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High temperature superconductors for power applications

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Abstract

High temperature superconductivity (HTS, discovered in 1986) remains an active area of research worldwide, because its higher T_c and, thus, more economical cryogenic cooling have raised the prospects for electric power application. The discovery of MgB_2 has rekindled the search for new superconductors with higher T_c. Recently, various acceleration programs have been launched in Europe, USA and Japan. The advance in HTS conductor has enabled the demonstration of various application prototypes, including, power cables, transformers, motors, and fault current limiters. However, full commercialisation of HTS application critically relies on the realisation of HTS conductors that are reliable, robust and low cost with low AC-losses. Worldwide activities are, therefore, focused on developing processing technologies to fabricate the so-called coated conductor based on YBCO to fulfil the stringent specifications. While a high critical current density of around 5 MA/cm^2 (77 K) has been achieved, the conductor cost is currently estimated to be 10–50 times higher than what would be accepted.

Keywords: Grain boundaries; Oxide superconductors; Power application; Superconductivity

1. Introduction

The discovery of the so-called High Temperature Superconductor (HTS) in 1986 by Bednorz and Müller[1] dramatically changed the prospect of electrical power applications of superconductors, because of the significantly increased critical temperature, T_c, where the employment of a more economical cryogen, liquid nitrogen becomes possible. Between 1987 and 1993, T_c was raised from 92 K as discovered in $YBa_2Cu_3O_x$ (YBCO)[2] to over 130 K as demonstrated in $Hg_2Ba_2Ca_2Cu_3O_y$.[3] At the same time, extensive efforts have been directed to develop practical HTS conductors with high current carrying capability, first concentrating on Bi-2223 ($Bi_2Sr_2Ca_2Cu_3O_z$) and latterly on YBCO-123 based coated conductor, referred to as "2nd generation conductor".

With low losses and high current carrying capability, HTS conductors will allow electrical devices to be built with higher efficiency and higher power density. It also enables novel devices, such as Superconducting Magnetic Energy Storage (SMES), magnetic bearings, fault current limiters and switches.[4] Furthermore, HTS offers environmental advantages: oil free transformers and devices with low magnetic field leakage.

In the hope of large scale HTS application in electrical power industry, significant public and private programmes have been initiated both to accelerate conductor development and to build prototypes in the USA, Europe, and Japan. The conductors developed so far have enabled various power device prototypes, such as power cables,[5–7] transformers,[8,9] motors,[10,11] and SuperConducting Fault Current Limiters (SCFCL).[12–14] However, large scale application has been hindered by high conductor and cryogenic costs. In this paper, the complicity of conductor engineering, materials status, and their potentials of application and commercialisation will be highlighted.

2. Conductor requirement

2.1. Current carrying capability

The complexity involved in developing high quality HTS materials is equally matched by the challenge to turn them into practical conductors. High critical current density, j_c, especially high engineering critical current density, j_e (j_c averaged over the whole cross-

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section of HTS composite), are prerequisite for power application. Depending on applications, j_e should be in the range of 10^3 to 10^5 A/cm^2 at 77 K, to ensure the compact design of HTS. Independently, some devices operate with high magnetic fields, therefore, candidate HTS materials should retain high j_e in a field of 0.05 to 10 T in the temperature range of 20 to 77 K.

2.2. AC-losses

In AC-applications, HTS exhibits AC-losses, which should be minimised since they translate into cooling costs during normal operation. Such losses are proportional to the square of the conductor dimension perpendicular to the surrounding magnetic field, i.e. the thickness for a planar conductor. Multifilament Bi-2223/Ag composites with close twist pitch have much reduced AC-losses, but, unfortunately, still do not qualify for AC-wire (<0.25 mW/Am). Another attempt was to insulate the Bi-2223 individual filaments from each other with an oxide barrier.[15] To reduce the anisotropy of Bi-2223 wire in magnetic field, round and square wire with reasonable AC-losses (0.53 mW/Am) have been demonstrated.[16] Thanks to its small thickness, coated conductor based on YBCO thin film is estimated to exhibit similar AC-losses to the multifilament Bi-2223/Ag composite. However, thin film based AC-wire might have to be developed if AC-losses are to be further reduced. For certain applications, e.g. FCL, effective reduction in AC-losses can be made possible through conductor geometry optimisation, leading to partial magnetic field cancellation.[17]

2.3. Electrical stability

Because of its strong non-linearity, HTS material is prone to the so-called "hot-spots" which could lead to burn-through of the material when overloaded.[13] Improved uniformity in j_c and I_c will minimise such effect, but total elimination requires good thermal stabilisation of the conductor. This can be achieved either through thermal management (e.g. by applying a heat sink or good thermal conductor), through electrical bypass to shunt excessive current from HTS (to reduce heating) or through the combination of both. Good electrical contact should be provided between the HTS and bypass at every point along their interface, so that the bypass can be effective.

2.4. Mechanical reinforcement

HTS are brittle ceramics with flexural strength around 50 MPa, rendering mechanical reinforcement necessary so that damage to the HTS can be avoided during device fabrication and operation (due to magnetic forces and thermo-mechanic stresses). Preferably it should be so reinforced that the HTS is pre-stressed under compression. High strength Bi-2223 multifilament composite with a strength of over 250 MPa and a minimum bending diameter of 5 cm has been demonstrated through lamination of steel bands on both sides of HTS.[18]

Reinforcement can also be achieved through alloy and hardening in the Ag sheets. A similar approach can be applied to YBCO coated conductor, where the mechanical properties of the metallic template substrate are an important parameter. Also, steel and fibre reinforced plastic composite have been successfully employed to strengthen Bi-2212 sheets, which are being developed for FCL application.[19]

2.5. Conductor cost

HTS conductors must offer a competitive advantage over conventional Cu conductor typically measured by the ratio of price over performance: 10–25 USD/kAm for Cu wires and 5–6 USD/kAm for $NbTi_3$ used for high field magnets. The present state of the art conductor (from ASC) based on Bi-2223 is estimated at 200 USD/kAm and it is further predicted that 50 USD/kAm would be reachable when mass produced, where the limitation factor seems to be the cost of noble Ag which is used as the sheath.[18] YBCO coated conductor appears more attractive because the raw materials are of relatively low cost. Although the present status of the complicated fabrication technology does not permit a concrete estimation, it is believed that a target of 5 USD/kAm would be possible if some of the fabrication routes being investigated finally evolve to mature technology.[18] Fig. 1 is a schematic drawing, showing what could be a fully engineered coated conductor, based on the above considerations.

3. HTS materials engineering for higher j_c

Both Bi- and Y-based oxide superconductors are of layered perovskite structure and exhibit highly anisotropic

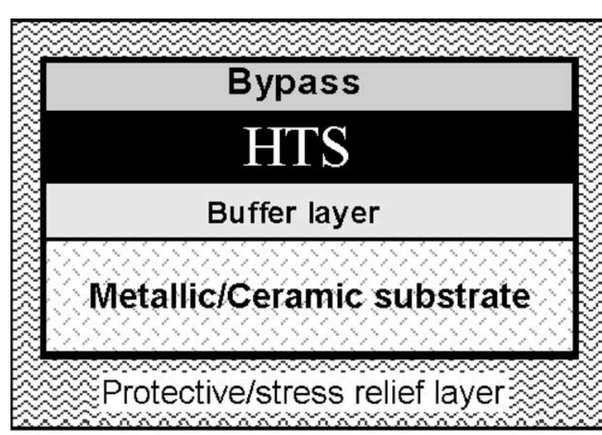

Fig. 1. Schematic cross-section of a fully engineered HTS conductor.

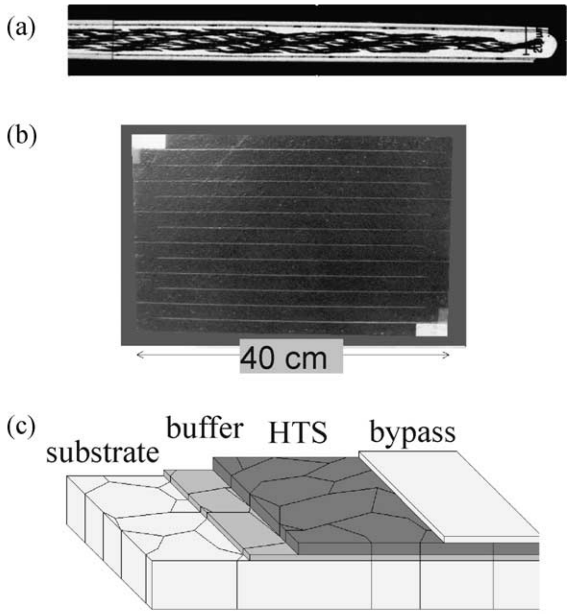

Fig. 2. HTS conductors under development for power applications (a) cross sectional view of Bi-2223, ASC, (b) a 5 m long meander of made of Bi-2212 ($Bi_2Sr_2CaCu_2O_{8+\delta}$) sheet, (c) schematic of YBCO coated conductor.

electromagnetic properties, with $j_{c\_ab} >> j_{c\_c}$. Furthermore, polycrystalline HTS, especially YBCO-123 show granularity or weak link, i.e. $j_{c\_intergrain} << j_{c\_intragrain}$. The combination of the above two factors has been a serious obstacle to the fabrication of high quality long wires for electric power application. Worldwide efforts have, therefore, been to develop process routes to HTS that is textured with extended overlapping of grains so that a global current could be efficiently transferred from one grain to the next. Fig. 2 shows HTS conductors that have been developed with the potential to become practical conductors.

3.1. Bi-2223 wire—j_c limit reached?

Texture in Bi-2223 (and Bi-2212) is typically achieved by powder in tube (PIT)[20] (e.g. see Fig. 3). j_c as high as 75 kA/cm^2 (77 K, 0T) has been achieved in a small sample with up to 50 kA/cm^2 ($I_c = 150$ A) reported for longer length conductor.[21,22] Such a value is still low compared to the 1 MA/cm^2 reported for Bi-2223 thin film.[23] Recent magneto-optical imaging reveals areas with $j_c = 180$ kA/cm^2 located throughout the Bi-2223 tape,[24] raising the hope that higher j_c could be achieved through better control of microstructure.

3.2. Bi-2212 wire and bulk

Besides PIT method, thin tape technology is also suited for depositing highly textured Bi-2212 tapes with thickness of less than 30 μm.[25] For bulk conductor, a so-called composite reaction texture process has been developed for texturing bulk Bi-2212 through the incorporation of an aligned MgO fibre mesh.[26–28] Fig. 4 shows the partial melt process of Bi-2212 in the presence of a MgO fibre network. By 895 °C in 1 atm pure oxygen, Bi-2212 melts incongruently to yield a non-stoichiometric Bi, Cu rich melt and two second solid phases, $(Sr,Ca)_{14}Cu_{24}O_x$ (14:24 phase) and $Bi_9Sr_{11}Ca_5O_y$ (9:11:5 phase) respectively. On cooling down, the microstructure remains relatively unchanged until 886 °C. By further cooling to 885 °C at 6 °C/h, Bi-2212 *a–b* oriented platelets have visibly crystallised predominately on MgO fibres, growing in the direction of the fibre plane. The growth rate of the platelets is estimated to be on the order of 10^{-6}cm/s and that in the *c* direction being some 60 times lower. The presence of MgO fibre network, while acting as nucleation sites for Bi-2212, hinder the growth of "out-of-plane" Bi-2212

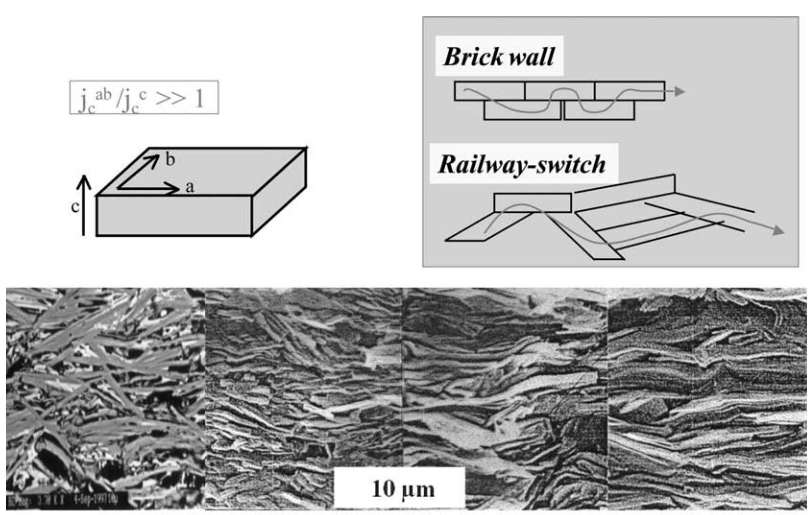

Fig. 3. Texturing of highly anisotropic Bi based HTS, (a) schematic anisotropic behaviour, (b) proposed super-current paths and (c) progressive texturing of Bi-2223 with PIT.

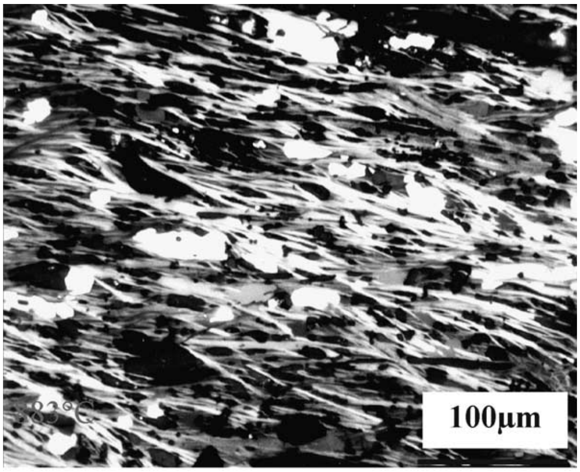

Fig. 4. Crystallisation of Bi-2212 from partial melt with plate-like crystals forming parallel to the incorporated MgO fibre mesh by slow cooling to 883 °C.

crystals, resulting in a highly textured microstructure with an *a–b* plane parallel to the MgO fibre plane, as already seen at 883 °C. Further annealing at 850 °C and lower temperatures result in highly textured Bi-2212/MgO composite with j_c well over 4000 A/cm^2 at 77 K.

3.3. YBCO coated conductor

YBCO coated conductor represents the most promising HTS candidate because of the demonstrated superior properties (i.e. high j_c, high current carrying capability and high magnetic field tolerance) and the expected low cost potential.[29–34] However, high j_c of YBCO material critically relies on a microstructure that is highly bi-axially (*a–b*) textured. Such a microstructure with the angle grain boundary <7° is typically realised through the epitaxial growth of HTS from a well textured template substrate. By carefully controlling the epitaxial deposition process, a j_c of over 5 MA/cm^2 at 77 K has been demonstrated,[35] compared with <1000 A/cm^2 for the non-textured polycrystalline YBCO. Work has concentrated on two areas, i.e. process of textured template and deposition of HTS layer respectively. The former has evolved into four branches, IBAD (Ion-Beam Assisted Deposition), RABiTS (Rolling-Assisted Biaxially Textured Substrate), ISD (Inclined Substrate Deposition), and ITEX (Ion Texturing). IBAD, pioneered by Los Alamos National Lab. (LANL) ,[31,32] utilises a second ion beam to mill away out-of-plane growth of Yttria-stabilised zirconia (YSZ), resulting in a highly textured YSZ template layer on substrate. After depositing a buffer layer (typically CeO_2) to the best lattice match, high quality YBCO and, subsequently, a shunt can be deposited (see Fig. 5). More recently, a high quality MgO template layer has been obtained by IBAD and, most importantly, with high deposition speed.[31] RABiTS developed at Oak Ridge National Lab.

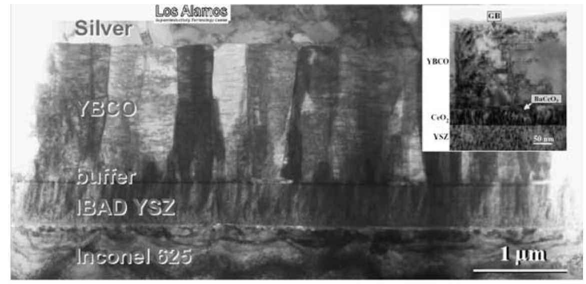

Fig. 5. A typical microstructure of IBAD derived YBCO coated conductor (insert shows the structure of the buffer layer where CeO_2, epitaxially grown on YSZ provides the best lattice match for YBCO).

(ORNL),[33] is based on cold rolling texture of Ni-based alloys. It appears to be a readily up-scalable process with over 100 m long textured Ni reported. Nevertheless, the difficulty with the deposition of a buffer layer compatible with HTS cannot be underestimated. It has been realised that sulfurization of the Ni alloy substrate enhances the epitaxy of the buffer layer.[36]

For the deposition of HTS layer, various processes are still serious contenders, e.g. PLD (Pulsed Laser Deposition),[34,37] MOCVD (Metal-Organic Chemical Vapor Deposition),[35] Electron-Beam BaF_2 Deposition, MOD (Metal-Organic Deposition, chemically derived or sol-gel)[18,38] and LPE (Liquid Phase Epitaxy).[39–41] PLD is readily applicable to produce thin film with multiple MA/cm^2 j_c, but it is a vacuum process and is considered to be less likely for up-scaling. Nevertheless, the combination of IBAD and PLD have produced various world records, e.g. 1 m long wire with I_c =135 A/cm_width (75 K) by LANL, 10 m long wire with I_c=67 A (j_c=1.73 MA/cm^2) from University of Göttingen[34] by depositing YBCO on an IBAD steel substrate with a modified high rate PLD, and 30 m long wire reported by Fujikura with I_c=40 A. The high rate PLD has been estimated to be potentially capable of 40 m/h of 4 mm wide wire. Presently, substantial interest is attracted to develop non-vacuum processes, mainly MOD,[38] which has a higher potential for high rate and low cost. A continuous deposition (reel-to-reel) process has been reported to produce a 1.2 m YBCO wire with I_c=120 A (j_c=1 MA/cm^2, 77 K), using a MOD process to deposit YBCO on RABiTS substrate.[38] Liquid Phase Epitaxy is another non-vacuum and fast (1 µm/min) deposition process, which can be of low cost.[39–41] By carefully controlling the working point (Fig. 6) REBCO will epitaxially grow on textured substrate. Critical to this process is the liquid flux composition and viscosity, chemical compatibility of the substrate (and buffer and seed layer), and the flux, and the selection of the working point. A 0.1 m continuously deposited $ReBa_2Cu_3O_x$ has been demonstrated on NiFe substrate tape with LPE.[41] LPE has also been applied to deposit both a conductive buffer layer and YBCO on substrate with a j_c of 0.6 MA/cm^2 reported in small samples.[40]

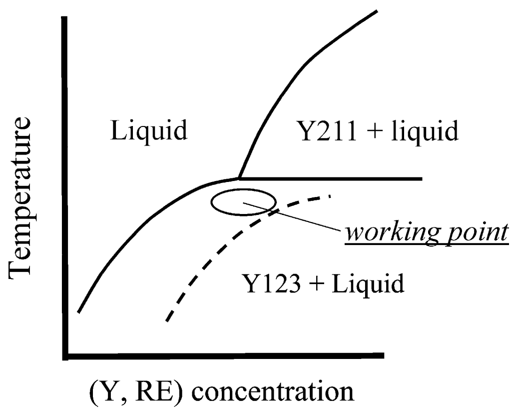

Fig. 6. Schematic phase diagram of (Y, RE)-123, showing the working point for LPE process.

Recent investigation with magneto-optical imaging[42] on the current percolation in HTS conductors indicate that the local fraction of current carrying section is significantly smaller than unity even in the *a–b* textured YBCO conductor. This further underpins the importance of grain boundary engineering. To challenge the weak linked grain boundary associated with YBCO, scientists at University of Ausburg have shown that the j_c across two grains misaligned by 24° can be dramatically enhanced to a level comparable to intragranular j_c by carefully doping with Ca.[43] The authors have further proposed that by increasing the aspect ratio of the YBCO grains to around 50 (typically 1 for RABiTS wire) and achieving a moderate texture of 10°, a $j_{c\_intergrain}$ of 4 MA/cm^2 could be reached.[44]

3.4. MgB_2

MgB_2, discovered in 2000,[45] rekindled considerable interest in HTS. High j_cs have been reported in bulk samples.[46,47] Because of its intermediate T_c (39 K), weak link free grain boundaries,[48] and low materials cost, MgB_2 clearly has high potential for application at the 20–30 K temperature range, e.g. MRI. Standard PIT process has yielded MgB_2 wire with high j_c of 1 MA/cm^2 at 4.2 K and 10 kA/cm^2 at 4.2 K and 6.5 T.[46] Amazingly, rolled Fe sheathed MgB_2 wire already possesses reasonable j_c without heat treatment. Current efforts are focused on the improvement of irreversibility line and fabrication of multifilament wire.

4. Applications

HTS represents a new class of conductor with unique properties, which would not only allow electric power devices to be more compact but also enable new applications, as shown in Table 1. Not included in the table are current leads and magnets.

4.1. Cables

HTS cables are expected to have high current carrying capability, which could be interesting for retrofit of existing underground cables to increase transmission capacity in a same duct. With HTS cable, lower losses could be expected and, thus, design with lower voltage levels possible. However, the AC-losses of available conductors are still too high, dielectric insulation at cryogenic temperatures (for designs with cold insulation) needs further understanding, and cable accessories (e.g. joints and terminations,) are still in the early stage of development. Above all, cooling systems with a high level of reliability and safety requiring a low number of cooling stations are yet to be demonstrated.

Various cable prototypes have been demonstrated, all exclusively based on Ag-sheathed Bi-2223. Among them, Southwire cable (Table 2) was energized during summer 2000 and since mid 2001, the cable is in "unmanned" operation. Since energizing the cable has been operating for 9500 h. The Detroit Cable from Pirelli is in its final phase before energization. So far, the cooling system represents a serious challenge.

4.2. Transformer

The major attraction for HTS Transformer lies in the potential for reduction (compared to conventional) in losses (<30%), volume (~50%), and weight (~70%). Furthermore, it offers over-loadability without accelerated aging and possible integration of a fault current limitation function. Presently, the main obstacle remains the strong j_c reduction in magnetic fields and high AC-losses at coil ends. The feasibility of such HTS transformers has been demonstrated by ABB's 3-phase 630 kVA (20 kV/0.42 kV) prototype, which was operated in an electric grid for 1 year.[8] In a pre-study on a 10 MVA prototype, it was concluded that fault current

Table 1
Main driving forces for HTS applications in electrical power

Benefits	Property	Application	Conductor
Higher efficiency	$R=0$	Motors, Generators, Cables, Transformers	Wire
Higher power density	j_c	Motors, Generators, Cables, Transformers	Wire
Novel opportunities	$R=0$	SMES	Wire
	$dm/dB<0$	Magnetic bearings	Bulk
	Transition	Current limiters, Switches	Wire & sheet

Table 2
Status of HTS prototype development worldwide

Application	HTS (supplier)	Company	Prototype development
Current Limiter	Bi2212-bulk (ABB)	ABB	6.4 MVA, tested
	YBCO-film (Siemens)	Siemens	1.2 MVA, tested
Cable	Bi2223-PIT (ASC)	Pirelli	24 kV–2.4 kA, 120 m
	Bi2223-PIT (SEI)	SEI/TEPCO	66 kV–1 kA 100 m, tested
	Bi2223-PIT (IGC)	Southwire	12.5 kV–1.25 kA, 33 m, tested
	Bi2223-PIT (ASC)	NKT	36 kV–2 kA, 30 m, tested
Transformer	Bi2223-PIT (ASC)	ABB	0.63 MVA, tested
	Bi2223-PIT (VAC)	Siemens	1 MVA (traction), tested
Motor	Bi2223-PIT (ASC)	ASC	5000 PS, tested
Flywheel	YBCO-bulk	Mitsubishi	1.4 kWh, tested

limitation integration is feasible, even with fast recovery to operation. Waukesha, together with IGC (Intermagnetics General Corp.) as wire supplier and Oak Ridge Nation Lab has tested a 1-phase 1 MVA (13.8/6.9 kV) device, with a next prototype (5–10 MVA) under development. Siemens has also completed a 1 MVA model for traction applications, which is cooled to 66 K to enhance the wire performance[9]

4.3. Motor

The potential benefits of a HTS motor are similar to that of HTS transformer. Of interest are synchronous machines with a superconducting rotor consisting of Bi–HTS based windings. An all-superconducting machine, where the armature winding is also superconducting, is not viable with the current Bi-based tapes because of the high AC-losses (caused by AC-currents in the armature winding). The main challenges are the low j_c of Bi-wires in magnetic fields and high conductor costs. A 5000 hp synchronous machine (6.6 kV, 1800 rpm, volume 7.5 m^3) has been reported with an efficiency of 97.2%.[10] Siemens has also tested a 400 kW prototype.[11]

4.4. Fault Current Limiter

A Fault Current Limiter (FCL) (see Fig. 7) represents a new class of electrical equipment which could enable delayed investment and a novel design of electric grids. Most HTS FCL concepts exploit the sharp transition of superconductors from zero resistance, at normal currents, to a finite resistance at higher current densities.[49] During normal operation, SCFCL operates with negligible impedance, and, in the event of fault current, SCFCL passively performs instantaneous limitation. It is an ideal FCL and is extremely suited for grids with high prospective fault currents. With SCFCL, it is possible to design grids with low impedance and improved power quality. The feasibility was demonstrated in a 1 year endurance test in a hydro power plant of a 3-phase 1.2 MVA limiter from ABB.[12] Based on YBCO thin film, Siemens has also built and tested a 3-phase 1.2 MVA (7.2 kV /100 A) model.[14]

In 2000, ABB tested a one phase 6.4 MVA prototype based on stacks of Bi-2212 meander composites.[19] 5 m long meanders are structured from Bi-2212 sheets (0.1 m^2) fabricated with ABB proprietary technology and are reinforced with steel bypasses and reinforced plastic composite to avoid ‘‘hot-spots’’ and enhance mechanical stability. At 8 kV_{rms}, the SCFCL curbed a prospective fault of 20 kA_{rms} to a peak value of 10.6 kA (9.5 I_N) at the first peak, and, finally, down to a value of 2.7 kA_{rms} (3.1 I_N) after 100 ms as a result of the warming up of the SCFCL, at which point the current is interrupted by a breaker.

5. Application prospects

A recent report produced for Oak Ridge National Lab by B. Lawrence et al. (‘‘High Temperature Superconductivity: The Products and Benefits’’, July 2000) projects tremendous market penetration and corresponding annual savings due to HTS devices ($500 million by 2010 and > $10 billion by 2020). The study expects the highest market to be for HTS motors (market penetration 1% in 2006 rising to 79% in 2020).

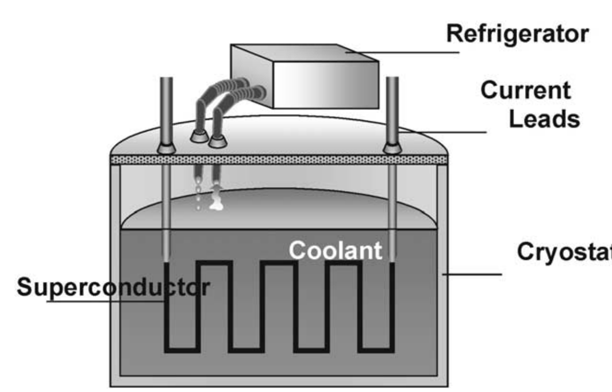

Fig. 7. Schematic drawing of a resistive superconducting fault current limiter with closed cooling cycle.

For other applications, the projections for the market penetration in 2020 are: transformers (76%), generators (50%), and underground power cables (80%).

However, there are serious hurdles to be overcome: first, the cooling system, and secondly, the performance/cost ratio of the HTS conductor. A general drawback for all applications is the need for an expensive and maintenance intense cooling system, especially in a utility environment. More economical cooling systems, e.g. Pulse Tube are being developed[50] but it will take time. Bi-2223 represents the "established" HTS conductor, but its potential as a practical conductor is seriously undermined by the price of the Ag sheath material. For widespread application, it appears that YBCO coated conductor is the only obvious candidate. However, a low cost production process has to be fully established first.

6. Conclusion

In pursuit of an ideal and practical conductor for electric power application, HTS activity goes on. Conductor technology for multi-filamentary Bi-2223 wire is, by far, the most established technology and the majority of prototypes demonstrated are based on Bi-2223 wires. However, the limited potential for low cost production and still high AC-losses are the major obstacles for wide application.

Bi-2212 based bulk conductor is potentially low cost, but, its application is limited due to it mechanical inflexibility.

Coated conductors based on YBCO-123 represent the strongest candidate because of its potential for low cost. Intense work is being directed to develop low cost up-scalable processes, with the focus on obtaining a well textured microstructure and enhancing the current carrying capability across grain boundaries. YBCO AC-conductors and robust electric bypasses have to be developed.

MgB_2 could become a really low cost conductor, but only suited for a temperature range of 20–30 K.

The high cooling cost (initial investment and maintenance) and high cost of the available conductor remain the biggest challenges to power applications for HTS. Although potentially a multi-billion dollar market, application will start slowly in niche markets to gain experience and customer acceptance, while conductor and cooling technologies further develop. A reliable cost competitive cooling system and a low cost conductor are prerequisite for a large scale application, which will still take many years to come.

Acknowledgements

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