SUPERCONDUCTING TRANSFORMERS

In an electrical power system, power is generated far away from the consuming areas. The electric power is transmitted from generating locations to consuming locations through transmission lines. A high voltage is desirable for transmitting large amounts of power in order to minimize the current and the associated I^2R losses, and reduce the amount of conductor used in transmission lines. A much lower voltage, on the other hand, is required for distribution, for various reasons connected with safety and convenience. The transformer makes the reduction in voltage easy and economically possible. Generally, electricity is transformed three or four times between the location of generation and the location of consumption making transformers one of the basic elements of an electric power system.

The physical basis of the transformer is mutual induction between two circuits linked by a common magnetic field, as shown in Fig. 1. The power transformer transfers electrical energy from one circuit to another, via the medium of the pulsating mutual magnetic field. Magnetic iron enhances the flux linkage between the circuits. The transformer coils are therefore made to embrace an iron core, which serves as a conduit for the mutual magnetic flux, ensuring that the flux links each coil fairly completely. The use of an iron core permits greater freedom in shape and relative position of the primary and secondary coils (Fig. 2), since the majority of the mutual flux is conveyed by the core regardless of the relative positions of the two sets of coils—primary and secondary.

Since transformers are employed extensively in a power system, their efficiency and losses are considered a serious issue. The transformer design selection is normally made on the basis of its lifetime cost which consists of the initial cost plus the cost of operating it over its lifetime. The lifetime cost of even a small loss could be significant. In addition, most larger transformers employ oil for cooling the windings and the iron core. Although the oil is an excellent cooling medium and is a good high voltage insulator, it has attracted the ire of environmentalists and fire departments due to the possibility of oil spills and fire hazards. Moreover, larger units are too heavy and bulky for normal transportation channels. Space in an urban environment is quite valuable. A more compact, light-weight transformer could more easily be sited, possibly even above the ground floor or basement levels. This could be a significant advantage. Some utilities have indicated that they might be willing to pay a premium for such an advantage. These difficulties have inspired designers and users to look for alternative transformer solutions. Superconducting transformers appear to offer a solution to most of these problems.

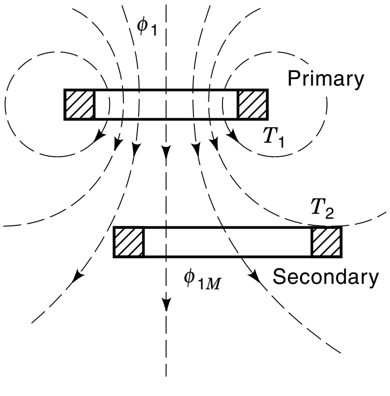

Figure 1. Flux linkage between primary and secondary in air.

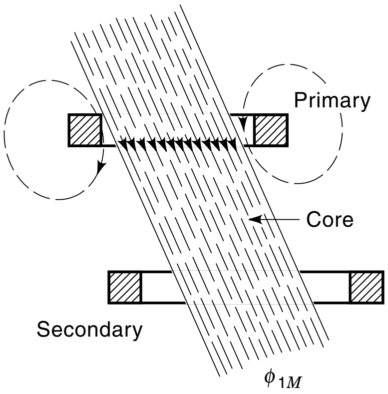

Figure 2. Flux linkage between primary and secondary with iron core.

A superconductor only operates within a space bounded by three parameters: current density in the superconductor, magnetic field experienced by the superconductor, and its operating temperature. The maximum operating current of a given superconducting wire is a function of these parameters. If any of these parameters is violated, the superconducting wire loses its superconducting property and becomes resistive. Once in the resistive state, it generates joule heating. This heating must be limited to a safe value in order to prevent permanent damage to the windings. The circuit breaker feeding the transformer could be used to disconnect it if the winding temperature exceeds a given upper limit. Since superconductors can sustain large current densities with potentially low losses, a superconducting transformer is expected to be smaller, lighter, and more efficient. In addition, since the superconducting transformer uses cryogenic liquids as dielectric and coolant, it is also free of environmentally unacceptable oil. During the eighties, several groups designed, built, and tested small transformers employing low temperature superconductors (LTS) Niobium–Titanium (NbTi) superconducting windings (1–6) cooled with liquid helium to around 4 K. Several problems were observed:

- First, the superconductor must operate in the presence of fluctuating ac currents in a moderately high magnetic field resulting in decreased stability and increased ac losses.

- Second, under system fault conditions, if the critical current of the conductor is exceeded, recovery to the superconducting state is too slow to allow automatic circuit reclosure.
- Third, the need to cool with liquid helium reduces economic benefits of such a device.

The discovery of high temperature superconductors (HTS) has revived interest in superconducting transformers. Presently, attempts are being made to design, build, and test transformers with HTS windings cooled with liquid nitrogen at 77 K. These HTS transformers are less likely to have the problems associated with NbTi transformers. For example, the use of HTS material greatly improves stability; the transformer could be designed to prevent quenching (i.e., transitioning to the normal state), and the consequences of ac losses could be potentially overcome by developing low-ac-loss HTS conductors and operating it at 77 K. References 7–9 have summarized the evolution of the superconducting transformers. Recently two HTS prototype transformers have been tested—a 630 kVA, three-phase transformer by ABB (10) and a 500 kVA, one-phase transformer by Kyushu University (11).

This article discusses potential system benefits associated with superconducting transformers, and reviews and summarizes the design requirements for such a device. It also compares and contrasts the requirements for transformers utilizing LTS and HTS conductors.

SUPERCONDUCTING TRANSFORMER CONFIGURATION

A superconducting transformer operates using the same principles and constituent parts as found in a conventional transformer. Both employ an iron core to contain magnetic flux, and primary and secondary windings to exchange power. However, the construction of the two types of transformers is quite different. For example, in conventional transformers primary and secondary coils are directly wound on the iron core and both iron core and coil assemblies are immersed in a tank filled with oil that cools both the iron core and the coils. On the other hand, in superconducting transformers, the iron core is usually maintained at room-temperature while the superconducting coils operate at cryogenic temperatures. The decision to maintain the iron core at room temperature is dictated by the fact that the iron core losses, due to hysteresis and eddy-currents, are substantial (almost 1 watt per pound) and they go up when the iron core is operated at cryogenic temperatures (12). The iron core permeability also goes down at low temperature which means more iron core is required to carry the same flux at low temperature than at room-temperature. The core losses would represent a major load on the refrigerator if the iron core were operated at cryogenic temperature. On the other hand, the superconducting windings must be cooled to cryogenic temperatures (between 4.5 K and 77 K) which necessitates that these windings be enclosed in containers which could hold vacuum or cryogen or both. These containers surround the iron core limbs and take the shape of hollow donuts. Since they surround the iron core, they must be constructed from nonmetallic material lest they form a closed circuit around the iron core and thus form a shorted secondary for the transformer, making the transformer unworkable. It is possible to employ metallic containers but a dielectric break must be included in the circumferencial direction to prevent flow of current in the container walls. The dielectric break makes these metallic cryogen containers more expensive and less reliable. The superconducting windings must be cooled with suitable cryogen (liquid helium for NbTi windings, liquid nitrogen for HTS BiPbSrCaCuO-2223 (BSCCO-2223) windings, or an intermediate temperature for Nb3Sn or BSCCO-2212 windings). Reference 13 describes the status of the HTS conductor technology and (14) discusses coils made from BSCCO-2212 material. Since these containers hold windings at low temperatures, their walls must be thermally insulating. For low temperature operation at around 4 K, a double wall construction is employed with multi-layer-insulation (MLI) insulation in the vacuum space between the walls. Additionally, an intermediate temperature (77 K) shield is also inserted between warm and cold walls of the cryostat. This makes the container design complex and expensive. On the other hand, if the windings operate at 77 K then single wall construction could be used for these containers. This makes design and construction simpler and the cost is substantially lower as compared to those of the low temperature coils. The cost of refrigerator (both capital and lifetime) is also much lower for devices operating at 20 K to 77 K than those operating at 4 K.

TRANSFORMER DESIGN AND ANALYSIS

The transformer design is obtained with an optimization process which involves varying several significant parameters which are interrelated in complex ways. A transformer is sized on the basis of its power rating, voltage, number of phases, frequency, and short-circuit reactance. It is also necessary to pay close attention to transformer type, service conditions, cost of losses, and the relative costs of conductor, iron, insulation, labor, machinery, and configuration. All these factors are considered when designing a superconducting as well as normal transformer.

Design Issues

It is possible in principle to construct a superconducting transformer without an iron core. Such transformers are characterized by a larger reduction in losses, size, and weight than those employing iron core but they require much larger excitation current (15–16). On the other hand, an iron core offers the following benefits:

- The core contains the mutual flux between the windings, and thus, reduces stray field which has adverse impacts on people and other equipment in the vicinity of the transformer
- The magnetic field experienced by the superconducting windings is reduced, thus reducing the amount of superconductor required
- The ac losses in the windings are reduced, which reduces the size of the refrigeration system

Since losses in the iron core are large, it is normally preferable to keep the iron core at room-temperature. This requirement to operate the iron core at room-temperature forces superconducting transformer configurations which differ from those of conventional transformers.

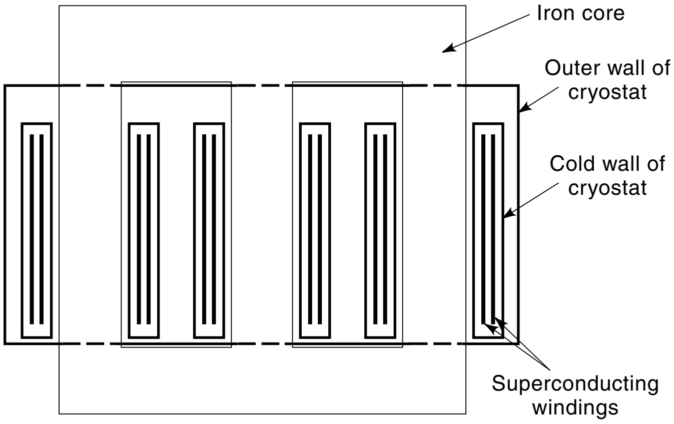

Figure 3. HTS transformer configuration.

A generic three-phase superconducting transformer is shown in Fig. 3. It has a set of concentric primary and secondary windings surrounding each leg of a three-leg transformer core. Since the windings operate at cryogenic temperatures, primary/secondary winding pairs are enclosed in individual cold containers (identified as cold wall of cryostat in Fig. 3). This cold wall must be made of nonconductive materials in order to prevent a shorted turn. A common warm wall encloses all three cold walls—this wall could be metallic.

Conductor Concepts

Superconductors being considered for transformers could be divided into two broad categories on the basis of their operating temperatures. LTS operate at liquid helium temperature (~4.2 K) and HTS operate at temperatures ranging from 20 K to 77 K (the temperature of liquid nitrogen). Two LTS conductor options are available; Niobium–Titanium (NbTi) and Niobium–Tin (NB_3Sn). Likewise, two HTS conductor choices are available in long lengths; BSCCO-2212 for operation at ~20 K to 30 K, and BSCCO-2223 for operation ~50 K to 77 K. This section discusses characteristics of these conductors and their pros and cons for application in a superconducting transformer.

Niobium-Titanium Conductors. Superconducting NbTi wires for 50 Hz to 60 Hz applications require very small diameters in order to minimize ac losses and improve intrinsic stability (17–19). These NbTi wires are characterized by very fine filaments (0.1 μm or less), high resistance CuNi matrix, and small wire diameter (~0.2 mm). A practical size conductor, capable of carrying hundreds of amperes, consists of many such wires.

Primary and secondary coils made with this conductor are generally housed in a common container filled with liquid helium. Since it is expensive to remove heat generated at liquid helium temperature (4 K) with a refrigerator, designs are always optimized to minimize heat generated at low temperatures. Since the specific heat of metals is very low at the liquid helium temperatures, a small heat input forces the conductor into its normal conducting state. Protection against the consequences of an unexpected quench is one of the most significant challenges for superconducting coils—the intensive and localized Joule heating can produce catastrophic damage (20). Moreover, the protection of ac windings is more critical than of dc windings, because of high matrix resistivity—it is not permissible for wire to carry its nominal current longer than a few milliseconds, otherwise permanent damage could occur. Thus, transformers employing NbTi windings must be designed carefully to avoid these problems. Similar design approaches must be used for Nb_3Sn conductors. These conductors have higher critical temperature than NbTi and it is therefore possible to operate them at higher temperatures (~10 K) as compared to 4 K for NbTi. Nevertheless, most problems associated with low temperature persist. The lack of economic feasibility and high cost of refrigeration stopped LTS transformer activities.

BSCCO Conductors. Although BSCCO conductors have a potential of operating at ~77 K and being cooled with environmentally friendly liquid nitrogen, no suitable design of an ac conductor exists at this time. The major problem is posed by high aspect ratios (1 : 10) of such conductors as shown in Fig. 4. Since hysteresis losses are directly proportional to filament diameter (17), losses induced by magnetic field perpendicular to the wide surface of the conductor are high and they pose coil cooling and overall transformer efficiency challenges. Furthermore, since a single strand of BSCCO wire could only carry limited current, it is necessary to wind several strands in parallel. If these strands are not transposed they can cause significant coupling losses. Iwakuma (21) has proposed a transposition scheme to minimize these coupling losses. Losses due to field parallel to the wide face of the conductor are likely to become acceptable.

The perpendicular field losses only occur in the end regions (10% of the coil axial length) of coils and with clever winding schemes, it might be possible to minimize these losses. Research is continuing at ASC and other places around the world but no one has yet published a credible conductor design. Until a credible HTS conductor is developed for ac application, the HTS transformer will remain elusive.

Since the specific heat of metals is high at higher temperatures, it is possible to absorb larger amount of heat at the higher operating temperatures of HTS for a modest temperature rise of the conductor. Nevertheless, ac losses in presently available conductors are still unacceptable due to cost/efficiency considerations. ABB has made a 630 kVA transformer (10,22) which employed BSCCO-2223 wire from ASC but its ac losses are unacceptably high for commercial deployment. On the other hand, this device has demonstrated that if a suitable HTS wire was available then it would be possible to

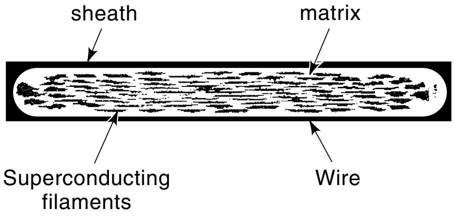

Figure 4. Highly aspected HTS conductor.

Figure 5. Model coil made by ABB, from wire provided by American Superconductor Corporation, for the 630 kVA transformer project in Geneva, Switzerland.

construct a practical transformer. Figure 5 (taken from Ref. 22) shows a Model coil made by ABB, from wire provided by American Superconductor Corporation, for the 630-kVA transformer project in Geneva, Switzerland.

Coated conductors employing YBCO films on a substrate are emerging as an alternative to BSCCO conductors. High critical current in HTS films deposited on crystellographically oriented substrates has been demonstrated recently by Los Alamos National Laboratory (LANL) (23) and independently by Oak Ridge National Laboratory (ORNL). Joint industry-laboratory programs are underway to scale up this coated conductor technology. A number of technological problems must be solved before a practical conductor could emerge. Production conductors are expected by a 2002 time frame.

The coated conductor promises significantly higher performance than the BSCCO, with projected cost/performance below the much discussed \$10/kA-m commercialization benchmark. Overall strand current densities of up to 50,000 A/cm^2 are expected to be achievable. In addition, the coated conductor films may ultimately be engineered to optimize filament dimensions and to eliminate filament coupling through the careful selection of layers within the conductor architecture.

Ac Losses

Losses in a superconducting coil are quite small under dc operation. However, these losses become significant if the coil current is ramped rapidly or if it carries ac as in a transformer. The ac losses are generally quite small, but the refrigeration penalty amplifies their effect. When the applied field is low, superconductor tends to screen penetration of field into interior of the conductor. However, higher fields fully penetrate a conductor. Under such a condition, hysteresis loss (watt) is given by the following formula (17,24) for decoupled filaments:

$$Q_h = \Delta B J_c a f$$

where

ΔB = field variation (peak-to-peak) (T)
J_c = critical current density of superconducting filament (A/m^2)
a = radius of filament (m)
f = frequency (Hz)

The largest loss component is usually hysteresis loss in the superconductor filaments. One way to reduce these losses is to make the superconducting filament diameter (2 a) as small as possible.

Another component of ac losses is due to coupling between filaments. This coupling takes place when the electric field between adjacent filaments is sufficiently large to cause a current flow between filaments through the matrix. Filaments are tightly twisted in a helical fashion and are surrounded by high resistivity matrix in order to reduce these coupling currents and the associated losses. The coupling losses are given by the following equations taken from (25):

$$P_c = \frac{1}{144}\cdot\left(\frac{c}{d}\right)^2\cdot\left(\frac{l_t^2\cdot B^2}{\rho_e}\right) \tag{1}$$

$$P_c = \frac{1}{16}\cdot\left(\frac{c}{d}\right)^2\cdot\left(\frac{l_t^2\cdot B^2}{\rho_e}\right) \tag{2}$$

where

P_c = loss per unit volume of the conductor (W/m^3)
c and d = conductor cross-sectional dimensions (width and thickness) (m)
l_t = twist pitch length (m)
B = rate of change of magnetic field (T/s)
ρ_e = matrix resistivity ($\mu\Omega$-m)

Equation (1) is used when the field is parallel to the wider face Eq. 2 of the conductor $d \ll c$. Eq. (2) is for the case when $c \gg d$.

It has been shown (26,27) that NbTi coils operating at liquid helium temperature must have a filament diameter on the order of 0.1 μm or less to make these coupling losses comparable to the losses in copper windings of a conventional transformer.

Both of these ac loss phenomena also apply to HTS conductors. HTS conductors are currently made in highly aspected tape shapes (1 : 10) as shown in Fig. 4. The hysteresis losses due to magnetic field parallel to the broad face of the conductor are acceptable since the dimension transverse to the field is small, but losses due to magnetic field perpendicular to the broad face of the conductor are excessively large. Although several industrial groups are attacking this problem, no method has yet been published for making a conductor capable of carrying large currents (comparable to those of LTS) while keeping hysteresis and coupling losses low. HTS conductors, however, have a couple of significant advantages over the LTS conductors—the temperature rise due to a transient heat input (i.e., by conductor movement) is lower at the higher HTS operating temperatures than when operating at liquid helium temperature, and they have a slow transition from superconducting to normal state which makes them inherently more stable. This advantage may translate into relaxed requirements on the acceptable filament size and other conductor configuration parameters. However, the ac losses in these wires must be low in order to make HTS transformers economically acceptable.

Another significant loss component is the heat conduction through current leads. One end of a current lead is at room temperature and the other end is at low temperature, and the heat is conducted along the length of the lead from warm to cold regions. In case of LTS transformers, conduction heat can be intercepted at the intermediate thermal shield, which is usually kept at ~70 K. The heat conduction between the 70 K and 4 K winding regions could be controlled by employing HTS current leads. However, in case of HTS transformers operating at the liquid nitrogen temperature (77 K), all of the lead conduction must be cooled by the liquid nitrogen coolant. A typical 100 A pair of leads conducts 8 W of heat load into the cold region.

Cryostat

To maintain the low temperature environment essential for operation of LTS and HTS magnets, they must be placed in special vessels or cryostats. These are vacuum insulated containers. Designs for LTS and HTS could be widely different; HTS cryostats are likely to be easier to design and fabricate than LTS cryostats. Since the cost of removing losses from low temperatures (4.2 K) is very high, usually a double or triple wall construction is employed. The innermost space contains the liquid helium and outermost wall operates at room temperature. An intermediate wall is normally employed which operates at an intermediate temperature such as liquid nitrogen temperature (77 K). In some applications, even another wall is introduced at 20 K to 30 K in order to minimize total refrigeration load.

On the other hand, a HTS cryostat operating at 77 K could employ a simple double wall construction. The outer wall is at room-temperature and the inner wall is at liquid nitrogen temperature. The space between the two walls is filled with multi-layer-insulation (MLI) or some other suitable thermal insulation such as various types of foam. Normally this simple construction reduces heat leak to an acceptable level.

Cooling System

Superconducting magnets can be cooled with a pool of liquid cryogen or cooled by conduction with a cryocooler. The majority of LTS magnets are cooled with liquid helium. Helium has the lowest boiling point (4.2 K) at atmospheric pressure of any known cryogen and has been the cryogenic fluid used in the LTS magnets. On the other hand, cost of helium is very high (~ $5/liter). Because of its cost, most facilities install a recovery and reliquefying system. A variety of devices are available worldwide. The choice of device is application specific as the designer must evaluate trade-offs. Primary among these are first-cost versus operating cost; first-cost versus reliability and ease-of-use, and dollar per watt of cooling required. Devices are basically two types; open-cycle or closed-cycle. The former are the simplest, lowest cost form of refrigeration available today and are quite simply open top "bucket" dewars. Closed-cycle systems do not require use of liquefied cryogens but rely on the refrigeration capacities of the gas and the cycle design to achieve the cryogenic temperatures desired. Helium is the predominant gas used in these devices. For larger applications such as a transformer, a closed cycle helium system is substantially more economical in long run than purchased liquid helium. With a closed cycle system, the warm helium returning from the cryostat is reliquified in a refrigerator and returned to the cryostat. A number of conduction cooled magnets which use no liquid cryogen have been built for operation at 4 K and higher temperatures using both HTS and LTS wires.

Economic Considerations

From a utility perspective, a transformer must have low initial and operating costs, and be light weight, compact, and environmentally benign with a lifetime of typically 30 years. To a great extent, a HTS transformer does have a potential to offer these advantages.

Conventional transformers are highly reliable and flexible in terms of their use in an electrical system. However, the dominant component of losses is the I^2R loss in the windings. The capitalized cost of these losses over the life of a transformer could easily exceed its initial cost. The superconducting transformers are attractive because of the potentially lower winding losses. However, there is an energy penalty associated with the input power consumed by the refrigeration system. This energy penalty can be substantial. To remove 1 W of losses at 4 K, 500 W of refrigeration power is required. However, only 20 W is required to remove 1 W from 77 K. This reduction in the refrigeration power has generated a lot of interest in transformers employing HTS conductors. An optimally designed HTS transformer is likely to have lower losses and lower life cycle cost than a conventional unit.

The higher current density capacity of superconductors compared to copper leads to a more compact and lighter design of transformers. Even for the identical core diameters, the core window width (space between iron legs) could be reduced in proportion to the space saving due to the utilization of superconducting windings. This reduces the iron core weight. Lighter core size also leads to lower core losses. A compact and light weight transformer might see new applications which were not feasible with the conventional transformers. Lower weight and compact size would make them acceptable for more urban applications. Smaller core windows also lead to lower leakage inductance which helps to improve dynamic stability of a power system. The low leakage inductance also improves the voltage regulation to the load, and therefore, it might eliminate complex and expensive tap changers.

The environmentally friendly aspect of a superconducting transformer gives additional impetus to application of these devices. They do not have environmental, health, and safety concerns associated with conventional transformers. In urban settings, most transformers are installed in the basement of high rise buildings. Environmental concerns are forcing utilities to employ oil free transformers. In a superconducting transformer, oil is replaced with liquid helium or liquid nitrogen. They are much more benign—nontoxic, nonflammable, and noncarcinogenic. However, in the event of a quench, a large quantity of helium or nitrogen gas could be released which could displace oxygen in the surrounding air and present a personnel risk. This risk can be mitigated by controlled release and installation of exhaust fans.

STATE-OF-THE-ART OF SUPERCONDUCTING TRANSFORMERS

With the advent of HTS conductors, the low temperature transformer design efforts have essentially been abandoned.

Several HTS transformers programs are currently active in Japan, Europe, and North America for operation at temperatures ranging from 20 K to 77 K. Both air-core and iron-core options are being pursued. The major HTS programs being pursued are listed below.

- ABB has built (28–30) and has been testing a 630 kVA, 3-phase transformer since March 1997. This is the world's first demonstration of an HTS transformer, one that was designed and built by ABB with HTS wire that was developed and manufactured by ASC. Following the success of this transformer, the Electricité de France (EDF), ABB, and ASC consortium is now developing a 10 MVA transformer (29). The 10 MVA transformer is a crucial next step on the path to a commercial-scale 30 MVA transformer. The 10 MVA unit will be built by ABB and will be tested by EDF in its grid by the end of 2000.
- Waukesha Electric and Intermagnetic General Corporation (IGC) is building a 1 MVA transformer (8). Waukesha will build the unit using HTS wire supplied by IGC. This unit is planned for testing in 1998.
- Kyushu University consortium designed, built, and tested a 500 MVA-class single phase HTS transformer (11) in 1996. This was the first transformer cooled by liquid nitrogen at 77 K and was operated at a steady state with a 500 kVA secondary inductive load.

Although HTS conductors are much more tolerant of transient heat input (primarily due to increased heat capacity of materials at higher temperatures than at 4.2 K), the ac losses are still significant and an attractive ac conductor configuration is still illusive. The highly aspected configuration of HTS wire (width = 10 × thickness) generates excessive hysteresis losses caused by the magnetic field component perpendicular to the surface of the conductor. These losses are sufficiently high that the total refrigeration power needed to remove them from 77 K environment is comparable to the I^2R loss in the windings of a conventional transformer. Thus, the efficiency (or life cycle cost) advantage is lost. How the ac loss problem will be solved and how the market will value the benefits of a superconducting transformer over conventional transformers is not yet clear. By the year 2002, a clearer picture might emerge about the feasibility of HTS transformers.

BIBLIOGRAPHY

1. H. Riemersma et al., Application of superconducting technology to power transformers, *IEEE Trans. Power Appar. Syst.,* **PAS-100**: 3398–3405, 1981.
2. Westinghouse Electric Corporation, Application of low temperature technology to power transformers, US Department of Energy, DOE/ET/29324-1, February 1982.
3. A. Fevrier et al., Preliminary tests on a superconducting power transformer, *IEEE Trans. Magn.,* **MAG-24**: 1477–1480, 1988.
4. S. Hornfeldt et al., Power transformer with superconducting windings, *IEEE Trans. Mag.,* **MAG-29**: 3556–3558, 1993.
5. M. Iwakuma et al., Quench protection of superconducting transformers, *IEEE Trans. Magn.* **MAG-27**: 2080–2083, 1991.
6. E. S. Yoneda et al., Tests on a 30 kVA class superconducting transformer, *Cryogenics,* **31**: 655–659, July 1991.
7. R. F. Giese, The status of progress towards high-temperature superconducting transformers, Work sponsored by the International Energy Agency, Argonne National Laboratory, November 1996.
8. S. P. Mehta et al., Superconductors transforming transformers, *IEEE Spectrum,* 43–49, July 1997.
9. R. C. Johnson, Status of superconducting power transformer development. *Proc. Amer. Power Conf.,* Chicago, April 1996, **58-1**: 89, subject 05-6, Illinois Institute of Technology.
10. D. Mikulis, HTS transformer for utility powering, *Modern Power Syst.,* June 1997.
11. K. Funaki et al., Preliminary tests of a 500 kVA-class oxide superconducting transformer cooled by subcooled nitrogen, *IEEE Trans. Appl. Supercond.,* **7**: 824–827, 1997.
12. P. K. Mukhopadhyay et al., Unexpected behaviour of core materials of electrical coils at low temperatures, *Cryogenics,* **34** (3): 241, 1994.
13. A. P. Malozemoff et al., Progress in BISCCO-2223 tape technology, M2S Conf., Beijing, China, February 28–March 3, 1997.
14. M. S. Walker et al., Performance of coils wound from long lengths of surface coated, reacted. BSCCO-2212 conductor, *IEEE Trans. Appl. Supercond.,* **7**: 889–892, 1997.
15. M. Yamamoto, A Study on a Coreless Superconducting Transformer, *IEEE Trans. Appl. Supercond.,* **3**: 889, 1993.
16. N. Okada et al., Fabrication and test of superconducting air-core autotransformers, *IEEE Trans. Magn.,* **MAG-28**: 430–433, 1992.
17. M. N. Wilson, *Superconducting Magnets,* Clarendon Press, Oxford, 1983.
18. T. Verhaege et al., A new class of ac superconducting conductors, *IEEE Trans. Appl. Supercond.,* **3**: 164, 1993.
19. K. Kamisada et al., Research and development of superconductors for commercial frequency, *IEEE Trans. Appl. Supercond.,* **28**: 291, 1992.
20. T. Veraege et al., Protection of superconducting ac windings, *IEEE Trans. Applied Supercond.,* **28**: 751, 1992.
21. M. Iwakuma et al., Electromagnetic properties in parallel conductors composed of Bi2223 multifilamentary wires for power transformer windings, Appl. Supercond. Conf., August 25, Pittsburgh, PA, 1996.
22. A. M. Wolsky, IEA implementing agreement for a co-operative programme for assessing the impacts of high-temperature superconductivity on the electric power sector, Argonne National Laboratory, January 1997.
23. S. Foltyn et al., '95 Spring MRS Meeting in San Francisco, California.
24. H. Brechna, *Superconducting Magnet System,* Berlin: Springer-Verlag, 1973.
25. K. Kwasnitza, AC losses of superconducting high-Tc multifilamentary Bi-2223/Ag sheathed tapes in perpendicular magnetic fields, *Physica C* **233**: 423–435, 1994.
26. J. H. Murphy, Advanced applications of superconductors, *Advances in Cryogenic Engineering,* **29**: 133, 1984.
27. Cha Gueesoo et al., Effect of the longitudinal magnetic field in a 2nd level superconducting cable, *Trans. KIEE,* **46** (1): 52–57, January 1997.
28. ABB and American Superconductor Corporation team up to demonstrate the world's first installation of a high temperature superconductor transformer, an ASC press release, Westborough, MA, March 12, 1997.
29. Electricité de France, ABB, and American Superconductor sign $15 million pact to accelerate HTS wire development for next generation power transformers, an ASC press release, Westborough, MA, January 12, 1998.

30. P. G. Thésond et al., High temperature 630 kVA superconducting transformer, Report 12-302, CIGRE Meeting, Aug. 30–Sept. 5, 1998, Paris.

SWARN S. KASI
American Superconductor
Corporation