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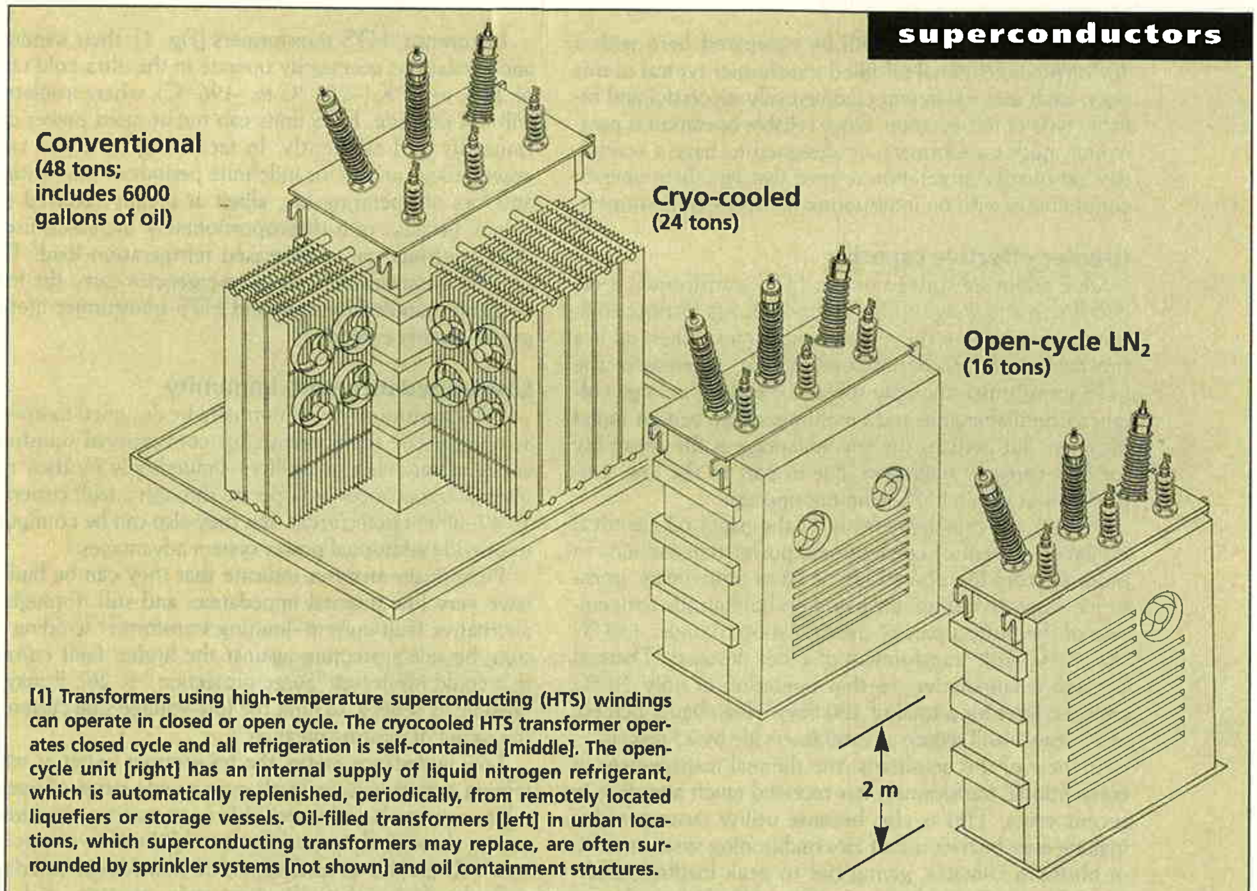

[1] Transformers using high-temperature superconducting (HTS) windings can operate in closed or open cycle. The cryocooled HTS transformer operates closed cycle and all refrigeration is self-contained [middle]. The open-cycle unit [right] has an internal supply of liquid nitrogen refrigerant, which is automatically replenished, periodically, from remotely located liquefiers or storage vessels. Oil-filled transformers [left] in urban locations, which superconducting transformers may replace, are often surrounded by sprinkler systems [not shown] and oil containment structures.

WAUKESHA ELECTRIC SYSTEMS

Transforming transformers

Use of high-temperature superconducting windings may soon turn power transformers into compact high-performers on good terms with the environment

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Transformers utilizing high-temperature superconductors are viewed as a "breakthrough" technology coming at a very "opportune time." Possible utility customers for the new equipment, as well as power transmission and distribution experts, have gone on record with this judgment [see "The need and the promise," p. 47].

High-temperature superconductor (HTS) properties, improved refrigeration reliability, and lower refrigeration costs make it possible to overcome the limitations experienced in the low-temperature superconductor (LTS) transformer designs of the 1970s and '80s. (Note that HTS and LTS are relative terms for superconductors operating more than 195 degrees below 0° C.)

Commercial success will depend on demonstrated reliability of operation and the scale-up of (HTS) manufacturing. The goal is to reach the high current densities already obtained in short conductor samples, except in long lengths and at reasonable cost. Such rapid progress is being made that commercially competitive and operationally superior HTS transformers are expected to be available in five to 10 years.

The potential for HTS transformers is being examined in major design and hardware development programs by several teams of engineers and scientists worldwide. The team to which the authors belong is led by Waukesha Electric Systems, in Wisconsin, and has three New York members—Intermagnetics General Corp., Rochester Gas & Electric Corp., and Rensselaer Polytechnic Institute—plus Oak Ridge National Laboratory, in Tennessee.

The Waukesha-led team has conducted a series of reference designs concentrating mostly on a 30-MVA, 138-kV/13.8-kV transformer rating. This rating is representative of a medium-power transformer class foreseen as comprising about half of all U.S. power transformer sales in the next two decades.

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Two of these designs will be compared here with a 30-MVA conventional oil-filled transformer typical of this class. Each uses a different commercially successful and reliable type of refrigeration. Since reliable operation is paramount, both transformers are designed to have a several-day, on-board refrigeration reserve that lets them operate continuously with no interruption of service to customers.

Greater effective capacity

One major advantage of the HTS transformer is reduced size and weight [Fig. 1]. Another is a distinct environmental plus—in the conventional transformer, oil is a fire hazard and potential contaminant, whereas in the HTS transformer, the only substance present in large volume is nonflammable and environmentally benign liquid nitrogen. But perhaps the key advantage is the capability for over-capacity operation, due in part to the low temperatures at which HTS windings operate.

Heat is the principal enemy of the paper-oil electrical insulation system of conventional power transformers. In order to meet the desired life of 30 or more years, transformer capacity ratings are based on holding the temperature of the hottest part of the insulation to under 110 °C (or 95 °C with transformers of older designs). Thermal damage is cumulative, so that operation at only 20 °C over the limit for a total of 100 days—less than 1 percent of 30 years—will reduce a transformer's life by 25 percent.

In view of this sensitivity, the thermal management of conventional transformers has received much attention in recent years. This is also because utility customers are making ever heavier use of air-conditioning systems, even in northern climates, giving rise to peak loading conditions that can last 10 hours or more on the hottest days of the year. Loss of insulation life can be significant under these conditions. So transformers are increasingly being purchased with excess capacity, just to meet maximum temperature limits that may occur only on a few days. The upshot is that they operate well below an optimal level most of the time.

Defining terms

Cryocooler: a refrigerator designed to operate in the range of low temperatures where common gases become liquid or solid. A Gifford McMahon cryocooler is one of several types that operate through an oscillating gas pressure used to carry heat away from a bed of material.

Eddy current losses: loss of energy as heat, caused by local currents induced in the superconductor or other metallic components by changing magnetic fields.

Liquefier: a refrigerator that cools gases until they condense into liquids; in some cases, the cooling is effected by the expansion of the gas itself.

Magnetic hysteresis losses: in ferromagnetic materials, the loss of energy as heat caused by a lag and irreversibility in the alignment of magnetic domains with respect to a changing magnetic field.

Resistive losses: loss of energy as heat caused by the passage of a current through material having electrical resistance. In a conventional 30-MVA transformer, this may constitute 60 percent of the transformer loss at rated load.

Superconductor hysteresis losses: loss of energy as heat, the cause being an irreversible penetration of a magnetic field into a superconductor because persistent superconducting currents are induced.

Total owning costs: the transformer's initial purchase price plus the effective cost of load-cycle–dependent losses.

In contrast, HTS transformers [Fig. 2], their windings, and insulations necessarily operate in the ultra-cold range of 20 K to 77 K (–253 °C to –196 °C), where insulations will not degrade. HTS units can run at rated power continuously and efficiently. In fact, at up to twice rated power, they can run for indefinite periods of time without any loss of operating life, albeit at greatly reduced efficiency because of a disproportionately increased use of liquid nitrogen or an increased refrigeration load. Thus one HTS transformer can in emergencies carry the loads normally handled by two, and HTS transformer lifetime can be greatly extended.

Low impedance with immunity

HTS transformers will normally be designed to operate as one-for-one replacements for conventional transformers, complete with an ability—limited only by their own internal impedance—to operate through a fault current of 10-12–times rated current. But they also can be configured to provide additional power system advantages.

Preliminary analyses indicate that they can be built to have very low internal impedances and still, through an alternative fault-current–limiting transformer winding design, be self-protecting against the higher fault currents that could result [see "Surge protection," p. 26]. It may be possible, if needed, to limit the low-voltage side current to the rating of existing breakers.

Low impedance makes the transformer better at maintaining output voltage levels over a wide range of operating power levels and better able to transmit power downstream through the power system. Utilization of this feature will involve consideration of transformer interfaces with the grid and the load in each situation, and may especially apply to new power construction where a complete system of compatible components can be installed in an economical way.

Conventional transformers are efficient (typically 99.3–99.7 percent for the 30-MVA class, depending upon loading); but there is considerable room for improvement. About 25 percent of the 7–10 percent losses in transmission and distribution systems occur in power transformers. The transformer loss costs more than $2 billion annually in United States alone.

Most of the conventional transformer's losses are due to resistive heating in its windings—and HTS transformers have zero winding resistance. Admittedly, the HTS versions still have ac losses in the iron core and low levels of other kinds of ac losses in the windings that require refrigeration power. Nonetheless, they can be substantially higher in efficiency than conventional transformers, to the extent that the reduced loss in each HTS unit can more than pay for its initial capital cost over its lifetime.

Design tradeoffs, cost drivers

Zero resistance and 10-100–times greater current density promise striking advantages in transformer size and performance. Classical resistive losses are eliminated, and the quantity of conductor in the HTS transformer windings can be reduced to tens as against thousands of kilograms for the conventional transformer. Since the windings in principle require little space and generate little resistive heat, it should be possible to make superconducting transformers inexpensively, with greatly reduced power capacity, much increased efficiency, and very much smaller size. While these advantages can be realized in large part, they cannot all be achieved to the same degree in the same transformer. As always, there are practical limitations and tradeoffs.

Ultimately, reductions in size will be limited by dielectric design considerations. The transformer must meet American National Standards Institute standard dielectric tests for system voltages and the associated basic impulse insulation test levels that are specified. For example, a 138-kV winding may need to withstand impulse voltages of 650 kV. The design of the transformer winding must include sufficient space for insulation if it is to accommodate these high voltages with commercially available dielectric materials and proven design approaches.

Iron core size, which is related to winding size, mainly determines overall transformer size and weight. Eddy current and magnetic hysteresis losses are produced in the core in direct proportion to the core volume. These losses tend to be on the order of tens of kilowatts, much too large to be economically removed by low-temperature refrigerators. HTS transformers are consequently designed to operate with cores near ambient temperature and isolated thermally from the windings. If the core is too large, its losses become excessive, and because these losses occur regardless of whether current (power) is drawn from the transformer, they contribute strongly to the total owning costs. So there are strong incentives to reduce core and winding size.

But reducing core diameter adds to the number of turns and so to the total length and cost of the HTS conductor. Though the superconductor winding has no classical resistive losses, there are several forms of eddy current and hysteresis losses, which depend on the magnitude of the ac magnetic flux density in the transformer windings, typi-

The lengths (and more) to which HTS must go

Continuous lengths of several hundred meters of high-temperature superconductor (HTS) are required for the construction of transformer windings. While many HTS families are known, the manufacture of long lengths is being developed in only a few of them.

The farthest along are several variations of the BiSrCaCuO family, with the numbers of atoms in the cations in the ratios of either 2212 or 2223. The BSCCO-2223 is currently manufactured in flat tapes up to 1 km long; fine filaments of the oxide superconductor are encased in a silver or silver alloy matrix by a powder-in-tube (PIT) draw, roll, sinter, and roll process. The BSCCO-2212 is currently being manufactured in wires or tapes up to 0.5 km long by either a PIT or a surface-coating process. The final step in either case is a melt and resolidification of the oxide.

TiBaCaCuO (TBCCO-1223) and YBaCuO (YBCO-123) have been made by various surface-coating or surface deposition processes, but have proved harder to produce in length in suitable form. Recent breakthroughs in producing YBCO with very high critical-current densities on nickel and nickel-based alloy substrates are beginning to change the picture. An avalanche of development activity worldwide covers a range of manufacturing approaches. High-quality conductor is being produced in 10-cm lengths, and apparatus is being scaled up to make longer lengths [see pp. 18–19].

In the figure, the best critical-current densities in short samples of these conductors (that is, the peak zero-resistance current per unit of oxide cross section) are combined with the authors' estimates of achievable substrate-to-oxide ratios in order to estimate achievable engineering critical current densities (current per unit of total conductor cross section). Assume for reference that each of these superconductors will be manufacturable in long lengths at a target cost of about $1000/kg—that is, for about the present cost of multifilamentary Nb_3Sn, the more expensive of the low-temperature superconductors. If so, an engineering critical-current density of at least 40 000 A/cm² will be needed to economically provide the ampere-turns of conductor required for HTS transformer applications.

This line of reasoning establishes a temperature range for the economical use of each of these conductor types in these applications. If conductor properties are improved, or if the manufacturing cost is lowered, then the practical range for each conductor type will shift to higher temperatures.

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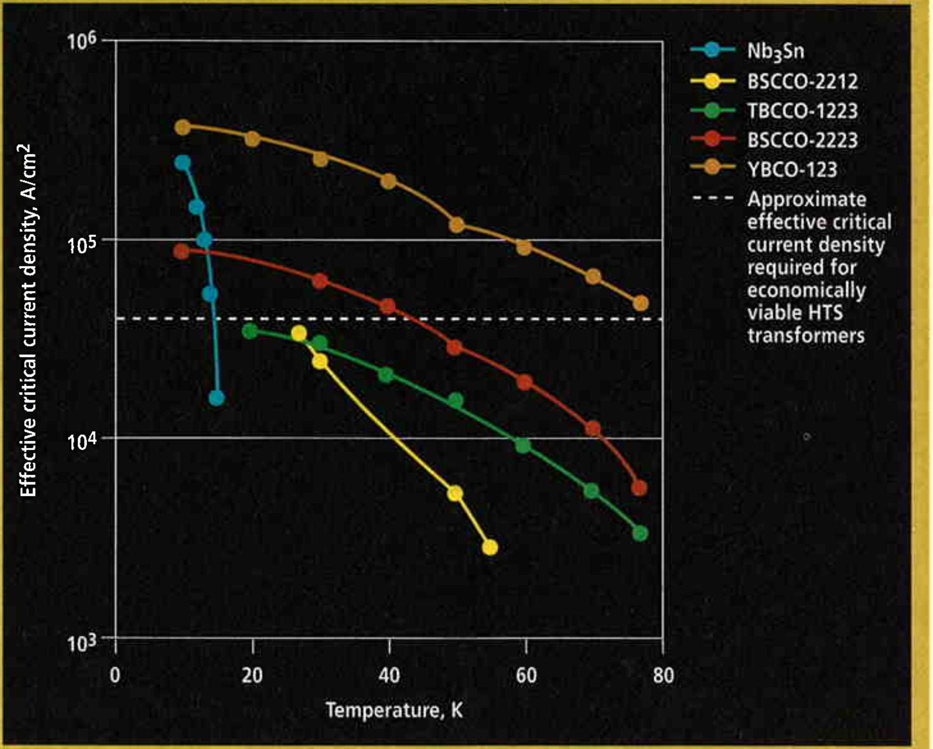

HTS transformers need a certain critical-current density for viability [dashed line]. The target levels shown for four high- and one low-temperature superconductor are based on test results for short samples and estimates of achievable substrate-to-oxide ratios. The BSCCO-2212 results are for dipcoat tape from Japan's National Research Institute for Metals and powder-in-tube (PIT) wire from Intermagnetics General, which also produced BSCCO-2223 in multifilament PIT tape form. The TBCCO is for spray-pyro tape made by General Electric, while the YBCO-123 tapes were produced by new techniques at the Los Alamos and Oak Ridge national laboratories. The low-temperature Nb_3Sn is multifilamentary.