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Energy and superconductors – applications of high-temperature-superconductors

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Abstract. More than 20 years after the discovery of high-temperature-superconductors (HTS) first applications in the energy sector are now becoming commercially attractive. Whereas still high end applications of low-temperature-superconductors (LTS) like NMR or MRI systems are the major drivers for industrial production, HTS based systems promise broader use in energy technology over the next few years. Due to their superior performance HTS materials enable more compact and lighter electric devices as well as an unbeatable improvement in energy efficiency. Moreover new devices like fault current limiters (FCL) are under development and field tests exhibit so far unknown properties for future electric grid design. Prototypes and first commercial systems like cables, generators, motors, FCL were successfully commissioned in the last few years. Based on these test results HTS systems will contribute significantly to the future key challenges in energy technology by reducing CO_2-emmission due to their outstanding efficiency and to the security of energy supply.

Introduction

About 100 years after the discovery of superconductivity by Heike Kamerligh Onnes [1] the promises of superconductivity for revolutionizing energy applications start to become true. Whereas the so called low temperature superconductors (LTS) have found their application for more than 50 years in the field of research and medicine the new generation of superconducting materials, the high temperature superconductors (HTS), enable new energy applications such as cables, motors, generators, magnets and fault current limiters.

Two outstanding properties of high temperature superconductors when cooled under their critical temperature break paradigms in electro technology:

- No ohmic restistance
- Highest energy density

The absence of ohmic resistance allows HTS-systems with superior energy efficiency *e.g.* magnetic billet heater saving about 40% electrical energy compared to conventional systems.

The high energy density enables the construction of lighter and smaller devices. As an example the diameter of a 6 MW off-shore wind power generator therefore can be reduced from 9 to 2.5 m.

LTS materials like NbTi and Nb_3Sn are established functional materials which are produced in industrial processes. These LTS allowed the installation of large accelerators for high energy physics as well as magnets for medicine and analytical applications. The metallic or intermetallic phases here enable a production process which can be derived from very advanced but still classical metallurgical processes like drawing, bundling and annealing. Due to their large scale availability and technically mature LTS applications are well established and system performances are still driven forward like for the impressive NMR-spectrometer with a frequency of up to 1 GHz installed in 2010 [2].

Highlights for LTS technology are also the Large Hadron Collider (LHC) at CERN or the envisaged fusion reactors like ITER [3].

Whereas availability and established processing are major advantages for LTS the necessity of cooling well below 10 K, usually with liquid Helium, is the major drawback preventing the use of LTS materials and systems in more price sensitive fields of applications such as the energy sector.

Since the discovery of high temperature superconducting materials in 1986 by Bednorz and Müller [4, 5] energy applications are becoming realistic due to their super-

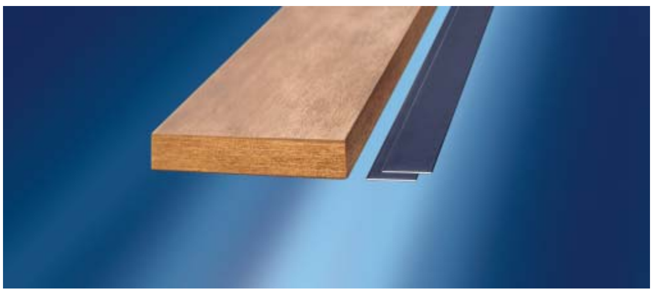

Fig. 1. Current density of copper *vs.* HTS wires.

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Fig. 2. 1 GHz NMR-spectrometer installation in Lyon, France (Courtesy of Bruker Biospin).

Fig. 3. Magnetic billet heater operating at WeserAlu, Minden, Germany (Courtesy of Zenergy Power).

ior operating temperature compared to low temperature superconductors. High temperature Superconductivity is thereby defined by a critical temperature above 77 K, the boiling point of liquid nitrogen.

The first commercial product based on HTS materials for industrial processing is the magnetic billet heater, which was introduced in 2007. For several years this product has proven its stability in industrial environment opening up opportunities for other HTS applications by demonstrating competitive reliability.

Processing of HTS materials

High-Temperature-Superconductivity is generally defined by a transition temperature (critical temperature, T_c) of more than 77 K, according to the boiling point of liquid nitrogen. So far, two materials have acquired technical relevance for HTS-wires:

- Bismuth (lead-)strontium-calcium-copper-oxide
  $(Bi, Pb)_2Sr_2Ca_2Cu_3O_x$
  $T_c = 110$ K
- Yttrium-barium-copper-oxide
  $YBa_2Cu_3O_x$
  $T_c = 92$ K

The critical temperature is a material constant and is not influenced by processing. In spite of intensive research and occasional press releases about new superconducting compounds, the materials known so far are the only compounds with a commercial potential.

Besides the critical temperature the characteristics of superconducting materials are described by two more critical parameters [6]. They are: critical current density (J_c) and critical magnetic induction (B_{c2}) or the upper critical magnetic field (H_{c2}). The relationship between these parameters is depicted in Fig. 4.

In electrical engineering applications, the current carrying capacity J_c of the HTS-wires is the decisive criterion for the technical applicability. All HTS are ceramic, oxidic materials with copper-oxide layers as a common basis. This special crystalline structure (Fig. 5) causes a strong anisotropy of the critical current density. Thus, the critical current density, parallel to the copper-oxide-layers, is several times higher than vertical to the layers. In the same way, the current carrying capacity through high-angle grain boundaries is very restricted [7, 8]. As it is not possible to produce a kilometre-long monocrystal, the industrial manufacture of HTS-tapes is faced with the challenge of aligning all small superconductor crystals equally within a HTS-wire. The critical current of a HTS-tape therefore depends on the texture degree and thus on the manufacture of the wire.

In this respect, texturising can be carried out either mechanically, like for HTS-tapes of the first generation (1G)

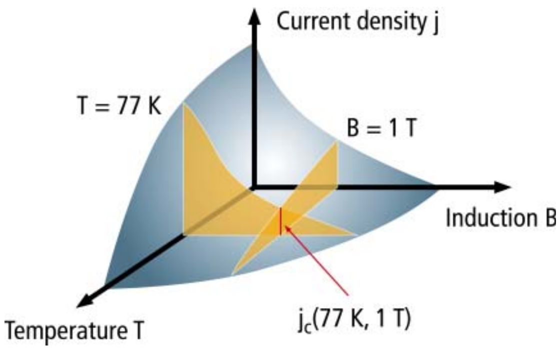

Fig. 4. Critical temperature (T_c), critical current density (J_c) and critical induction (B_{c2}).

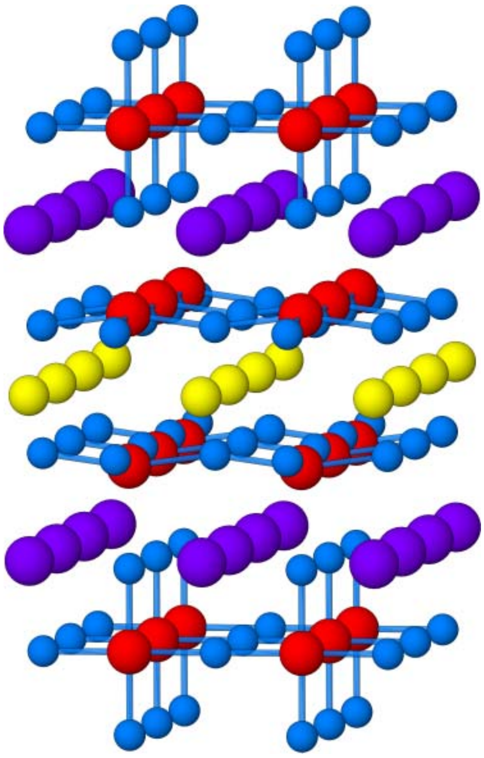

Fig. 5. Crystalline structure of $YBa_2Cu_3O_x$ with copper oxide layers.

on the basis of bismuth-(lead-)strontium-calcium-copper-oxide, or by aligned crystal growth, as is used for the HTS-wires of the second generation (2G) on the basis of yttrium-barium-copper-oxide.

Other important features of HTS tapes are their behavior in external magnetic fields and under AC conditions.

Starting from a certain magnetic field strength (lower critical field, H_{c1}), magnetic field lines in the form of flow tubes penetrate all HTS-materials, and superconductivity completely fails from the upper critical magnetic field H_{c2} onwards. This flow penetration occurs with all type II superconductors under nearly all technically relevant application conditions for HTS-wires. If these HTS-conductors receive current, the Lorenz force will have an effect on the flow tubes, and the tubes will move vertically to the current direction and cause electrical losses [9]. The introduction of artificial pinning centers into the HTS material is therefore one of the basic challenges in HTS materials development in order to prevent flux flow in the HTS wires under operation and thus increase the upper critical field H_{c2} [10]. The pinning centers can be introduced by nano-precipites during crystallisation, by direct implementation of nano-particles [11] and by co-crystallization of normal conducting nano-columns [12]. This development is still ongoing and one of the most active research fields worldwide.

At least some power engineering applications like transformers and high speed rotating machines like turbo generators require a conductor material exhibiting especially low alternating current losses and high operating currents. These requirements can be met by modifications of the strip transmission conductors (for 2G HTS wires) towards longitudinally patterned HTS layers [13, 14] or by stranding of individual conductors to a high current Roebel-type cable [15]. As these special applications are considered to be more long term and require much larger amounts of HTS wires than actually available, the worldwide research effort on this aspect is remarkable but so far less than for artificial pinning centers.

For other purposes such as magnetic levitation HTS bulk materials are widely produced. These bulk materials, in particular YBCO, are manufactured as single domain samples via melt-textured-growth [16]. Applications [17] and processing are described elsewhere as levitation is not considered as an application in the energy technology sector.

First and second generation HTS tapes

In order to be usable in electric devices the ceramic oxide-based HTS materials have to be processed to windable wires or tapes. The basic challenge faced during the manufacture of flexible and long conductors of ceramic HTS-materials is their brittleness. The manufacture of thin filaments or thin layers is considered as the solution to this problem. When sufficiently small dimensions are used, the materials are flexible, as it is known for glass fibres, to mention just an example. As for a first generation (1G) of HTS tapes the processing to thin filaments was preferred the second generation (2G) of HTS tapes are based on thin film technology, thus these HTS tapes are also called Coated Conductors. HTS-wires of the first generation (1G) are based on the material bismuth-(lead-)strontium-calcium-copper-oxide (BSCCO) and the filament principle; HTS-wires of the second generation (2G) are based on the material yttrium-barium-copper-oxide (YBCO) and the layer principle.

HTS-wires of the first generation are manufactured according to the Powder-in-Tube (PiT) procedure [18]. During this process, an easily workable metallic cladding tube is filled with fine powder of the oxidic basic materials that are required for the manufacture of the superconductive phase and afterwards it is shaped by drawing to form a thin wire. The further combining of many individual wires that have been shaped in this way to a wire bundle, which is again further shaped after placing it into a cladding tube, leads to the formation of a great number of finest filaments of parallel individual wires that are separated by the metallic cladding material (Fig. 6). As soon as the desired final wire thickness has been reached, the oxidic basic materials present in the individual filaments are then transferred into the superconductive phase in a multi-stage annealing procedure. This phase formation has to take place under high temperatures (approx. 900 °C) and under oxygen atmosphere so that only few (noble) metals under which Ag shows the best characteristics are worthy of consideration for metallic cladding materials. The application of high pressure during annealing increased the performance reached significantly in the last years [19]. The geometrical alignment of the superconductive crystallites into individual filaments required for a high critical current density is carried out by several rolling steps between the heat treatments. While doing it, there is, however, only a parallel alignment of the CuO-levels and not a complete alignment of all crystal axes taking place. Due to the occurring plate-like microstructure, it is possible to reach cur-

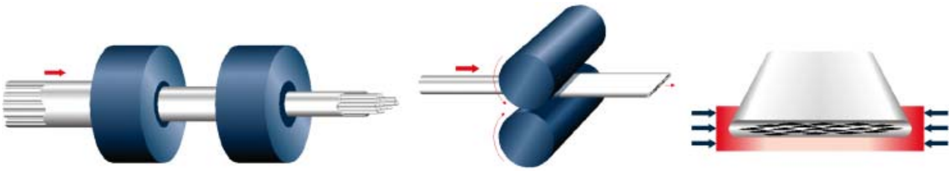

Fig. 6. Manufacturing process for HTS-wires of the first generation (drawing, rolling, annealing).

rent densities of 10–100 kA/cm^2 in the superconductive filaments. Thus, these densities lie below the maximum reachable current densities of completely oriented samples by the factor ten to hundred. In connection with the basic, physical properties of the HTS (low coherence length), the crystalline structure of the BSCCO-phase causes the HTS-phase to adopt a very low irreversibility field with increased temperatures and thus a highly reduced current carrying capacity in the magnetic fields so that it is not suitable for magnetic field applications at temperatures >50 K.

To overcome these restrictions of first generation HTS types a layer design forming the basis of the HTS-wires of the second generation (Fig. 7) was developed by research groups worldwide. Based on a metal substrate strip (grey), ceramic buffer layers (blue) are firstly deposited, afterwards the actual superconductor layer (red) is applied [20]. A metallic protection layer acting as an electrical shunt completes the full architecture.

The layer deposition can either occur through physical or through chemical processes [21]. In this respect, physical deposition processes, such as sputtering, Pulsed Laser Deposition (PLD) or electron beam evaporation require a high-vacuum while chemical processes, in particular Chemical Solution Deposition (CSD or MOD, metal organic decomposition), work under normal pressure [22]. Metal Organic Chemical Vapour Deposition (MOCVD) occupies an intermediate position which only requires a moderate vacuum [23]. In general, a higher performance of the superconductive layers is achieved using the physical deposition procedures because of the high-vacuum technology required which, however, coupled with the lower rate of deposition result in the drawback of higher production costs. Lower energy costs and investments for chemical deposition technology offer both a challenging and economic path towards low cost medium performance HTS conductors.

In second generation conductors the superconductor layer is textured by an aligned growth of the superconductor layer on the buffer layer lying underneath and acting as a template. Thus, this buffer layer has to be textured first. With regard to physical procedures, this can be done by special vacuum evaporation processes (Ion Beam Assisted Deposition – IBAD [24]; Inclined Substrate Deposition – ISD [25]). Special, already textured metal substrate strips can be used as an alternative, economical and scalable approach. They can be manufactured in long lengths by standard rolling and annealing processes and serve as texture template for the aligned growth of the buffer layer and the following HTS-layer. While any metal alloys, such as high-strength, non-magnetic nickel-basis alloys can be used in IBAD- or ISD-procedures, textured metal substrate strips are mainly restricted to nickel alloyed with tungsten [26].

Currently, HTS-wires of the first generation are commercially obtainable in limited amounts. Due to the high raw material price because of the high share of silver required in the metal matrix, clearly better chances for a commercial breakthrough are attached to the second generation of HTS-wires. First wires are already available, however, the complex manufacturing processes still require high development expenditure as regards to the improvement of the properties on the one hand and the process stabilisation and scaling on the other [27, 28].

The following table summarizes the actual published typical superconducting performance of 1G and 2G HTS tapes. For 2G tapes the values in addition are differentiated by deposition processes. Higher performances for PVD processes in table 1 represent both: higher general potential of the process regarding performance and so far much longer development time of more than 20 years compared to chemical processes with only about 10 years. The unit J_e (engineering current density) refers to the parameter of main relevance for electro technical engineer-

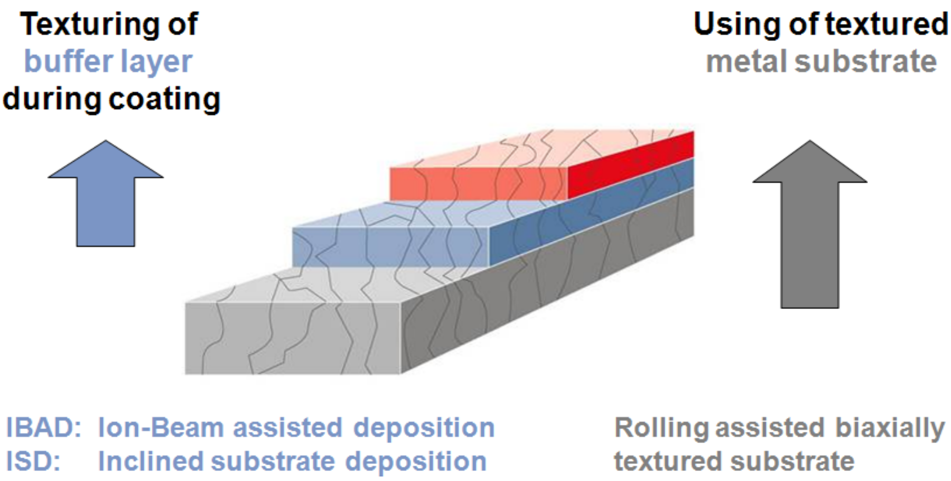

Fig. 7. Layer architecture of 2G HTS tapes with strategies for inducing texture.

Table 1. Actual performance of technical HTS tapes (77 K, self field, 1 μV/cm, = 100 m) [29].

Type	J_c [kA/mm^2]	J_e [A/mm^2]
1G HTS tapes	0.3	100
2G HTS tape		
Only PVD processes	50	250
combined PVD and CSD processes	25	100
Only CSD processes	10	50

ing, the overall current density including the complete support structure of the HTS tape whereas the critical current density (J_c) exclusively refers to the superconductor cross section.

Energy applications of HTS materials

For safe, reliable and sustainable energy supply, efficient generation, transmission, distribution and use of electrical energy are crucial. The application of High-Temperature-Superconductivity can play an integral part in the future extension of the grids. In principle, conventional equipment, such as cables, transformers and generators can be extended much more efficiently, compactly and easily because High-Temperature-Superconductors make a ten-fold to more than one hundred-fold higher power density possible compared to conventional conductors such as copper and aluminium. However, HTS also enables completely new types of equipment, such as superconducting fault current limiters for effectively and safely limiting short-circuit currents and superconducting magnetic energy storage (SMES) for fast and highly efficient storing of electrical energy. Worldwide research programs are ongoing for realizing the expected benefits for enhanced electric power technologies [30, 31].

Compared to conventional equipment, the application of HTS components can considerably reduce losses. Some examples have been listed in Table 2. Although conventional equipment is already highly efficient, this can be even further improved by HTS. Thus, especially at high power and over long lifetime there are huge energy saving potentials.

Actually most prototypes and early stage commercial HTS systems are realized with 1G HTS conductors. This first generation HTS tape technology has rapidly enabled the production of larger volumes of 1G HTS-tape conductors. Thus, a number of cable and motor demonstration projects were successfully realised in recent years. However, the use of 1G HTS-tape conductors for commercial products has already been greatly restricted by the high conductor price. 2G conductors, however, offer the perspective of a more economical mass production. Due to the more complex manufacturing technology, however, the production volume of 2G conductors is currently still limited. As the geometric dimensions of 1G and 2G conductors are comparable, 1G conductors can be relatively easily replaced by 2G-conductors in the foreseeable future.

Table 2. Energy savings by superconductivity.

Examples	Loss reduction
Generators	– Some MVA 30–40% – >100 MVA 40–50%
Transformers	– Stationary 50% – Mobile 80–90%
Magnets	– High-field magnets >95% – HTS-fusion magnets 20%
HTS-current leads	20–30%
Induction heating	50%
Magnetic separator	>80%

Energy distribution

It is of great importance to generate, transmit and distribute energy efficiently and safely in order to supply our society and economy reliably with energy. In this respect, some of the great challenges are safe integration of increasing regenerative energies, sustainable supply of the increasing energy demand, further reduction of the grid losses and economical modernisation of power systems. While doing so, superconducting power equipment, such as generators, cables, transformers, current limiters and magnetic energy storage will play a significant role because they offer a large number of technical and economic advantages compared to conventional solutions [32].

Superconductivity offers a significantly higher current density with lower voltage drops as well as an active short-circuit current limitation. Based on these fundamental characteristics, some clearly defined advantages for network planning and building up of power systems arises as summarised in Table 3 [33].

Efficient and safe transmission and distribution of electric energy is the most important task of electrical infrastructure. In the face of the ever growing current consumption and the increasing power supply of regenerative energies, the demands on energy distribution are changing. Both developments place previously unknown demands on power cables. In this context, superconducting cables represent a very interesting alternative to the conventional

Table 3. Consequences of the use of superconductivity for dimensioning and design of power systems.

Main HTS Characteristic	Consequence for Power System Dimensioning	Consequence for Power Systems
Low impedance and low voltage drops	Longer line lengths at HTS voltage level	Lower total line length Less switchgear
	Longer line lengths at subordinate voltage levels	Fewer substations
High current carrying capacity	Higher power rating per feeder	Lower total line length Less switchgear
	Reduced number of voltage levels	Omission of one voltage level at generation and transmission level
Short-circuit limitation	Dimensioning to lower short-circuit currents	Short-circuit free power systems

Fig. 8. LIPA HTS cable project (Courtesy of AMSC).

technology. Superconducting AC cables have already been tested for quite a long time in pilot projects. As for example a 600-metre-long 138 kV cable system with a rated power of 574 MVA, which was put into operation in the grid of the Long Island Power Authority (LIPA), USA, in 2008 [34]. Up to now, the cable in the LIPA-grid has been the longest superconductor cable and the cable with the highest rating operated in a transmission grid. Worldwide there are about 20 HTS cable projects in different voltage levels and lengths in Japan, China, Korea, United States, Netherlands, Denmark and Germany. In 2007 a first project was finalized in Albany, USA, (34.5 kV, 800 A, 30 m, 3-ph.) already with a 2G HTS wire section [35].

Generation of electric energy

About 95% of electrical interconnected power systems are supplied by large synchronous generators. In synchronous generators, the rotor or armature, which generates a permanent magnetic field, rotates in the stator. This stator consists of several windings which have been inserted into a magnetic iron yoke. The width of the air gap between rotor and stator is significant to the magnetic design of the generator. The electrical power is taken off the copper windings of the stator. The constant field magnet of the rotor can be advantageously realised with a superconducting field winding. The iron teeth in which the stator winding has been embedded can be omitted because, using the superconductive rotor, higher magnetic flow densities can be produced than with conventional rotors (copper winding or permanent magnets). Thereby, a so-called air gap winding is realized, even when the enlarged gap is not filled with air, but with non-magnetic material. With this design weight and size reductions by one to two thirds compared to a conventional machine of the same capacity are possible. Consequently, either a weight and size reduction or a higher nominal capacity under the given framework conditions (higher power density) can be achieved using a superconducting design.

One example for HTS generators is the equipment of a run-of-river power station in Bavaria, Germany, with a superconducting hydro power generator [36]. In the course

Fig. 9. HTS rotor for hydro power generator (Courtesy of Converteam).

of the modernisation of the power station a conventional solution would not have been economical with (of) a turbine renewal and the associated increase of the generator output power under the prevailing constructional restrictions (protection of historic monuments of the building). The higher power density of the superconducting generator makes 1.7 MVA in the size of 1.25 MVA possible. A total increase of 36% of the generator output power could be reached by the implemented modernisation measures.

Other fields of application for power generation with HTs system are under evaluation worldwide. Wind power generators were identified as one of the most promising applications in the last years resulting in several prototype and demonstrator projects worldwide [37].

Electrical grid safety

Apart from load flow and stability of the power system, safe operation of the grids plays a significant role in planning and operating electrical power systems. Ideal fault current limiters are characterised by low impedance in normal operation, fast and effective current limitation in case of the faults and automatic recovery. Conventional measures for short-circuit current limitation either cause a constant impedance increase also in normal operation (for ex-

Fig. 10. Commercial resistive type FCL (left) and biased iron core-type FCL (right) (Courtesy of Nexans Superconductors and Zenergy Power).

ample adaptation of the transformer impedance, short circuit-current limitation choke), or they have to be replaced after each incidence (for example fuses, Is-limiters). Superconducting fault current limiters, however, meet all the demands on an ideal current limiter. The application of this new type of operational equipment in electrical power systems promises numerous technical and economic advantages.

Presently, superconducting fault current limiters (FCL) are becoming commercially available at least for the medium voltage level from 5–50 kV. High voltage FCL are under development and are expected to be available within the next five years. The technical feasibility and reliability of this new type of equipment was shown on the medium-voltage level in several demonstrator and field tests [38]. In 2008 and 2009, further prototypes were put in operation on the medium-voltage level. For the first time in HTS systems for electrical grids several projects have been realized without any public funding since 2009 (Fig. 10) [39]. This underlines the great interest of the utilities in this technology. Up to now more than 20 FCL projects in the medium voltage level worldwide are already finalized or will be finished within the next two years. Three high voltage prototype FCL are planned or under construction in the United States, Germany and China. It becomes apparent that the resistive superconducting fault current limiter, which is outstanding due to its simple function and compact design, is developed most frequently. In this type of FCL the HTS material is quenched by exceeding the critical current in the fault state. The complete energy is dissipated in the HTS material thus requiring homogeneous and stable HTS material, high recooling power and in the case of high voltage FCL advanced bushings delivering high voltage power into the cryostat. DC-biased iron core design FCL is much more tolerant against lower quality HTS material and high voltage. However the design requires large amounts of iron as the power dissipation taking place in the iron core results in more higher weight and a larger footprint [40].

Motors

In rotating machines such as motors high-temperature-superconductivity offers the chance of overcoming technical restrictions arising from conventional technology and thus opening up new potential. Consideration is given to machines with an output of more than approx. 2 MW in a large speed range of low-speed drivers for the generation of high torques up to high-speed drivers with outstanding performances.

Less weight, same output – The high current density in the superconducting wires and tapes (1G or 2G conductor) allow a compacter winding and thus a smaller and lighter design of the machines with, on average, 35% to 50% the weight of conventional synchronous motors of equal torque

Smaller size, greater power density – The superconductive windings can generate a higher magnetic induction B more economically than the common copper wire technology due to their higher current carrying capacity of more than 150 times of conventional copper. This is one of the incentives for compacting devices and systems, because the power density of the entire machine scales with B^2.

Higher efficiency – Thanks to the characteristic of superconductors for transporting electric current without resistance, the resistive rotor losses, which are otherwise unavoidable and often difficult to cope with, do not occur. Naturally, the power that is used for cooling the rotor has to be taken into consideration. However, for the given power range, the energy required for the cooling device costs much less than can be saved thanks to having no Ohmic loss.

Other remarkable advantages with varying impact for each field of application are high partial load efficiency, low noise, low synchronous reactance, harmonic-free voltages, cyclic load insensitivity, mechanical compatibility and significantly reduced maintenance.

Numerous development programs have been started world-wide in order to test the technical feasibility of these

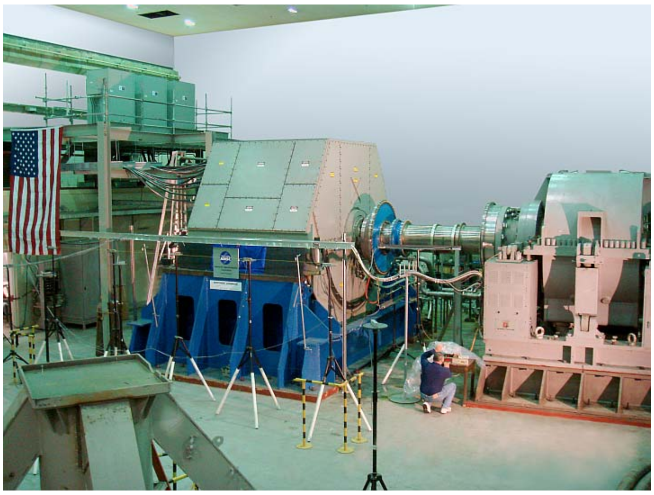

Fig. 11. 36.5 MW ship propulsion motor (Courtesy of AMSC)

features: in Japan and Korea, in America and in Europe. Of particular interest in order to realize most advantages offered by HTS technology are island applications such as ship propulsion. New cruise liners today are planned as fully electrical ships in major parts opening up possibilities for ship-builders to significantly increase efficiency and use of the ship by integrating HTS technology.

Slow-speed motors for this application were successfully built and tested in Europe (4 MW, 120 rpm, 320 kNm) [41] and in the United States. The ship propulsion motor completed in 2008 had an output power of 36.5 MW at 120 rpm. The weight of less than 75 t for the HTS system has to be compared to a conventional copper motor (21 MH, 150 rpm) [42] of about 183 t showing the enormous potential for weight and size reduction.

Industrial heat treatment

With a new type of device with superconductive magnets for industrial metal heating, a new dimension of performance in the manufacturing of profiles and pipes from nonferrous metals, such as aluminium, copper and brass, is possible [43]. The system improves the preconditions for extrusion of profiles and pipes. In this process, metal is forced with high pressure through a forming tool so that a metal bar of a clearly defined cross-section is formed. Before reshaping, the raw material, the so-called billet, has to be heated up. The superconductive magnet heater works according to the principle of a normal eddy current brake. In the device there is a superconductive magnetic coil operated with direct current, with the pressing billet being rotated in the generated field by two electro-motors, whereby the braking effect of the magnetic field has to be overcome. This results in the rotating material becoming heated. A magnet heater consumes approx. 40% less energy than an induction furnace operated with alternating current (Fig. 12) and around 60% less energy than a gas furnace of comparable power. A first commercial HTS system has been operating since 2007 in an industrial production line in Minden, Germany, without any failure.

Conclusion

Superconductivity has to be considered as one key technology of the 21st Century opening up new horizons for energy technology. Whereas today still the main commercial impact comes from LTS materials applications such as NMR or MRI systems HTS strongly ploughs into the market with first industrial applications such as magnetic heaters. Efficient power generation, distribution, transformation and conversion are major challenges which can be mastered by the broad use of HTS technology. Prototypes for most applications have been tested over the last few years successfully up to MW class systems and high voltage applications. First efforts are also being made to combine medium size systems with complete superconducting substations with cables, FCL transformers and energy storage systems all on the basis of HTS technology as at Puji substation of the Southern China Power Grid with a 35 kV superconducting cable system and a 35 kV superconducting fault current limiter (FCL) commissioned to live-grid operation in 2008 [44].

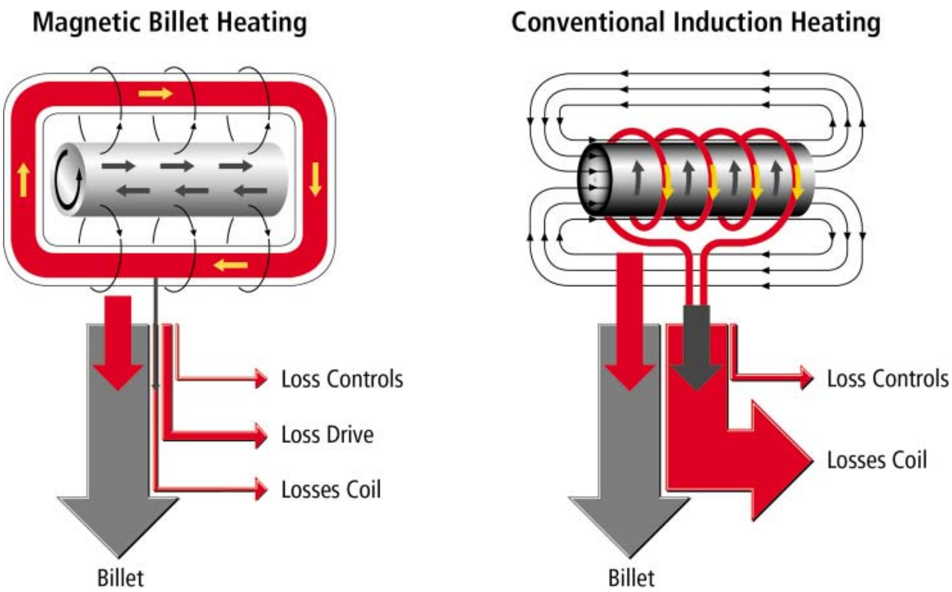

Fig. 12. Energy flows for superconductive magnet heaters and conventional induction heaters.

In order to realize these potentials the economic production of large amounts of HTS-wires and tapes is of paramount importance. Further development and significant investment is necessary in order to meet the estimated future demand of more than 500,000 km HTS wire per year. At the same time, Cryogenic technology for the reliable allocation of cooling power at operation temperature of the HTS systems between 30 and 77 K has to be further improved. In particular results on maintenance free devices have to be transferred from small coolers to higher power ratings.

In the next few years several new prototypes and commercial applications will broaden the basis for HTS technology. With the worldwide effort of industry and research groups superconductor technology will conquer an essential part of the future energy technology market.

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References

[1] H. Kamerlingh-Onnes, *Koink. Acad. Watenschappen Amsterdam*, **1911**, *18*, 168.
[2] A. Bhattacharya, *Nature*, **2010**, *463*, 605.
[3] N. Mitchell *et al.*, *IEEE Trans. Appl. Supercond.*, **2008**, *18*, 435.
[4] J. Bednorz *et al.*, Z. Phys. B, **1986**, *64*, 189.
[5] C. Politis *et al.*, Z. Phys. B, **1987**, *66*, 279.
[6] J. W. Bray, *IEEE Trans. Appl. Supercond.*, **2009**, *19(3)*, 2533.
[7] D. C. van der Laan *et al.*, *Supercond. Sci. Technol.*, **2010**, *23*, 014004.
[8] B. Holzapfel *et al.*, *Physica C*, **2000**, *341–348*, 1431.
[9] R. Woerdenweber, *Rep. Progr. Phys.*, **1995**, *62*, 187.
[10] F. Goemoery *et al.*, *Supercond. Sci Technol.*, **2007**, *20*, 271.
[11] Gutierrez *et al.*, *Nature Materials*, **2007**, *6*, 367.
[12] A. Ichinose *et al.*, *Supercond. Sci. Technol.*, **2007**, *20*, 1144.
[13] P. N. Barnes, *IEEE Trans. Appl. Supercond.*, **2005**, *15(2)*, 2827.
[14] F. A. List *et al.*, *IEEE Trans. Appl. Supercond.*, **2007**, *17(2)*, 3355.
[15] W. Goldacker *et al.*, *Supercond. Sci. Technol.*, March **2009**, *22(3),* 34003.
[16] H. Fujimoto, *IEEE Trans. Appl. Supercond.*, **2009**, *19(3)*, 2933.
[17] D. H. N. Dias *et al.*, *IEEE Trans. Appl. Supercond.*, **2009**, *19(3)*, 2120.
[18] B. Fischer *et al.*, *Inst. Phys. Conf. Ser.* **2000**, *167*, 463.
[19] N. Ayai *et al.*, *IEEE Trans. Appl. Supercond.*, **2009**, *19(3)*, 3014.
[20] H. C. Freyhardt *et al.*, *Trans. Appl. Supercond.*, **1997**, *7*, 1426.
[21] I. Van Driessche *et al.*, *Measurement Science Review*, **2005**, *5*, 19.
[22] T. Izumi *et al.*, *Physica C*, **2009**, *469*, 1322.
[23] O. Stadel *et al.*, *IEEE Trans. Appl. Supercond.*, **2007**, *19(2)*, 3483.
[24] J. R. Groves *et al.*, *IEEE Trans. Appl. Supercond.*, **2009**, *19(3)*, 3311.
[25] W. Prusseit *et al.*, *Physica C*, **2005**, *426*, 866.
[26] J. Eickemeyer *et al.*, *Supercond. Sci. Technol.*, **2001**, *14*, 152.
[27] S. Fleshler *et al.*, *Physica C*, **2009**, *469*, 1316.
[28] V. Selvamanickam, *IEEE Trans. Appl. Supercond.*, **2009**, *19(3)*, 3225.
[29] Communication at Applied Superconductivity Conference, Washington, USA, August **2010**.
[30] O. Tsukamoto, *Physica C*, **2008**, *468*, 1101.
[31] A. P. Malozemoff *et al.*, *Trans. Appl. Supercond.*, **2002**, *12(1)*, 778.
[32] W. V. Hassenzahl *et al.*, *Proceedings of the IEEE*, **2004**, *92*, 1655.
[33] R. Bach *et al.*, EW Verlag 2009, ISBN Nr. 978-3-8022-0970-3.
[34] Maguire *et al.*, *IEEE Trans. Appl. Supercond.*, **2009**, *19(3)*, 1692.
[35] H. Yumura *et al.*, *IEEE Trans. Appl. Supercond.*, **2009**, *19(3)*, 1698.
[36] J. Kellers, International water power & dam construction, **2009**, *8*, 28.
[37] A. Abrahamsen *et al.*, *IEEE Trans. Appl. Supercond.*, **2009**, *19(3)*, 1678.
[38] M. Noe *et al.*, *Supercond. Sci. Technol.*, **2007**, *20*, 15.
[39] R. Dommerque *et al.*, *Supercond. Sci. Technol.*, **2010**, *23*, 34020.
[40] F. Marconi *et al.*, *IEEE Trans. Appl. Supercond.*, ASC **2010**, submitted.
[41] W. Nick *et al.*, *J. Phys.: Conf. Ser.*, **2010**, *234*, 032040.
[42] S. S. Kalsi, *IEEE Trans. Power Engineering Society General Meeting*, **2004**, *2*, 2047.
[43] J. Kellers *et al.*, Heat processing (7) ISSUE 3 **2009**, 205
[44] Y. Xin *et al.*, *IEEE Trans. Applied Superconductivity and Electromagnetic Devices*, ASEMD **2009**, 392.