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SUPERCONDUCTING MOTORS, GENERATORS, AND ALTERNATORS

Superconductors are very promising and exciting materials for electric power engineering in general and for electric machines in particular. By allowing very high current densities and by suppressing the Joule losses, superconductors improve the performance of electric machines by reducing weight, improving efficiency and, to a lesser degree, by increasing compactness. The reduction of losses results in long-term savings in capital cost, making superconducting machines attractive from an economic point of view. Since a cryogenic system is required to maintain the superconducting state, these advantages appear only above a critical (breakeven) size or rating, such that where the refrigeration penalty is negligible. Superconductivity is thus attractive only for large electrical machines. Small motors (up to a few kilowatts) will not be superconducting except if room-temperature superconductors are discovered, which is highly improbable.

The critical size is reduced when the operating temperature increases. Devices with high-critical-temperature superconductors will be attractive for lower ratings than systems cooled with liquid helium.

Electric Machines—General Structure(1)

An electric machine is reversible. It can operate as a motor, converting electrical into mechanical power, or as a generator, converting mechanical input into electricity. The electromagnetic force or torque is produced in two ways. The first one is the interaction between currents, called armature currents, and a variable-reluctance structure (variable-reluctance machines). The second and more widely used way is the interaction between currents and a magnetic field called the excitation field. The mobile part can be either the armature or the excitation. But as the energy transfer to a moving part creates losses except by electromagnetic way, the armature is preferably stationary.

The torque per unit volume is proportional to the excitation field component perpendicular to the current times the armature ampere-turn loading, as shown below. The armature ampere-turn loading is the total armature current divided by the mean armature circumference. The expression for the maximum torque ($\Gamma_{\max}$) for a three-phase machine is simply:

$$\Gamma_{\max} = \sqrt{2}\ B^0 K \pi r_o^2 L \tag{1}$$

where

B^o = excitation field component
K = armature ampere turn loading
r_o = mean armature radius
L = active length
N_s = total series turns per phase
k_d = winding factor

I = rated armature current
ϑ_{mach} = approximate machine volume

$$K = \frac{3\, N_s\, k_d\, I}{\pi\, r_o}$$

$$\pi\, r_o^2\, L \approx \vartheta_{\text{mach}}$$

The excitation field is created either by permanent magnets or by current flow in a winding. Permanent magnets are limited in magnetic induction and are made of very expensive materials, but they are not dissipative. They are well suited particularly for small machines (kilowatt range). The currents in a conventional conductor produce heat through the Joule effect ($R\, i^2$ where R is the resistance and i the current), dissipating energy. The current capacity is hence limited by the ability to remove heat. Better cooling conditions increase the current capacity but reduce the efficiency. The current density (current per unit cross-sectional area) is then limited by thermal and economic factors. The allowable current density in copper is on the order of amperes per square millimeter (5 MA/m^2 to 10 MA/m^2). With such values the amounts of conductor required to produce magnetic fields without magnetic materials are large, leading to huge Joule losses. Thanks to the peculiar properties of soft magnetic materials (high relative permeability), the total current (ampere turns) required to produce a given magnetic induction is greatly reduced. For this reason practically all electric machines have a magnetic circuit with slots where the windings are embedded.

The armature ampere-turn loading is limited by Joule losses and by the current density allowable in the conductors, because the space they can occupy is limited.

The magnetic circuit has other advantages than the reduction of the excitation current. It confines the flux within the machine and reduces the stray field to negligible levels. It also prevents magnetic disturbances to other equipment. The magnetic circuit is also very useful from a mechanical point of view. When the conductors are inserted into slots they are subjected only to a reduced electromagnetic force, since the field concentrates itself in the teeth. The electromagnetic force is mainly applied at the interface between the slots and the magnetic teeth. The torque is then essentially supported by the magnetic circuit and not by the conductors. The reduced mechanical stresses on the conductors are an important advantage, because the mechanical strength of copper is low. In a slotted structure, no special care need be taken in order to reduce the eddy-current losses in the conductors, since they only see low fields. Without magnetic teeth, a strong mechanical support structure must be provided in order to sustain all the electromagnetic torque, and the conductors should follow the finely divided Litz wire configuration to avoid large eddy-current losses. However, the magnetic circuit is heavy, the increased magnetic induction it provides is limited by saturation, and it creates pulsating torques, because the alternation of magnetic teeth and slots produces local magnetic variations. The magnetic teeth also reduce the space available for conductors and thus the armature ampere-turn loading. The slotted structure is also not convenient for insulation, so that the maximum voltage is limited (to about 30 kV).

Superconducting materials show promise for electric machines because they offer the possibility to increase both the excitation field and the armature ampere-turn loading (2,3). Superconductors are particularly convenient for producing magnetic fields that are constant in time. Since the current densities in superconductors can be very high (up to a hundred times the allowable value in copper, i.e., hundreds of megamperes per square meter), the required quantity of conductor to produce a given field is greatly reduced from that with conventional conductors, even without the help of magnetic materials. The magnetic circuit is usually nearly removed when using superconductors. Magnetic materials are in general used only to form a magnetic shield in order to avoid large stray fields outside the machine. Current maintenance in a superconducting winding does not cost any energy, due to the absence of losses for constant current and constant external field. The disappearance or large reduction of the magnetic circuit leads to a light and saturation-free structure with

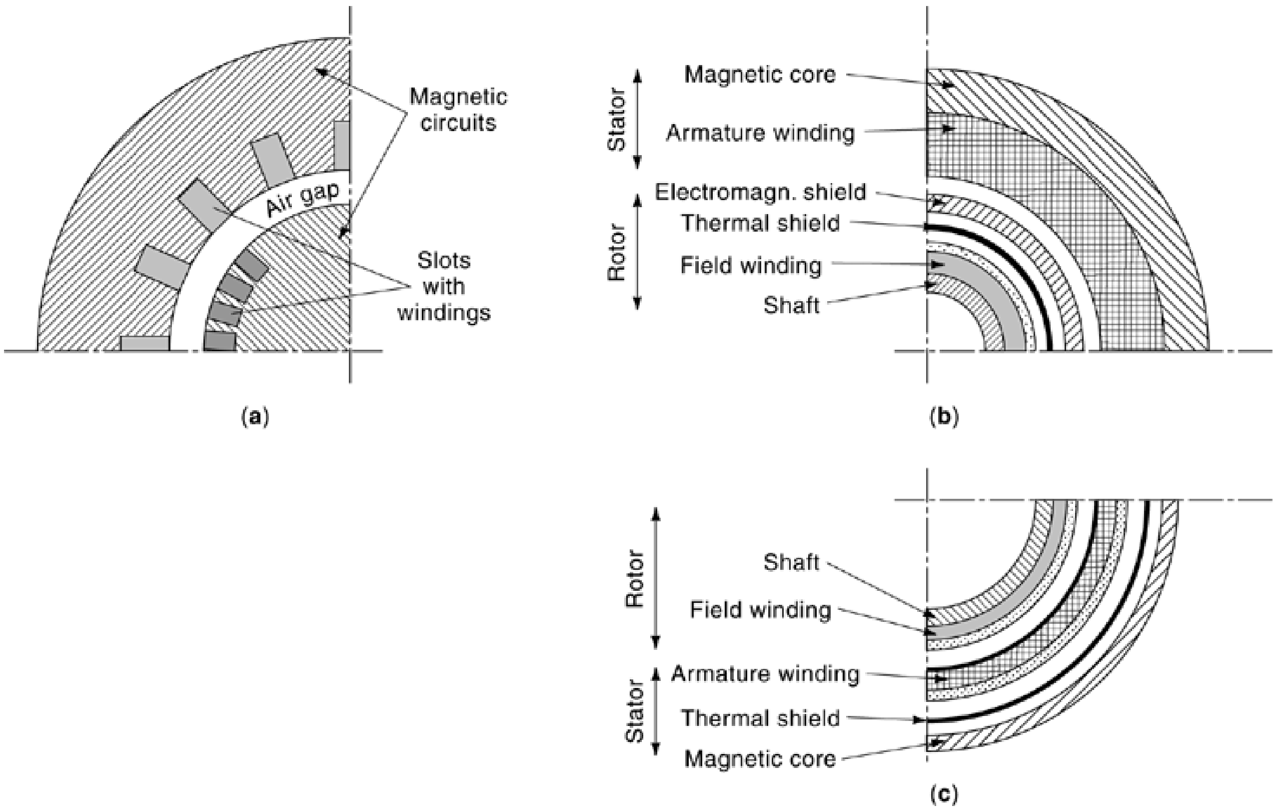

Fig. 1. Schematic cross sections of ac generators. (a) classical; (b) superconducting field winding; (c) fully superconducting.

more active space for conductors and insulation materials. The ampere-turn loading and the voltage can then be increased. The absence of iron teeth will decrease vibration by suppressing torque ripples. Acoustically very quiet electric machines can be designed.

However, the torque is applied directly to the conductors. They must therefore be supported by a suitable structure. An armature without magnetic teeth subjects the conductors to large forces at twice the frequency of rotation, which must be restrained by novel means of support for which high reliability must be maintained. Figure 1 shows the main differences between a conventional machine and superconducting ones (for synchronous machines).

The weak point of a conventional machine is in general its insulation, which degrades badly with time. It is very sensitive to thermal cycling, and overheating strongly affects its lifetime. A cryogenic system is hence very favorable from this point of view: it almost completely avoids thermal cycling in operation. Moreover, at low temperatures all aging process are slowed down. The cryogenic components of superconducting machines should thus last longer, particularly if the machine remains at low temperature. Numerous thermal cycles from room temperature to cryogenic temperature must be avoided. Furthermore, they are costly in time and energy.

The very high current densities in superconductors make them very attractive for the armature by increasing the ampere-turn loading. However, the armature currents are in general alternating, so that losses appear in the superconductors. This is an important disadvantage in a cryogenic environment. In order to

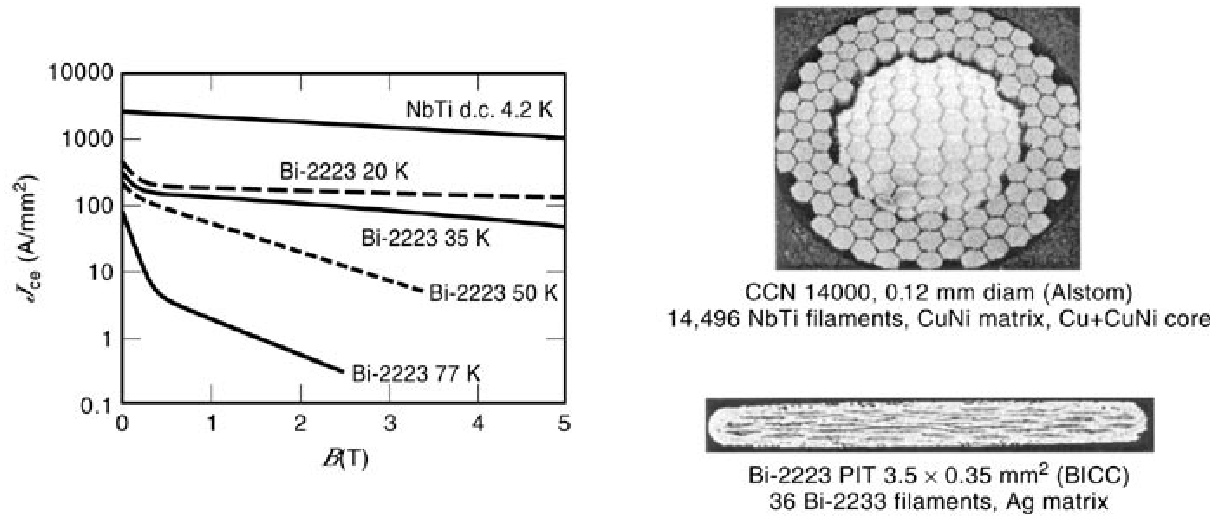

Fig. 2. Engineering critical characteristics of superconducting materials and wire cross sections.

discuss this point and for the sake of completeness, some information about superconducting wires (materials and ac losses) will be given in the following sections.

Superconducting Materials for Electric Machines

Classes of Materials. Superconductors divide themselves into two major groups: the low-T_c and the high-T_c materials. The low-T_c superconductors (LTSs), the earlier ones, are industrial materials with high performance in terms of current capacity under high fields (1 T—5 T, Fig. 2). However, they operate in general only at temperatures near 4.2 K, which require a complex but well-controlled cryogenic system. The most common low-T_c superconducting multifilamentary composites use niobium titanium (NbTi) with typical cost of about 1 $/kA·m to 2 $/kA·m. This figure of merit, the cost of 1 m of wire carrying 1 kA, enables comparisons between materials. The compound niobium tin (Nb_3Sn) is only used for very high-field applications (> 8 T) and is less used for electric machines. Its use is more complicated than that of NbTi, due to the long thermal treatments required after winding it, and its cost is higher (5 $/kA·m to 10 $/kA·m).

High-T_c superconductors (HTSs), assuming similar costs and performance to those of NbTi, will lead to a reduction in cryogenic costs (capital and especially operating costs), but the main advantage is the improvement in the stability of the superconducting state, which leads to higher reliability. At 20 K the specific heats are 200 times higher than at 4 K. The specific heat, being the amount of heat input necessary to raise the temperature, represents the materials inherent brake on temperature rise. HTSs are thus less sensitive to thermal disturbances.

Even with the large research effort focused on HTSs, these materials have not yet achieved the state of development stage of NbTi. HTSs are very complex anisotropic ceramic materials, difficult to fabricate in a conventional wire or cable. Intrinsically brittle, they are sensitive to mechanical stresses, and their transport properties under fields are still much poorer than those of NbTi (Fig. 2), except for highly oriented, essentially epitaxial films. They are also very expensive materials, and the current price is the main barrier to their economic development. Their cost must be lowered to 10 \$/kA·m to be competitive (4). At present it is nearly 50 times higher.

There are two main routes to fabricate HTS wires. The more advanced one is the (powder-in-tube) (*PIT*) technique (5,6) based on bismuth-compound filaments embedded in a silver or silver alloy matrix (Fig. 2). Lengths of Bi–PIT tapes as long as 1 km are produced routinely by several companies throughout the world, and their typical critical current densities are shown in Fig. 2. Still higher critical current densities are obtained on small samples ($J_c = 760$ MA/m^2 at 77 K, 0 T; $J_e \approx 250$ MA/m^2). Some specialists think nevertheless that the limits have almost been reached. The pure silver matrix unfortunately is not suitable for ac applications, due to the high ac coupling losses, and new PIT wires are under development for ac applications (5) (silver alloys, resistive barriers, etc.).

The second route consists of so-called coated conductors (7) and has much potential. Yttrium compounds are deposited in thick films (a few micrometers) on industrial flexible textured metallic substrates through a buffer layer. Very good performance has been obtained with these coated conductors, but only for short lengths. The *engineering* current density (overall current density including substrate) is large in liquid nitrogen (on the order of 200 megamperes per square meter at 77 K at present), and its decrease under field is small. A lot of difficulties must be overcome to fabricate long, high-performance coated conductors, and there is now no low-cost industrial deposition technique. High quality Y superconductor bulk pellets, up to 100 mm in diameter (8), have been processed, and they can be used in some special machines (hysteresis, reluctance, trapped-field, etc.).

Ac losses. One of the most spectacular properties of a superconductor is its absence of resistive losses. This is true, however, only for non-time-varying electromagnetic quantities (dc conditions). As soon as the magnetic induction varies with respect to time, ac losses appear in superconducting wires. The magnetic induction can be external or due to the current in the wire (self-field). The ac losses have two main consequences. On the one hand, they induce a temperature rise in the superconductor. Since the temperature margin is very small (≤ 1 K) for low-T_c materials (NbTi for example) such a rise can easily quench the superconducting coil, that is, destroy its superconductivity. On the other hand, ac losses are very expensive energetically, since they are dissipated at low temperatures. They therefore greatly reduce the advantage of using superconductors. From the second law of thermodynamics, the removal of energy at a cold temperature (T_c), requires work at a high temperature (T_0), usually room temperature. For an ideal closed cycle the ratio of the minimum required work (W_{min}) at T_0 to the energy (Q) to be removed at T_c is given by Carnot's expression

$$\left.\frac{W_{\min}}{Q}\right|_{\text{theoretical}} = \frac{T_o - T_c}{T_c} \tag{2}$$

(Fig. 3). As shown in Fig. 3, this minimum work increases rapidly at low temperatures. In order to take into account the real cycle and the imperfections of the thermodynamic transformations, this ratio should be divided by the efficiency factor of the refrigeration system:

$$\left.\frac{W_{\min}}{Q}\right|_{\text{real}} = \frac{1}{\eta_{\text{refr}}}\frac{T_o - T_c}{T_c} \tag{3}$$

This depends mainly on the cold power and little on the cold temperature (Fig. 3, Ref. 9).

The ratio W_{min}/Q in real conditions [Eq. (3)] is called the *specific work*, and its reciprocal the *coefficient of performance*. To calculate the cost of refrigeration, the losses at low temperature must be multiplied by the specific work. For an efficiency factor of 10%, it amounts to 740 W/W and 29 W/W for cold temperatures of 4

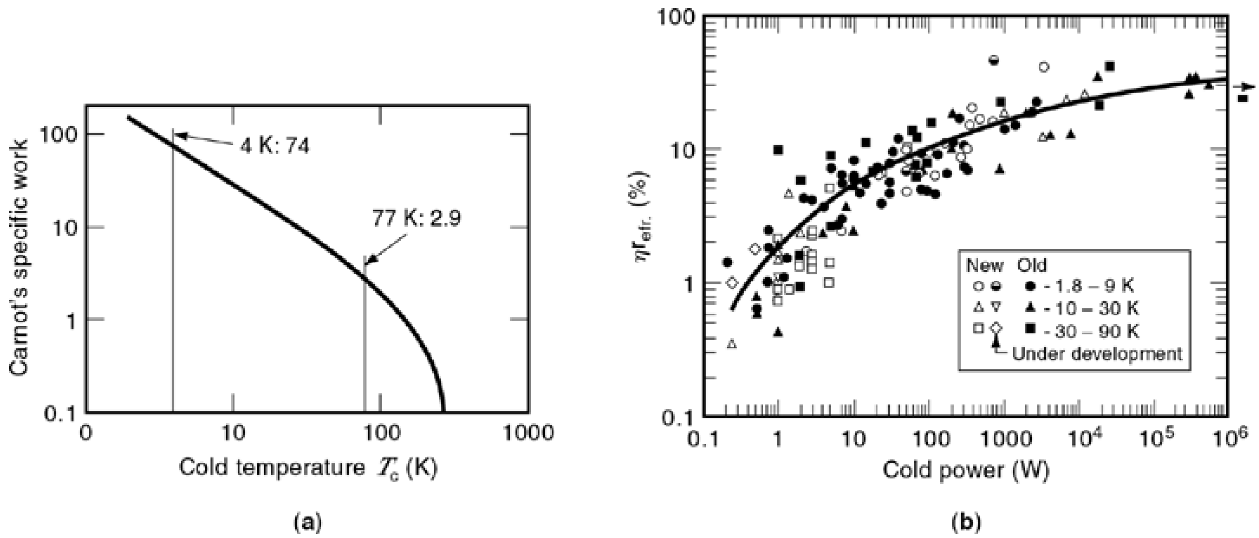

Fig. 3. (a) Carnot's specific work and (b) efficiency factor as functions of the cold power (9).

K and 77 K, respectively. These two figures illustrate the advantage of operating at high temperatures from a cryogenic point of view and again underlines the interest in using HTSs. The ac loss cost is especially high for LTSs, and it must be reduced to an ultralow level for the system efficiency to be acceptable.

A simple way to understand the ac losses is to consider the Maxwell–Faraday law (curl $\boldsymbol{E} = -\,\partial\boldsymbol{B}/\partial t$). This shows that an electric field appears as soon as the magnetic induction varies with time. The induced electric field associated with a current density (transport current or persistent currents) results in losses. The losses per unit volume are the scalar product of these two vectors.

If it is not possible to suppress the ac losses, it is possible to reduce them by a suitable multifilament structure. This will depend on the field configuration (self-field, transverse or axial field), but ultralow-ac-loss superconducting strands are generally achieved with very fine twisted filaments embedded in a high-resistance matrix or with resistive barriers between filaments. The strand diameter should be low as well. Ac NbTi wires have small ($<$ 0.2 mm) elementary strands with hundreds of thousands of filaments ($\leq$ 0.2 μm) in a CuNi resistive (0.4 $\mu\Omega{\cdot}$m) matrix (Fig. 2). The first NbTi low-ac-loss composites were developed only in the eighties when the technology for fine filament fabrication was sufficiently developed (10). Those strands have greatly extended the potential range for superconductivity (11). For high-T_c materials the requirements are less severe, since the cost of removing the ac-loss heat is reduced (29 W/W at 77 K compared to 740 W/W at 4 K). Nevertheless, no oxide superconducting tape actually fulfils them with present HTS wire technology.

The ac losses explain why superconducting devices are confined to applications with dc current and without or with time-varying fields, but in the latter case, protected from them.

Classes of Electric Machines and Their Superconducting Versions

There are many different classifications of electric machines, but the primary one is between dc and ac. Dc machines have been widely used for adjustable-speed drives because the speed can be varied with a simple electronic power supply. But due to the very large advances in easily controllable power electronics [silicon switches as gate turn-off (*GTO*) thyristor and the insulated-gate bipolar transistor (*IGBT*)], ac machines can now run at variable speed with good dynamic performance and with high efficiency and reliability. Ac machines are simpler to build and require much less maintenance than dc machines. Dc motors are nevertheless still common in the industrial world for adjustable-speed operations.

Dc machines are homopolar or heteropolar. In a homopolar machine neither the current nor the magnetic field changes in direction (polarity), contrary to the heteropolar machines, where the magnetic field has an odd number of poles. Dc machines are complicated by difficulties of current collection from the rotating part. The problem is especially difficult for heteropolar machines, where complex commutation problems occur. A superconducting field winding suits homopolar dc machines well (12). Efforts have been devoted to superconducting homopolar machines for marine propulsion in the United Kingdom (12), the United States (13), and China. A program is still being carried on in the United States with HTS coils (13).

Ac machines are synchronous or asynchronous. Except for very special cases (hysteresis motors, for example), the asynchronous type is not well suited to superconductive technology, since the torque in an asynchronous motor is directly proportional to the armature losses, whereas the main interest of superconductivity is precisely the absence of losses. The use of external room-temperature resistances may be imagined, but the structure then becomes complex and of dubious utility. Moreover, the air-cored structure of such superconducting machines results in a very low power factor, another disadvantage.

In contrast, superconductivity offers advantages of reduced weight and improved efficiency in building synchronous ac machines. A lot of work has been devoted, throughout the world, to these machines, especially in the form of large generators with a superconducting field winding and a room-temperature resistive armature (14). The excitation is powered by a dc current and is subjected to a time-constant field under balanced synchronous operation. The operation is called balanced when the currents in the phases are the same in amplitude. Synchronous machines work better in balanced conditions and therefore are usually operated in such conditions, which are very favorable for superconductors. The superconducting winding is protected by an electromagnetic shield from time-varying fields during transient or unbalanced operations, to avoid quench initiation and to reduce the cold-power requirements. The resistive armatures are unconventional in that their structure is *air-cored*, with only an external iron shield instead of a slotted magnetic circuit.

New concepts of armature windings have been proposed (15). A superconducting armature is unfortunately problematic due to ac losses (ac currents and rotating fields). It was only in the eighties that superconducting ac armatures were successfully designed and built, thanks to the emergence of ultralow-loss ac NbTi strands (11). It is still difficult to design an armature using present HTS wires.

All electric machines are based on the formula for the electromagnetic force: $\delta \boldsymbol{F} = I\, \delta \boldsymbol{l} \times \boldsymbol{B}$ (I = current, $\boldsymbol{B}$ = magnetic field, $\delta \boldsymbol{l}$ = elementary wire length). There are then two main configurations:

- Radial field and axial current (drum type)
- Axial field and radial current (disk type)

Homopolar Superconducting Machines. The homopolar machine is one of the oldest types of electric machines. Faraday built one in 1831. Figure 4 shows disk- and drum-type homopolar machines. If the current and magnetic field are constant in time, the torque is also constant. The absence of torque ripple makes the machine acoustically very quiet. Torque or speed control is also easily achievable. Nevertheless, in a homopolar structure it is not possible to put turns in series as in heteropolar machines, and the current must therefore be very high to produce a large torque. By the same token, the voltage can be inconveniently small, especially for low-speed machines. As an example with a rating of 10 MW at 100 rpm, the current reaches about 1,000,000 A in a disk 2 m in diameter submitted to a field of 2 T (upper limit of conventional machines) and the voltage only reaches 10 V, neglecting any losses (disk and brushes). The high currents must be transferred to the rotating part, and that is the main problem occurring in homopolar machines, leading to large losses and short lifetimes. Their development has consequently been limited, although some advances have been made (12), with the use of solid brushes as well as liquid-metal contacts.

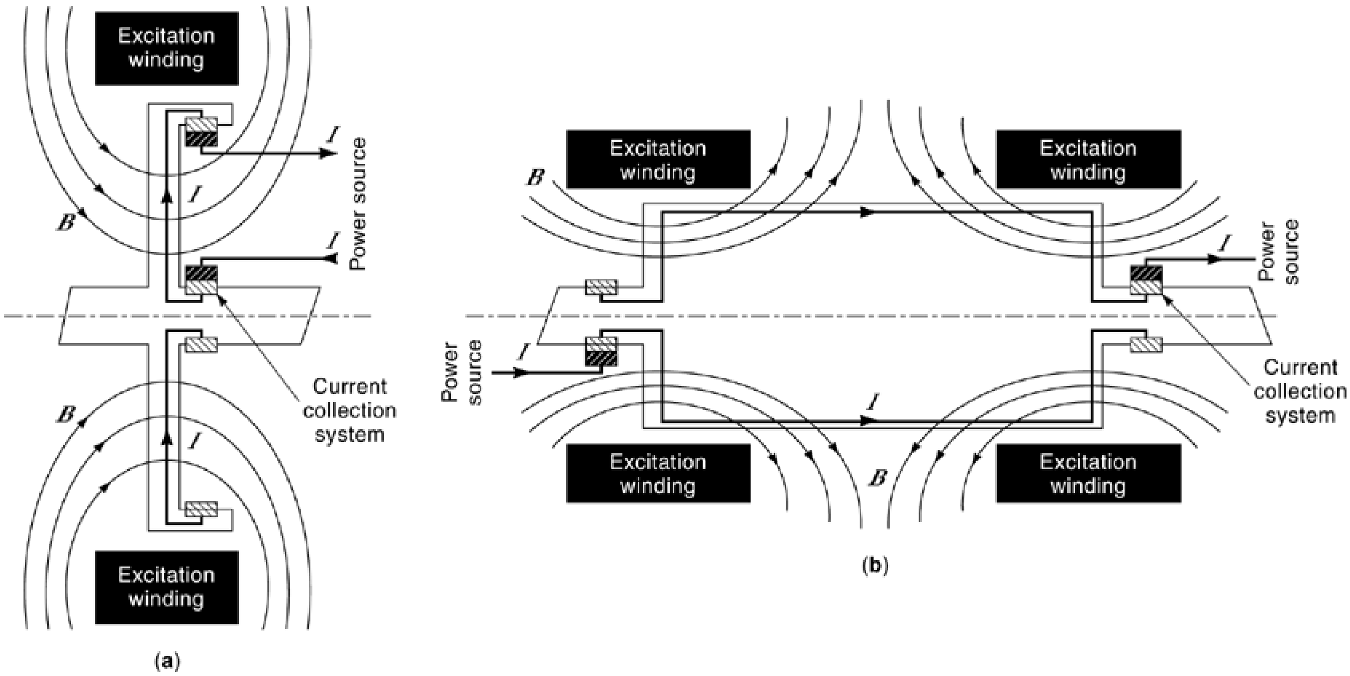

Fig. 4. Essential schemes of (a) disk-type and (b) drum-type homopolar machines.

Superconductors are convenient for the excitation of homopolar machines, since high fields (5 T to 6 T) are achievable. The operational conditions are moreover very favorable for superconductors. The electromagnetic torque is not supported by the excitation winding, and the field imposed by the armature current on the excitation wire is reduced. Nevertheless, due to current-collection problems, little development has been carried out on such machines, except for marine propulsion.

Several such machines were built at the International Research and Development (*IRD*) Company in the United Kingdom from the end of the sixties until the beginning of the seventies (12). They were disk machines, and the rating of the Fawley motor reached 2.4 MW. More recently, the Naval Surface Warfare Center in the United States developed a 300 kW superconducting (NbTi) homopolar machine of drum type. It was installed in a boat, the Jupiter II, (13), which in 1980 successfully demonstrated through sea operations the feasibility of marine propulsion by superconducting machines. The NbTi coils were recently replaced by HTS coils thanks to advances in those materials.

Ac Synchronous Superconducting Machines. An ac synchronous machine (Fig. 1, Table 1) consists of a polyphase ac armature interacting with an excitation field. As in other machines, the field can be radial (drum classical structure) or axial (disk structure). The latter configuration is very little used. Due to serious problems with current transfer at high ratings, the armature is in general stationary (the stator) whereas the excitation is the rotating part (rotor). The rotor is nearly always inside the stator. The static polyphase armature with polyphase balanced currents produces a rotating field, which rotates at the same speed (the synchronous speed) as the rotating part. The rotor then only sees a dc field under balanced steady-state conditions. The excitation field is produced either by a winding fed by dc currents or by permanent magnets. In the latter case no power supply is needed, but the excitation field cannot vary appreciably, and that is a limiting problem for generators supplying a network with a constant-amplitude voltage. However, permanent magnets are particularly convenient for motors, since controllable variable frequency power converters are available.

Table 1: Comparative parameters of 300 MVA, 3000 rpm ac generators (24)[a]

Parameter	Classical	First-generation superconducting (32)	(33)	(34)	Fully superconductions (24)
Voltage, phase–phase (kV)	18	20	12.6	20	20
Armature current (kA)	10.2	7.2	13.7	10.2	7.2
x_d (p.u.)	1.94	0.33	0.71	0.35	1.75
x_d' (p.u.)	0.38	0.26	0.48	0.27	1.2
A-c winding losses (kW)	993	800	1200		350 (175)
Field winding losses (kW)	1205	(75)	(75)		(50)
Field radius (mm)	550	280	380		300
Armature radius (mm)	650	711	875		650
Outer radius of magnetic shield (mm)	1275	1320	1240		1065
Active length (mm)	3400	2000	1400		1130
Rotor weight (tons)	37	25	25	25	15
Stator weight (tons)	165	50	35	125	20

[a]Losses between breckets are cold losses multiplied by the specific work to bring them back to room temperature.

Most electric energy is produced by ac synchronous generators directly connected to the network through a step-up transformer. The stability of the generator on the power system plays a very important part and requires a lot of attention. In a network the generators are subject to various disturbances such as changes of load, and they should rapidly recover stable operation. The stability is partly determined by intrinsic parameters of the machine, but can be improved by external actions like excitation current control.

For motors supplied by a converter, the stability is determined essentially by the converter and only to a small extent by the machine itself.

Since synchronous machines play a key role in the production of electricity, they are a subject of constant innovations and improvements in manufacturing and operation. They have attained very high performance as electromechanical converters. As an example, the efficiency has been raised to the remarkable level of 99% for a 1500 MVA rating. The technological limits in terms of power density and efficiency using conventional means are nearly reached, and only superconductivity can bring a major technological leap.

A superconducting winding can increase not only the excitation field but also the armature ampere-turn loading, even if this remains resistive. Since the iron structure is no longer necessary with a superconducting excitation, the iron teeth disappear and more space is available for the armature conductors. This increases the armature loading by a factor of approximately 2 even with resistive wires. On using superconductors for the armature instead of resistive wires, the enhancement is still much higher. The following figures give some orders of magnitude:

- Conventional machines: $K = 100–250$ kA/m,
- Air gap armature: $K = 300–350$ kA/m,
- Superconducting armature: $K = 600–800$ kA/m.

It must be remembered, though, that unfortunately air-gap armatures subject the conductors to the entire torque.

A superconducting armature is therefore very attractive, but unfortunately it develops ac losses due to the alternating currents and the rotating field. With present HTS wire technology these losses are too high. Only ultrafine NbTi filament ac wires are now available, and they impose a large refrigeration penalty (740 W/W) for operating at 4 K. The relatively recent availability of ac NbTi strands (at the end of the eighties) and the wish to avoid liquid-helium cryogenics have resulted in only a few successful developments (16–19). The main work has thus been carried out on a superconducting field winding associated with a resistive armature.

Superconducting-Field-Winding AC Machines. The gain in these machines [Fig. 1(b)] is essentially brought about by the increase of the armature loading and, surprisingly, only a little by the enhancement of the excitation field. In an air-core configuration the field decreases rapidly with increasing radius. In a $2p$-pole cylindrical structure with an internal excitation concentrated at a radius r_f, the field decreases as $(r_f/r)^{p+1}$ ($r > r_f$). The field winding and the armature (radius r_0) cannot be very close, due to the cryogenics vessels and the thermal and electromagnetic shields. The ratio r_0/r_f thus can easily reach 2, leading to a decrease of the field by a factor of 8 for a four-pole machine. The field on the excitation winding is limited because the electromagnetic stresses are proportional to the field squared. For this reason the excitation field at the armature is kept at approximately the same value (around 1 T) in a superconducting synchronous machine as in conventional machines. The power per unit volume is nevertheless increased by at least a factor of two, thanks to the higher armature loading. The improvement in weight is larger, since the air-core structure avoids the heavy magnetic circuit. There is only a small ring of laminated steel around the armature winding in order to reclose the flux within the machine. People have imagined replacing this magnetic shield by a conducting shield in order to decrease the armature weight even more (20). Such a shield is based on the eddy currents induced in it. This solution, favorable from the weight point of view, would decrease the efficiency because the Joule losses of the induced currents are higher than the iron losses in a magnetic shield.

Savings in volume and weight are not always relevant for stationary applications, and they do not justify a complete technology change. Indeed, in a power plant the turbine driving the generator is much heavier and bigger than it. However, a higher power density makes it possible to build machines with higher rating than conventional technology. This was the main reason for the early investigations into superconducting generators (see the section “Historical Background and Current Trends” below).

The 99% efficiency of a 1500 MVA generator is enhanced by about 0.1% to 0.2% due to the absence of excitation Joule losses. The cryogenic losses even at 4 K are very small, and negligible for high ratings. An upper limit for the cryogenic losses in a 1500 MVA machine is 200 W (although a reasonable value would be lower than 100 W). Even with a specific work of 1000 W/W, they represent only 0.013% of the rating. This improvement may appear very small; nevertheless the savings capitalized over the generator lifetime can match the initial cost of the machine. However, these savings must not be overwhelmed by higher maintenance and operating costs. Economic benefits are achievable only if reliability and maintenance are at least as good as with conventional generators. Indeed, nonoperation during one single day per year will completely cancel the gain due to lower losses. The reliability question and the uncertainty of a completely new technology are the two main reasons that have largely deterred the use of superconductivity in electric machines. Reliability is a key problem for superconducting machines, though numerous superconducting systems have demonstrated great reliability. The BEBC bubble chamber at CERN has worked 24,000 h with rated current of 5700 A and has stayed cold during nine years without any intervention. Stationary cryogenics is now a proven technology. However, present cooling systems for machines, using water and hydrogen, are not simple. Hydrogen requires in particular a rather complicated seal system and is dangerous.

The loss savings may be much higher for some special drives with low weight requirements, as in mobile applications. In order to decrease the weight of the conventional electric machines, the current densities are increased using sophisticated cooling technologies. A consequence is a reduction in efficiency. Electric machines for mobile systems (space, planes, trains, etc.) are lighter but less efficient than their homologs for stationary applications. As an example let us consider transformers for high-speed trains. Their efficiency reaches in some conditions only 90%, compared to 98% for conventional transformers, but their weight is reduced by a factor of two. Superconducting machines are therefore very attractive solutions for mobile applications.

The magnetic circuit close to the conventional armature conductors limits the voltage in general to around 30 kV, much below the level of a transmission network (200–750 kV). The generators are hence connected to the power grid through a step-up transformer. Due to the elimination of the magnetic teeth, it is possible to extend the voltage upward. A direct connection of the generator to the transmission system can be considered (21). The elimination of the step-up transformer would result in a simplification of the power generation system, and in a still higher efficiency. Researches have been carried out along the same lines for the conventional generators, and concepts for conventional machines operating at transmission-level voltages have been known for decades, but technical problems are numerous. Recently ABB (Asea Brown Boveri) has presented a new high-voltage conventional generator offering a direct connection to the power network (22).

Electromagnetic Shields. The superconducting winding is in general surrounded by an electromagnetic shield that protects the superconducting wire from time-varying fields under transient or unbalanced operations. As soon as it is subjected to external time-varying fields, eddy currents are induced and cancel those fields (23). The superconducting winding only experiences very attenuated time-varying fields, leading to ultralow ac losses.

The electromagnetic shield is a conducting cylinder or a squirrel cage. The lower the resistivity of the shield is, the better its shielding performance is. For this reason shields are often cold, to benefit from the reduced resistivity of metals at low temperatures.

A very effective shield limits the rate at which the excitation field can be changed, whereas quick changes are required for transient stability. Compromises are necessary. Also, electromagnetic shields are subject to very large electromagnetic stresses under severe transients, such as sudden short circuits, and they should be mechanically designed with great care to withstand those stresses.

For a generator, the electromagnetic shield plays an important part in stability. To damp mechanical oscillations after a perturbation, losses are required and superconductors are not convenient. So the electromagnetic shield acts also as a damper. Unfortunately, a good shield for the superconducting winding is a bad damper, because the resistivity must be very small to shield very small field variations. Good damping is achieved by a shield with a large resistivity, operating in general at room temperature. Consequently the electromagnetic shield system often consists of several shields at different temperatures. The multishield system protects the superconductor and damps the oscillations.

Fully Superconducting Machines. A fully superconducting ac generator [Fig. 1(c) potentially surpasses the advantages of the superconducting-field-winding generator in mass, size, and efficiency by increasing the armature ampere-turn loading. By introducing the superconducting stator and ac wires for the excitation (24), the cryogenic rotor can be simplified with the elimination of the electromagnetic and thermal shield system [Fig. 1(c)]. The magnetic shield remains outside around the armature winding so as to avoid iron losses. The magnetic shield can operate at an intermediate temperature between 4 K and 300 K (80 K, for example), since the specific work decreases rapidly as the temperature increases (Fig. 3). It may act as a thermal shield as well. The superconducting armature increases the freedom to select electrical characteristics and thus to benefit from optimized system performance. For example, the synchronous reactance can be selected over a very wide range of values. It will nevertheless be higher than in the superconducting-field-winding generator, since it is proportional to the armature ampere-turn loading.

Steady-State and Transient Stabilities. Better power density and efficiency are not the only advantages of superconducting machines. Superconducting generators improve the steady-state and transient behavior of the network (25,26,27). The reactive load capacity is enhanced as well. These advantages are due to the lower value of the synchronous reactance.

In steady-state synchronous balanced operation, the electrical diagram of one phase of a linear and isotropic synchronous machine is very simple. It consists of an electromotive force E in series with a reactance

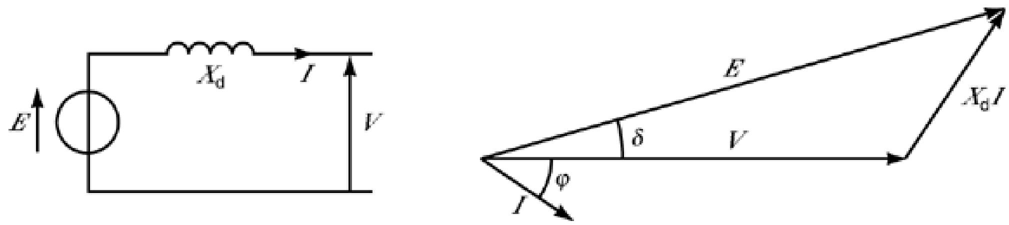

Fig. 5. Balanced steady-state equivalent circuit for one phase (star representation) of an ac generator.

X_d called the synchronous reactance (Fig. 5). The latter is the inductance of one phase, taking into account the two other phases (for a three-phase machine), multiplied by the electric pulsation rate. A resistance may be added to take losses into account but it is generally negligible compared to the synchronous reactance. E is proportional to the excitation current. The expressions for the power in a three-phase synchronous machine, neglecting the losses, are

$$P = 3VI\cos\varphi, \qquad P = \frac{3\,E\,V}{X_d}\sin\delta \tag{4}$$

Here δ is called the internal angle and plays an important part in steady-state stability. In steady-state operation where the generator is connected to the network, the voltage V is constant. Neglecting the regulation of the excitation current, the electromotive force E is constant as well. The steady state stability limit for the internal angle [Eq. (4)] is $\pi/2$. This equation also shows that the lower the synchronous reactance is, the higher the static stability is, since the internal angle is lower for a given power.

A magnetic circuit increases the inductances. For this reason, a superconducting generator with an air-core armature has a lower synchronous reactance than a conventional one with a iron-core structure (Table 1). Roughly speaking, the reactance reaches 1/5 to 1/3 that of the conventional machines. Moreover, the voltage regulation of the generator is simpler with a low synchronous reactance. Figure 5 shows in fact that the electromotive force varies less with respect to the armature current when the synchronous reactance is low.

Figure 5 is no longer valid in the presence of transients. The machine is then represented by two axes, with the d axis (excitation-field axis) perpendicular to the q axis. Depending on the rate of the disturbance, the transient (X'_d) and/or subtransient (X''_d) reactance will have to be considered. These reactances are linked to the synchronous reactance by dispersion coefficients, which depend only on the geometry:

$$X''_d \approx X''_q = \sigma_k X_d, \qquad X_d = \sigma_f X_d$$

A parameter commonly used to characterize the transient capability is the critical fault-clearing time (*CFCT*). It is the maximum delay during which the generator can be subject to a fault (short circuit) and still remain in synchronism after the fault has been cleared. Figure 6 shows that the subtransient reactance is the key parameter in determining the CFTC. The synchronous reactance plays a limited part, though a low value is slightly favorable. However, low values of the subtransient, transient, and synchronous reactances results in very high short-circuit currents and huge electromagnetic stresses on the machine. The machines must be mechanically designed not only for rated operation but also to withstand torques during fault conditions.

New systems have been considered to improve the stability, especially for fully superconducting generators, which are inherently unstable due to the absence of loss for damping. The control of energy transfers

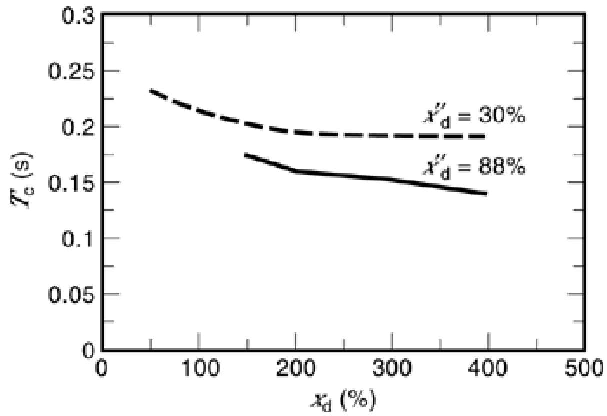

Fig. 6. Influences of x_d and x_d'') on the critical-fault clearing time (24).

between the machine and a superconducting magnetic energy storage (*SMES*) provides good stability (28,29). The SMES can also absorb a part of the energy during a fault and thus increases the CFCT. Stability problems still require a lot of work, and new systems afford challenging opportunities.

Cryogenics

Cryogenics comprises all the techniques related to low temperatures. These are complicated but well mastered now. Nevertheless, superconducting machines pose an additional difficulty due to the need to rotate one cryostat (30), sometimes at high speed (3600 rpm). The mechanical stresses are important, and the effect of centrifugal forces should be considered with great care. In particular, the liquid flows radially outward and is compressed, resulting in a temperature rise. This effect is not negligible for liquid helium. However, better heat exchange between the fluid and the superconducting coil is obtained due to the rotation.

The mechanical structure must not only withstand the electromagnetic forces of the winding itself as in other superconducting devices, but also the entire torque of the machine during normal operation and, above all, severe transients. The machine must not be destroyed by a sudden short circuit, for example. Huge overtorques (up to 10 times the rated value) can then be experienced. The resulting stresses are very severe and can be extreme on the electromagnetic shields. But the thermal losses through the mechanical structure should be kept to a very low level because of their very high cost at 4 K (700 W/W). Special machine structures make it possible nevertheless to suppress the torque on the field winding (31). The vacuum vessel should be very tight, since dynamic pumping is problematic due to the rotation. The isolating vacuum should be maintained at a cryogenic level over a long period.

Two components require special attention for a rotating cryostat: the helium transfer coupling and the differential contraction system, which has to cope with the rotation. The transfer of liquid into a rotating cryostat with low losses is not a simple problem, but it has been solved. The classical solution is a bayonet-type connection (Fig. 7) with a rotating seal system operating in general at room temperature. Ferrofluidic, mechanical, or labyrinth seals can be used.

The cryostat for a superconducting armature is special as well. It is stationary, but it is subjected to rotating fields. All the central parts of the cryostat thus require electrically insulating materials to avoid eddy currents. Fiber-glass–epoxy composites have suitable electrical, mechanical, and thermal properties, but their

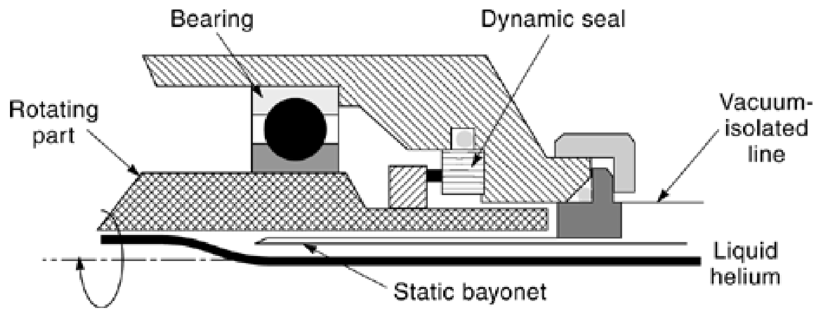

Fig. 7. Very simple example of a helium transfer system for a rotating cryostat.

use poses some difficulties in a helium cryogenic environment. Attention should be focused on helium tightness (particularly at room temperature), reliability of the adhesive joints, and resistance to thermal shocks.

Table 1 (24) gives some characteristics of a conventional and different superconducting generators (32, 33,34) with a rating of 300 MVA at 3000 rpm.

Historical Background and Current Trends

The first superconducting machines were constructed and tested (35,36) as soon as superconducting wires with high current capacity under field were available in the sixties. For experimental reasons, these first superconducting field windings were stationary. The first machine with a rotating superconducting field winding was built at MIT (37). A 50 kW synchronous machine with a superconducting field winding and a superconducting 400 Hz armature was built by Dynatech (38), but the large ac losses in the armature precluded satisfactory operation. Fully superconducting machines were abandoned up to the eighties. With the Dynatech exception, up to the eighties, only the field winding was superconducting; the armature remained resistive and operated at room temperature. Considerable research and development on these machines was carried out (14,39,40), because there was then a large motivation. The rapid growth of the electric energy demand was requiring generators with ever higher ratings, but the resistive generators showed technological limits (1,800 MW), which had been rapidly reached. Only superconductivity pushed the limits and brought the possibility of building generators with higher ratings in order to answer the electrical demand. The numerous programs throughout the world have led to large-scale experiments for electrical and also cryogenic investigations, demonstrating the possibility of building superconducting generators. The main technical problems were solved, though a lot of R&D is still required to meet the conditions necessary for building industrial products. Nevertheless, since the eighties, only generators with medium ratings (600 MW) have been required, due to the moderation of the electric energy demand. Most of the programs for ac generators were then reduced or stopped. The reasons were not technical. The market conditions are unfavorable to superconducting generators only because their critical size (between 500 MW and 800 MW for 4 K superconducting generators) is around or even above the market rating. Only the Japanese have continued their effort, in particular with an ambitious program called Super GM with three 70 MW superconducting model rotors (41).

The critical (breakeven) size is difficult to give with accuracy—firstly because some data are difficult to evaluate (reliability, investment and operating costs for completely new devices, etc.) and secondly because the critical size strongly depends on the application. Weight saving for a generator is not posted in the same way for a stationary application (power plant) and for a moving system (train, ship, plane, etc.). A weight reduction of 1 kg represents savings of about $700 to $800 for a plane, and $15,000 to $20,000 for a satellite (cost of launching), but much less for a power plant. The critical size of a superconducting generator will consequently be lower for an airplane than for a stationary power plant.

Superconducting ac generators have mainly been developed for large electric networks. Nevertheless, generators for airborne applications have been studied and designed (42,43) because their light weight is then of great interest.

Though the main developments have concerned ac generators, work has also been done on motors, especially in the United Kingdom (12), in the United States (13,44), in Japan (45), in Finland, and in China, where homopolar machines for marine propulsion have been studied.

The emergence of superconducting strands able to operate under magnetic fields at industrial frequencies (50 Hz or 60 Hz) with ultralow losses changed the technical situation in the eighties (11). The Dynatech experiment of 1967 could then be reconsidered with confidence, and some small-scale fully superconducting machines experimentally proved the possibility of designing satisfactory 50 Hz armature windings (16,17, 18,19). Due to the absence of industrial motivation to develop superconducting generators, these successful experiments stayed at the laboratory scale.

On the other side, superconductors could be an attractive option for high-performance lightweight electric drives. The discovery of high-T_c materials has reinforced this interest because cryogenic systems at higher temperatures than 4 K are much simpler and more practical than to those at 4 K. The use of electric drives is continually increasing, and weight constraints are becoming more and more severe. In high-speed trains, for example, increasing speed requires more powerful motors. Their weight should be reduced as much as possible in order to limit the load per axle tree to avoid rapid track degradation.

Super-GM (46)). The Japanese are the only ones who have not only continued on working on superconducting machines but also reinforced their programs since the seventies. In 1988 the Ministry of International Trade and Industry (*MITI*) launched a very ambitious project called Super-GM (an engineering research association for Superconductive generation equipment and materials). The objectives were to develop a superconducting technology for electric power generation, including the design of 200-MW-class pilot generators and the construction of 70-MW-class models. This large project is commissioned by *NEDO* (New Energy and Industrial Technology Development Organization). It involves 16 members from industry and research institutes. The research and development program includes work on superconducting materials (both LTS and HTS), structural materials, the machines themselves, and helium refrigeration systems. Three different large rotors with NbTi field windings were built and successfully tested using a common resistive stationary armature (Table 2). Through the three rotors numerous critical issues were investigated and tested (field winding, NbTi conductor, excitation control, damper structure, thermal contraction system, etc.). The experimental programs were carried out in a special test facility (Fig. 8). The superconducting windings are cooled by liquid helium using a 100 l/h liquefier through a transfer coupling. Basic steady-state operations were performed, but also severe tests such as three-phase sudden short-circuit and excessive negative phase. The tests began in 1997 and were completed in 1999. Machine A was connected to the 77 kV power grid and supplied 40 MVar. A power of 79 MW was achieved with machine A, which has operated with 82 MVar. Machine B reaches the remarkable power of 79.7 MW. It operated more than 1500 h with 44 successive starts and stops. It ran 814 h at its rated capacity of 79 MW. The quick-response machine (machine C) supported a current rise of 3200 A/s (3.8 T/s) without quenching. The refrigeration system ran 9320 h without failure, and the estimated mean time between failures (*MTBF*) reached 14637 h (about 20 months). Super-GM was a very successful project, which demonstrated the satisfactory and reliable operation of superconducting generators with significant power even during severe conditions. The technology was developed and experimentally qualified for 200 MW rating. Japanese workers are analyzing all the results, but design and construction of the 200-MW-class pilot generator have been deferred.

Permanent-Magnet Superconducting Machine (47). Superconducting armatures could be designed in the eighties thanks to the emergence of ultralow-ac-loss NbTi strands at that period. They brought a large benefit by strongly increasing the armature ampere-turn loading with low losses even when referred to room

Fig. 8. Superconducting generator on the stage of the Super-GM testing center (from left to right: liquid-helium dewar, superconducting generator, driving motor). (By courtesy of Super GM.)

Table 2: Main specifications of Super-GM model machines (41)

	Description		
	Slow Response (0.1 p.u./s)		Quick Response (1 p.u./s)
Characteristic	A	B	
Rating (MVA / MW)	83 / 74.7	83/74.7	73/65.7
Voltage (kV)	10	10	10
Current (A)	4792	4792	4215
Speed of rotation (rpm)	3600	3600	3600
Synchronous reactance (p.u.)	0.35	0.35	0.45
Field current, rated/max (kA)	3/3.6	3/3.6	3.2/4.5
Rotor structure:			
Warm damper	Single layer	Squirrel cage	Three layers
Cold damper/radiation shield	Three layers	Single layer	Single layer
Thermal contraction system	Double bearings	Flexible disk	Flexible support
Superconductor (NbTi)	High stability	High current capacity	Low ac loss
Stator	Air gap winding, double transposed copper conductor, water cooling		

temperature using the high specific work (740 W/W). In view of their reduced size and especially weight, superconducting drives are particularly attractive for mobile systems with low-weight requirements. However, these applications subject the drives to severe mechanical stresses due to shock and vibration. Therefore the fully superconducting design with cryogenic field winding and armature has not been thought to be the best suited one for those applications, especially with a NbTi field winding. Rotating 4 K cryogenics is very complicated and appears unlikely to withstand a severe mechanical environment. It is much simpler to cope with high stresses with a stationary cryostat. There are a lot of NbTi windings in magnetic resonance imaging (*MRI*) apparatus, used on trucks, that nevertheless operate safely and reliably. These observations have led to a hybrid structure with a permanent-magnet rotor and a NbTi armature. The rotating part is very simple and robust, and high performance is obtained with the superconductor in the stationary armature. Permanent

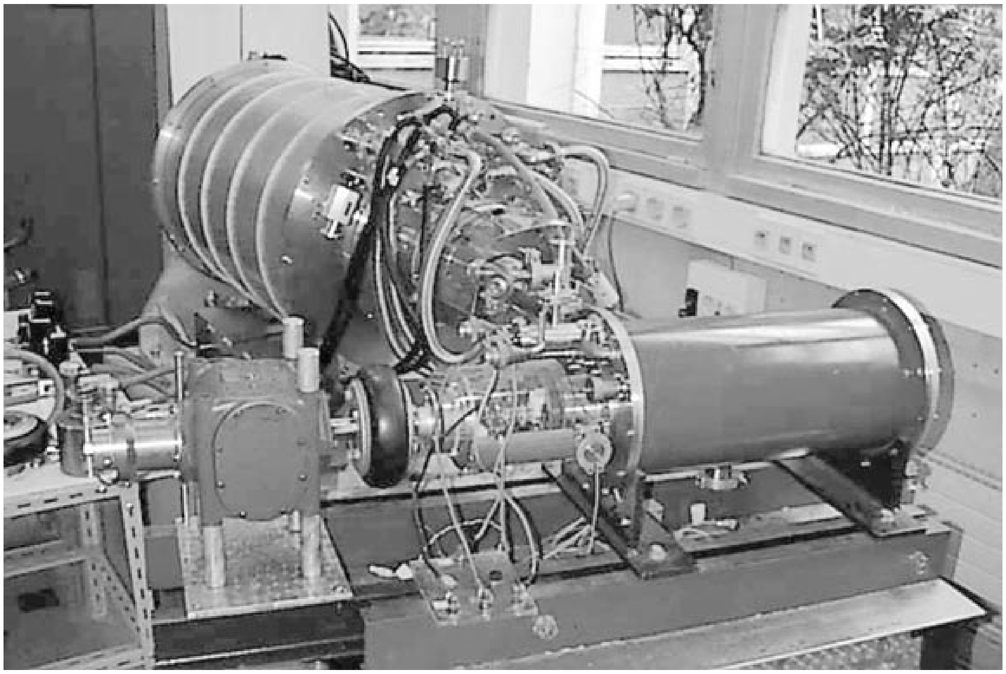

Fig. 9. Permanent-magnet (NdFeB) superconducting (NbTi) motors: 15 kW, 750 rpm (foreground) and 150 kW, 400 rpm (background).

magnets obviously produce a slightly lower field than a superconducting field winding, but this is acceptable for the NbTi armature in terms of critical current density and ac losses. Two machines were built (Fig. 9) with the support of the Délégation Générale de l'Armement (*DGA*), France. The 15 kW, 750 rpm model successfully experienced a large number of tests in steady state and transient operation. Its was powered by a pulse width modulation (*PWM*) voltage inverter for variable speed that was easily controlled. However its size was too small to be representative of a real machine because the critical size is greater than a megawatt, and a 150 kW, 400 rpm demonstrator followed. The latter passed successfully its first electrical tests in long-term and constant-speed operation.

The permanent-magnet rotor might be replaced with a HTS field winding (48). Operation at around 30 K enables one to cope with a severe mechanical environment much more easily that at 4 K. The field winding can be cooled by helium gas consisting of vapors from the liquid in the armature vessel.

High-Temperature-Superconductor Motors and Generators. A 1500 W HTS motor was built using Bi–PIT racetrack coils operating at 20 K (49). US researchers from Reliance Electric and American Superconductor Corporation (*ASC*), with support from the US Department of Energy, are working on motors using HTS rotating field windings and a conventional resistive armature (50). The rotor is wound with a Bi-2223–PIT tape from ASC and cooled to about 30 K by helium gas circulation. The superconductor is protected by an electromagnetic shield. The latter is composed of a cold copper shield and an external rotating vessel that acts as a damper. The present structure of PIT with a silver alloy matrix results in ac losses. Several motors were built. A 100 kW, 1800 rpm designed prototype was successfully tested in 1996, and it delivered 150 kW continuously at the rated speed with the superconducting field winding operating at 27 K. The same year the design and construction of a second motor was launched. Its rating of 750 kW at 1800 rpm (4160 V, 104 A) corresponds to about the critical (break even) size for superconducting motors, though this parameter is difficult

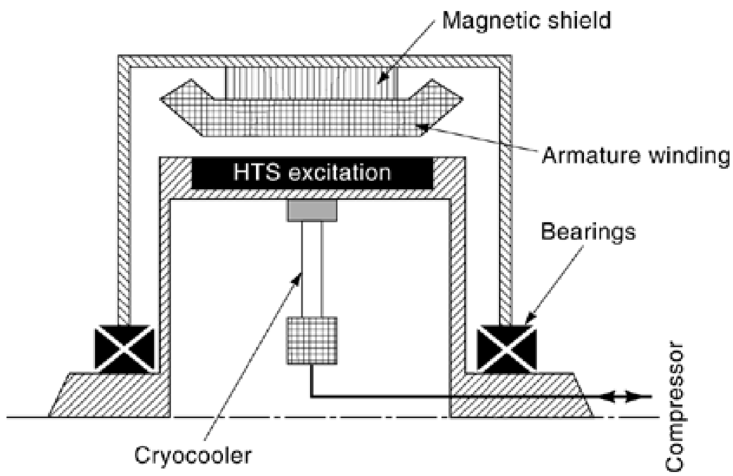

Fig. 10. 19 MW HTS motor concept (from Ref. 51).

to evaluate. The air-core armature is cooled by water, and the supporting structure uses G-10 fiber-glass–epoxy composites. A Brayton closed-cycle helium refrigerator produces He at about 24 K to cool the HTS winding through forced circulation. The estimated thermal loads reach 24 W for the rotating cryostat and 5 W for the field winding. The motor is now at the final assembly stage. The next step will be a 3.7 MW precommercial prototype.

The US Navy is interested in HTS large drives for surface combat ships or submarines. The considered rating is 19 MW. The HTS motor is expected to be one-fifth the size and the weight of conventional machines (51). The HTS motor design was based on a 12-pole synchronous machine with a HTS field winding. The HTS coils are not cooled by a cryogen but are conduction-cooled with cryocoolers at a temperature in the range from 20 K to 40 K. The Gifford Mac Mahon cryocooler cold heads used are put directly on the support of the HTS coils (Fig. 10) and are supplied with high-pressure (about 1.6 MPa) helium from an external compressor. These cryocoolers have reliability in accordance with the requirements for those motors. The armature is air-cored and resistive. Another advantage for such applications is the acoustical quietness of superconducting machines due to their air-cored armature. The design of a 20 MW HTS motor was recently funded by US Navy.

Work is also being done on HTS generators, especially for mobile systems such as airborne applications where the reductions of weight and losses are of prime interest. The US Air Force has a program for megawatt-class generators using HTS field windings (52).

Special Machines

Reluctance, Hysteresis, and Trapped-Field Motors (53). Superconductors for motors can be either wires (for windings) or bulk. YBCO pellets have large sizes [up to 100 mm in diameter now (8)] and good electromagnetic properties in liquid nitrogen (77 K), and consequently represent a new and attractive opportunity for motors. A variable-reluctance structure containing such a rotor made of materials with different magnetic permeabilities can produce a torque. The larger the difference of permeability is, the larger the expected torque is. Superconductors, with permeability near zero (diamagnetic behavior) are therefore potentially attractive. Several reluctance motors up to 10 kW have been built with bulk YBCO and tested in liquid nitrogen (54).

The torque in an asynchronous motor is created by the losses in the rotor. The rotor is subjected to a rotating field. Ac losses appear in superconductors as soon as the external field is time-varying. This is considered in general as a drawback, but it can be used in a hysteresis motor. The rotor consists of a bulk pellet or an assembly of bulk YBCO pieces. The ac losses in the superconductors, called also hysteresis losses, produce the torque. This is an attractive principle for small motors in special applications (cryogenic pumps, for example). It has been studied experimentally in models with ratings up to 4 kW (55).

Rare-earth permanent magnets such as NdFeB have magnetization about 1.5 T at 300 K. Materials with higher magnetization would result in better performance—in particular, a larger torque per unit volume. The attainment of trapped fields as high as 11.4 T at 17 K in bulk YBCO samples (56) opens new and attractive opportunities for electric machines (57). Bulk superconducting pieces with a trapped field could be used in synchronous machines. The operation is slightly different than that of a permanent-magnet motor, since a HTS sample works at constant magnetic field and flux, whereas a permanent magnet works at constant magnetization. Moreover, the magnetization is different for the two cases: it is constant in a permanent magnet, and conical in a cylindrical HTS material. The main problem is the magnetization of the HTS samples. The fields required are very high: 6 times the mean magnetization for zero-field cooling and cylindrical conditions.

Supersat (58). A superconducting machine of a new type, called Supersat, has been developed. Supersat is based on rotating ferromagnetic plugs saturated by an external static field produced by a superconducting solenoid. The Fe–Co plugs act as permanent magnets with a magnetization of 2.4 T, and they are all magnetized in the same direction. The rotor is bulk and is convenient for very high rotation speeds. This is a disk-type machine with an axial field and radially distributed armature conductors.

Conclusions

Though the technical problems are not completely solved, the further development of superconducting machines is not determined by the technology but by the market. Superconducting machines offer better characteristics and performance (weight, efficiency, electric behavior, etc.) than any conventional technology. The deregulation of the electricity market and the progress in high-T_c materials present a good opportunity for superconducting devices. The cost of HTSs is at present one of the main economic limitation on those devices.

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PASCAL TIXADOR
CNRS-CRTBT/LEG