A. *Layout of tapes*

The projected current requires a large number of HTS-tapes in parallel. The optimization of this number is therefore a key issue with respect to the economic viability of the busbar. We developed a simulation tool to analyze the effect of self-field on different arrangements of tapes. The critical current of REBCO tapes is strongly dependent on temperature and magnetic field and moreover on the direction of the field. As an example, Fig. 1 shows the field and angle dependence for the tape TPL4120 from Theva. It has a width of 12 mm, a critical current of $I_c \geq$ 570 A at 77 K and a surround copper stabilizer of 10 µm.

For the simulations, the tapes are modeled by a number m of equidistant current paths coplanar and parallel to the tape. In a heuristic way the field and angle dependence can well be parametrized by an elliptic expression [10]:

$$I(B_x, B_y) = \frac{I_0}{m} \cdot \left(1 + \frac{\sqrt{(c \cdot B_x)^2 + B_y^2}}{B_0}\right)^{-b}$$

B_x, B_y, are the field components parallel and perpendicular to the tape, c, b, B_0 and I_0 are suitable fit parameters [10].

It is not yet decided if DEMO200 will be equipped with tape from Theva or S-Innovations (SuperOx). With the tape from Theva the simulation must include the tilt angle of about 30° of the crystallographic c-axis of the HTS-layers with respect to the normal direction (Fig. 1). However, the resulting effect on busbar critical current, self-field and Lorentz-forces is small and the simulations show, that it can furthermore be attenuated with an alternating orientation of the tapes.

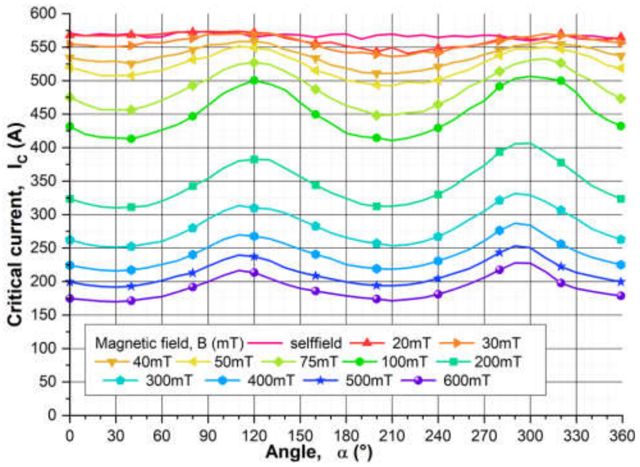

Fig. 1. Field and angle dependence of critical current for Theva TPL4120. 90°, 270°: normal direction, magnetic field perpendicular to the tape.

In order to reduce the required amount of HTS material, DEMO200 will be operated at T = 70 K in subcooled liquid nitrogen (LN). In the simulations the increase of critical current is considered by introducing a lift factor [11] I_c (70 K) / I_c (77 K) = 1.5.

A number of different tape arrangements have been analyzed with this procedure. As expected, the number of required tapes decreases with increasing overall radius. The finally selected configuration does not only take the required number of tapes into account, but also manufacturing and installation aspects. It is based on dense stacks of 15 tapes with a width of 12 mm. Four such stacks are disposed in a rectangle and form a module. The ten modules are arranged with their centers on a ring of 230 mm diameter (Fig. 2, right). This arrangement fits into a cryostat with an inner diameter of 300 mm. Moreover, it complies with the series connection of ten modules.

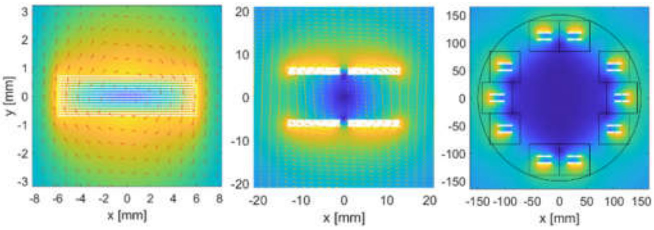

Fig. 2. Arrangement of tapes in DEMO 200 (T = 70 K): left: single stack with 15 horizontal tapes, middle: arrangement of 4 stacks in one 20 kA module, right: arrangement of ten 20 kA modules in DEMO200.

B. *Superconducting Modules*

The four stacks of each module are placed in an H-shaped steel structure. The two stacks in each half of this structure are separated by a welded copper tape (amplitude 12 mm, period 2 cm) as a distance holder. Fig. 3 shows such a pair of stacks. Two more stacks are placed in the lower half of the H-type structure (not visible). The H-profile with four mounted stacks is housed in a cage made of steel sheet and provided with large holes for LN-access. In total, the module has a square cross section 28 x 28 mm².

The warm outer tube of the cryostat is a stiff structure with a given total length. The thermal contraction of the HTS-tapes when cooled down to LN is expected to be about 3‰, i.e. ~1.8 m on the target length of 600 m. To compensate this contraction, the HTS stacks are mounted in a wave shape (Fig 3). The waves have an amplitude of about 1 cm at ambient

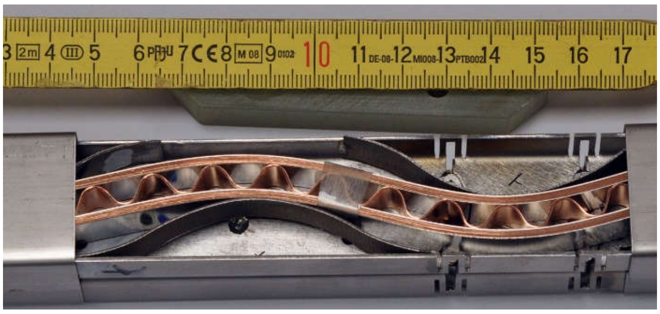

Fig. 3. Wave arrangement of HTS-stacks for thermal compensation. Two HTS-stacks and the welded distance holder are visible. Also visible are the laminar sheet springs to guide the wave.

temperature (RT) and a fixed wave length of about 10 cm. They are guided by lamellar steel springs in order to avoid local compressions ('buckling', [12]) when warmed back to RT. The thermal contraction of the H-profile (3‰) is compensated by small spring-type incisions also visible in Fig. 3.

Beside the modules described above, an alternative module design is investigated within the DEMO200 project. It is based on HTS cross conductors (CroCo) of KIT [13] and is described in detail in [14].

C. Lorentz Forces

A key challenge of a busbar with such high currents are the Lorentz forces within and between modules. Within the stacks the resulting forces are always compressing. The compressing forces between stacks lying on top of each other within the modules are compensated by corrugated copper-tapes (300 µm) between the stacks, see Fig. 3, which act as hard springs. The forces between the two assemblies of stacks lying side by side in the H-profile are considered by the rigid steel structure. This structure, together with the steel cage also stabilizes the module with respect to the Lorentz-forces between modules.

In a first step, the expected Lorentz forces F_L were evaluated by numerical simulation. From the self-field calculations described above, local fields and currents are already known such that the Lorentz forces are directly derived. The forces on the stacks are a superposition of the forces inside the module, directed towards the center of the module, and the forces between modules, directed towards the center of the whole arrangement. For the inner stacks both contributions partly compensate. The total forces on the entire modules are directed towards the center. Table I gives the maximum occurring forces on a single tape, a stack, and a module obtained from simulations. The forces on the modules reach more than 3 kN/m.

TABLE I
CALCULATED LORENTZ FORCES IN DEMO200

Force [N/m]	Max $\lvert F_{L,x}\rvert$	Max $\lvert F_{L,y}\rvert$	Max $\lvert F_L\rvert$
Tape	111	162	181
Stack	1534	1579	1826
Module	3082	2904	3384

In a second step the stability of our structure with respect to these forces was tested at RT. A module was equipped with copper-tapes instead of HTS to reduce the resistance at RT. The module and a return conductor were placed close to each other, to maximize the repelling Lorentz force. The setup was fed with a pulsed AC current of 22.5 kA$_p$. This exceeds the nominal current. Thus, the forces within the module are adequately induced. The repelling peak force between module and return conductor also reached a value near the maximum force expected for the DEMO200 assembly. After a large number of tests including different orientations of the module a visible degradation could be observed neither on the tapes, the stacks nor the steel structure. Thus, the mechanical support structures of the HTS-modules are validated with respect to the Lorentz forces.

D. Current Leads

For high-current HTS-applications, the current leads are often the dominating contribution to the resulting heat load [15]. We therefore designed a gas-cooled modular current lead consisting of ten 20 kA units (Fig. 4) each feeding one busbar module. In DEMO200, these units are connected in series, whereas in the target application, a parallel connection will be suitable.

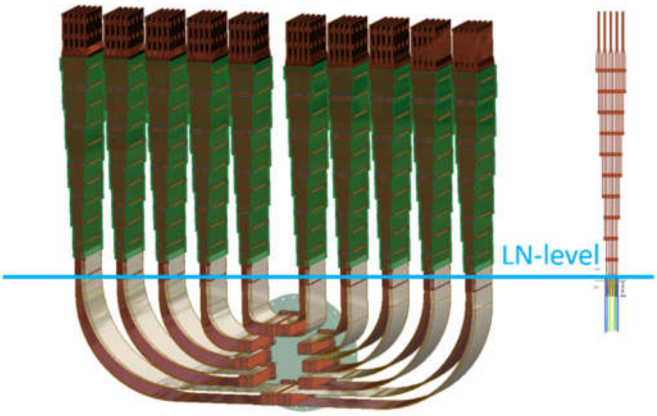

Fig. 4. Current leads for DEMO200, left: 10 units.

The current lead units consist of parallel copper bars housed in a glass-fiber reinforced plastics (GFRP) cage which guides the evaporating nitrogen meandering along the leads. The number of copper bars is reduced towards the cold end (Fig. 4, right), reflecting the decrease of the resistance with temperature. HTS-tapes are soldered to the cold end of the Cu leads. Since they are operated at 77 K while the busbar is cooled to 70 K, the number of tapes joining the current leads and the modules must exceed the number of tapes in the modules by about the lift factor of 1.5.

III. OVERALL DESIGN

The DEMO200 design in the overview: Ten rigid modules (chap. II.B) with quadratic cross section are joined in a compact ring arrangement and placed in a tube-shaped cryostat. This cryostat is cooled with its own circuit operated with subcooled LN at a pressure of 5 bar (abs) and an entrance temperature of $T = 67$ K. The temperature of this circuit is maintained with a heat exchanger operated with pumped LN [16].

The front ends of the cryostat are closed with GFRP-discs with ten integrated copper blocks (Fig. 5). The HTS-tapes of the busbar modules are soldered to one side of the copper-blocks and the tapes of the corresponding current leads to the other side. The copper blocks were optimized with respect to their ohmic resistance. The 10 modules are connected in series, so that a feeding current of 20 kA is sufficient. Fig. 5 shows the overall design of DEMO200.

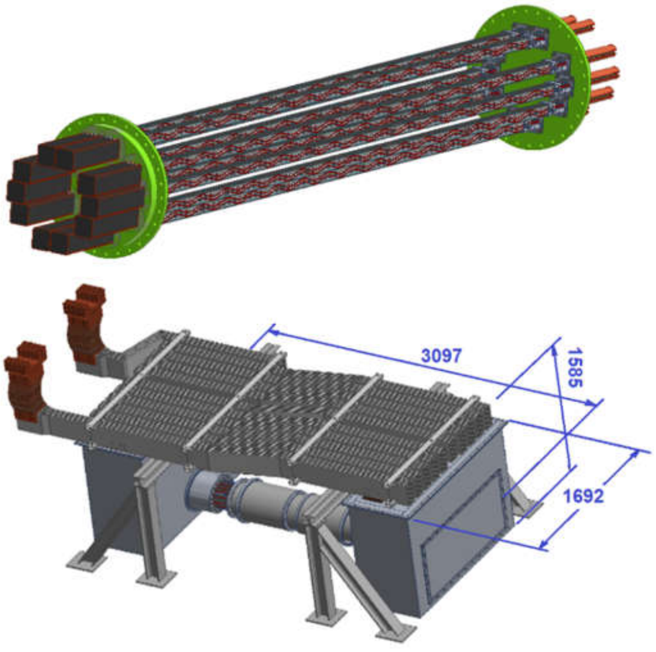

Fig. 5. Overall design of DEMO200. Top: busbar with ten modules. Bottom: DEMO200 with tube cryostat, cold boxes and series connection.

The current leads are placed in rectangular cold boxes and cooled with LN at ambient pressure. The evaporating LN yields an effective gas cooling. The nitrogen level can be maintained by a refrigerator or by supply of LN. The LN mass flow necessary for a reliable cooling was estimated with reasonable assumptions. For both current leads mass flows of 72 kg/h each are expected, for the busbar the required mass flow is about 67 kg/h. For a large-scale application this is acceptable.

IV. Subscale Test

In a first step we will install a subscale setup with three modules for a functional test under simplified conditions. The modules are identical to the target setup. Three modules will be tested: two stack modules as described in chap. II.B and one CroCo-module [14]. The tests will be conducted at $T = 77$ K in an open bath cryostat (LN). Again, the three modules will be connected in series. Different aspects of DEMO200 will be tested:

At $T = 77$ K the nominal current (20 kA) will not be reached, instead we expect a critical current of about 15 kA. The results can then be extrapolated to the target temperature of 70 K.

The stability of our structure with respect to Lorentz forces will again be tested with large pulsed currents, now at $T = 77$ K. A current source with pulses of 30 kA for 100 ms is available. The return conductors are placed on the same side near the modules in order to generate large repelling forces comparable to the forces expected in DEMO200.

Moreover, we will test the functionality of the length compensation. For this we use a stable structure at RT outside the cryostat. This rigid structure maintains the HTS-modules at a constant length, such that contraction and dilatation during a cooling cycle must be compensated by the wave shape of the HTS-stacks (Fig. 3). Finally, also the contacts are tested. In the subscale test the HTS-stacks are simply soldered on copper-blocks which are linked to the current source by flexible copper-braids. The soldering procedures in DEMO200 is similar. In thorough pretests we achieved contact resistances of 10 nΩ per tape.

Fig. 6 shows the setup of the subscale experiment. The modules are integrated in a stable GFRP-structure (Fig. 6, top) with supports in a spacing of 20 cm. All mechanical parts of the subscale-test are manufactured and will now be assembled in a 6 m long bath cryostat.

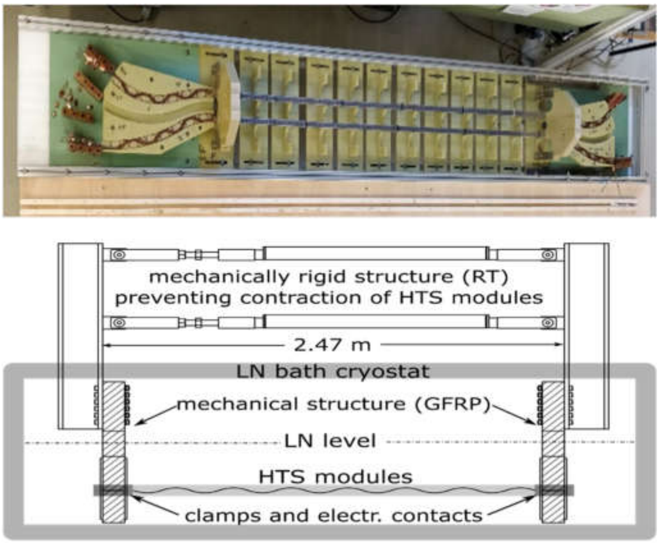

Fig. 6. Subscale-test, setup. Top: two HTS-modules with current feeds. Bottom: rigid structure at RT to maintain the modules at a constant length.

V. Conclusions

The project DEMO200 shall demonstrate the feasibility of a busbar for a DC of 200 kA. All the features of a real-life device are addressed such that the functionality can be evaluated. With its modular structure it can easily be adapted to a wide range of currents. Furthermore, the project will yield a basis for a rigorous cost estimation in order to assess the economic viability of such a large investment.

In the present state of the project the design process of the HTS-modules has been concluded and the modules have been mechanically tested with respect to the expected Lorentz-forces. The design of the busbar, the current leads and the cryogenic concept are finalized. A subscale-test is actually assembled. If it is successful, the manufacturing of DEMO200 will start immediately.

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