

HIGH TEMPERATURE SUPERCONDUCTING SYNCHRONOUS MOTORS: ECONOMIC ISSUES FOR INDUSTRIAL APPLICATIONS

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Paper No. PCIC-2006-31

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Abstract - High temperature superconducting materials offer the capability to reduce losses in large industrial motors (greater than 1000 horsepower in rating) by 50%. This loss reduction can be accompanied by an overall motor size reduction. The application of high temperature superconductors in high horsepower electric motors is described and the potential benefits of these motors are discussed. The economic viability of high temperature superconducting based electric motors for industrial applications depends upon the cost of the superconducting wire. A discussion of wire component costs for readily available first generation high temperature superconducting wire as well as the future, lower cost, second generation high temperature superconducting wire is presented showing that economically viable high temperature superconducting based motors will require second generation wire. A review of the state-of-the-art in industrial motor lab prototype demonstrations of high temperature superconducting based motors is presented showing the rapid advancement of this technology. The application advantages of high temperature superconducting motors in pump and fan systems are also discussed.

Index Terms — synchronous motors, high-temperature superconducting, pumps, fans, energy efficiency, electric motors.

I. INTRODUCTION

Superconducting materials have the unique property of being able to carry current with negligible resistive losses. This near no-loss property occurs when the superconducting material is operated below a critical temperature, magnetic field, and current density level. Before 1986, the critical temperature of superconducting materials was in the range where liquid helium (at 4.2 Kelvin) was the required cooling fluid for superconducting coils. (Note that the Kelvin temperature scale is used for low temperature systems and that degrees Celsius = Kelvin - 273 and zero Kelvin is absolute zero). The cost to cool superconducting coils using these low temperature

superconducting (LTS) materials was prohibitive when considering their use in industrial electric motors. In 1986 the discovery of high temperature superconducting (HTS) materials raised the interest of rotating machinery manufacturers as the critical temperature of these materials exceeds the boiling point of liquid nitrogen (77 Kelvin or 77 K). Fig. 1 shows the critical temperature of superconducting materials versus their date of discovery.

The discovery of the Yttrium and Bismuth based materials, YBaCuO and BiSrCaCuO, respectively in Fig. 1, resulted in active development of HTS wire and coils for industrial electric motor and utility generator applications. Although these materials do superconduct in liquid nitrogen (77 K), they can carry higher currents at higher magnetic fields when their operating temperature is dropped. For superconducting motors, these materials are typically cooled to the 30 to 40 K temperature range. For a 6000 hp (4480 kW) industrial motor, the input power to the cooling system for the superconducting coils operating at 30 K will be about seven kW or 0.16% of the rated output power of the motor.

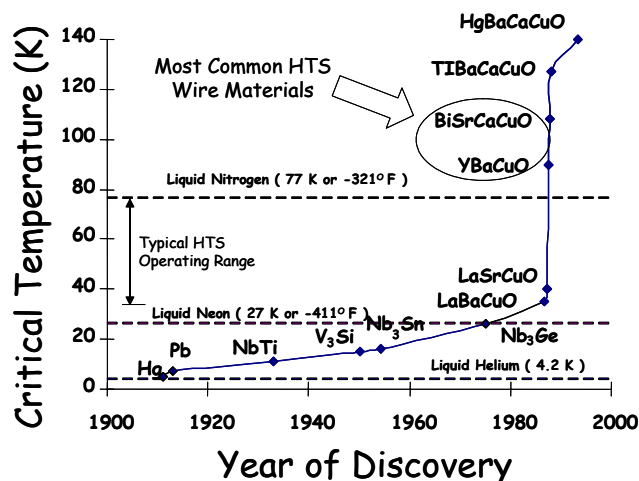


Fig. 1 Critical temperature of superconducting materials

The cost to cool superconducting coils is roughly proportional to the inverse of the operating temperature in Kelvin. Therefore, a 6000 hp motor operating with LTS materials at 4 K would require at least 1.2% of its rated power for cooling the superconducting coils. This 1.2% loss will significantly impact the motor efficiency, making LTS based industrial motors in this rating range not practical in applications where the motor efficiency is considered the main market driver.

Research directed at the development of economically viable HTS based industrial motors has been going on for over 18 years [1-7] and has included the demonstration of a number of motor prototypes in ratings up to 5000 hp (3730 kW). Superconducting technology promises substantial loss reduction for motors in the rating range of 5000 hp and above accompanied with motor volume reduction. Loss reduction of a factor of two compared to energy efficient induction motors of the same rating appears feasible. Along with loss reduction, significant volume and weight reductions are also possible, thereby making HTS based motors a technology that will impact large motor users.

This paper provides an overview of 1) how HTS materials are used in motors, 2) how HTS motors performance compares to induction motors, 3) the impact of HTS wire type and cost on the economic viability of HTS motors for industrial applications, 4) the history of industrial motor lab prototype demonstrations using HTS materials, and 5) application advantages of HTS motors compared to induction motors for typical pump and fan installations. Performance comparisons will concentrate on both first cost and operating cost considerations for the HTS based machines compared to energy efficient induction motors in the 5000 hp rating range and above.

II. HTS MATERIALS IN INDUSTRIAL MOTORS

A. Synchronous Motor With HTS Field Winding

Superconducting materials remain lossless when carrying DC current in the presence of a DC magnetic field. Although low loss superconductors that can operate in AC magnetic fields are under development, the most likely first application of HTS materials in industrial motors will be with DC current coils. A synchronous motor with a rotating HTS field winding and a copper stator winding is the motor topology that is currently being developed for industrial applications. ¹ Fig. 2 shows a cut-away view of this type of motor.

The HTS coils are located on the rotor and are thermally insulated from the rest of the machine components by a vacuum insulation space which has an outer vacuum jacket that is the outer surface of the rotor. Heat conduction from the room temperature drive shaft and the opposite drive end shaft extension to the cold space (where the torque is created) is reduced through the use of composite torque tubes [8]. Although the HTS coils are kept at cryogenic temperatures, the motor shaft, bearings, and outer rotor surface will be at room

temperature or above due to the extensive thermal insulation system employed in the rotor. The superconducting field winding is energized by a rotating, non-superconducting, brushless exciter.

The HTS coils are cooled by a cryogenic fluid or gas that is introduced from the cryocooler (the low temperature refrigerator) through a cryogenic transfer coupling that is located at the end of the opposite drive end shaft extension. The cryocooler system required for a 6000 hp motor is 0.5 m³, which is about the size of a three drawer file cabinet. In early applications of HTS motors it is expected that a second cryocooler of this size, for redundancy, will also be supplied to reduce the concerns of cryocooler reliability and to aide with rotor cool down. Rotor cool down will require about three days, so it is expected that the motor rotor will be cooled down once and then remain cool except during major motor maintenance activities.

Advances in cryocooler reliability and reduction of maintenance have been made in parallel with HTS materials development. A cryocooler of the rating required for a 6000 hp motor, today, has a required maintenance cycle of 10 000 hours. Smaller cryocoolers, developed for HTS based electronics, have been developed to be maintenance free, with field-proven MTBF of over 500 000 hours [9].

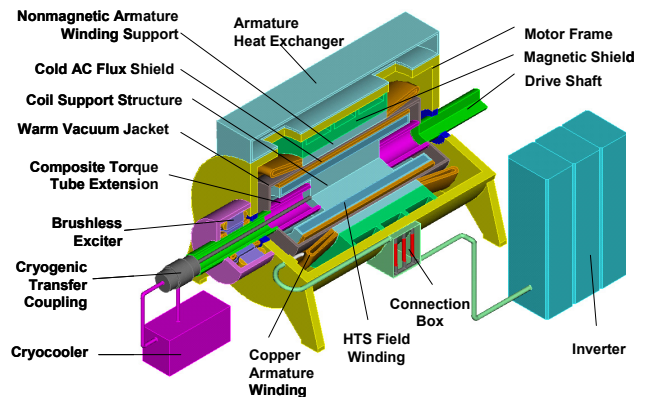


Fig. 2 Synchronous motor with HTS field winding

In HTS synchronous motors of this type the HTS wire current density in the field winding is raised to a very high level, in excess of 20 000 amps/cm², so that the magnetic field at the armature winding is in the range of 1 to 2 Tesla, a factor of two or more higher than that which is normally produced in a conventional motor. The ability of the HTS coils to carry such a high current density, with little to no loss, is the key performance characteristic of HTS wire that is used to make the superconducting motor smaller and more efficient than a conventional motor of the same rating. By increasing the magnetic field level in the armature winding, the power density of the motor can be dramatically increased. A high power density results in lower overall motor losses since the copper stator winding and stator electrical steel losses are reduced because there is less copper and electrical steel in the machine.

The armature winding on the stator is made up of coils of copper wire that are located in a nonmagnetic support structure. Electrical steel stator teeth are not used since the high magnetic field levels in the stator would result in an unacceptable increase in stator core loss. The copper conductors are constructed from Litz wire with transposed conductor strands in the slots to

¹ This work is partially funded by the U.S. Department of Energy through a Superconductivity Partnership with Industry program under Cooperative Agreement DE-FC36-93CH10580

reduce eddy current losses in the stator conductor. Outside (radially) of the stator conductor support structure is the laminated magnetic shield (the stator core) which is constructed from electrical steel. The armature winding is commonly liquid cooled since the stator winding conductors are thermally isolated from the stator core by the nonmagnetic stator winding support structure.

Methods to reduce AC flux in the HTS coils due to motor and power source transients (which will produce losses in the superconductors) are described in [4]. The motor is inverter powered by an adjustable speed drive (ASD). Line start HTS motors are possible, but the additional losses and rotor heating that would result during starting would be difficult to remove from the cryogenically cooled rotor.

The HTS synchronous motor topology, as described above, results in a few advantages over a conventional induction or synchronous motor. The rotor is held at a constant temperature, therefore eliminating electrical insulation and rotor structural issues associated with repeated thermal cycles. The rotor construction with the composite torque tubes and outside vacuum space tube, combined with the smaller rotor size results in two pole rotors that are stiff shaft in larger motor ratings. The stator winding is located in an electrical insulating slot structure that places more dielectric material between the copper conductors and the stator core, thereby reducing dielectric stress (measured in volts per mil) from the winding to a grounded surface. These advantages are in addition to the size and efficiency advantages that are highlighted in other sections of this paper.

B. Example Design Comparisons

Large synchronous motors with HTS field windings will be more efficient than conventional motors. To illustrate this point, parametric design studies were conducted on a 6000 hp, 3600 rpm, 2 pole, HTS synchronous motor and the performance results were compared to a high efficiency induction motor of the same rating. Full load loss distribution for these two motors is shown in Fig. 3.

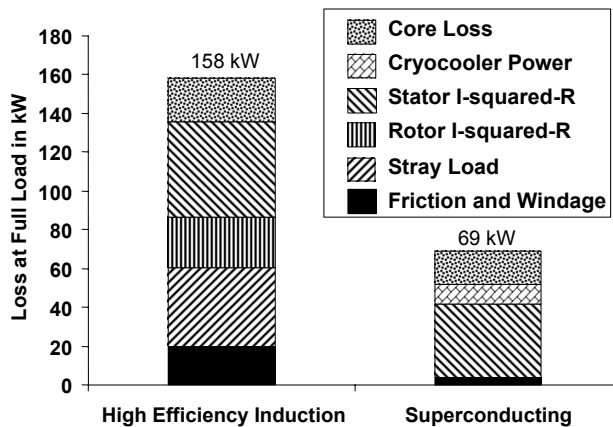


Fig. 3 Loss distribution of 6000 hp, 3600 rpm motors at full load operating conditions.

Table I contains a comparison of the performance and size of the two machines. The full load loss of the HTS motor is 44% of

the full load loss of the high efficiency induction motor. In addition, the 6000 hp HTS motor has an active volume (defined as $\pi D_o^2 L/4$, where D_o is the stator outer diameter and L is the stator stack length) that is 59% of the active volume of the induction motor. The volume reduction is what drives the stator copper I^2R loss, rotor friction and windage, and stator core loss reduction in the HTS motor. These losses are reduced because there is less material in the HTS machine. Loss values in Fig. 3 are for sine wave operation of each machine. Stray load loss in the HTS motor is assumed to be negligible since the HTS motor does not have rotor inter-bar currents or air gap surface losses from magnetic field harmonics related to stator or rotor teeth (since there are no steel teeth in the HTS machine). Inverter related losses in the HTS machine are not expected to be any larger than in an induction motor, so the loss and efficiency comparison results discussed here will apply equally well to inverter driven machines.

TABLE I
6000 hp, 3600 RPM, 2 POLE MOTOR COMPARISONS

	HTS	Induction
1. Full load efficiency [%]	98.5	96.6
2. Active length [m]	0.81	0.99
3. Rotor OD [m]	0.26	0.45
4. Stator-core OD [m]	0.67	0.79
5. Active Volume [m ³]	0.28	0.48
6. Overall Volume Without Stator Heat Exchangers [m ³]	1.70 Including Cryocoolers	2.21
7. Overall Volume Including Stator Heat Exchangers [m ³]	3.34 Including Cryocoolers	7.95

Row 6 of Table I compares the motor size over the frame but without the stator winding cooling heat exchangers. The HTS motor value includes the volume of two cryocoolers, one is required for continuous motor operation and the other is a backup. Even with this extra cryocooler volume the HTS motor is 23% smaller in volume than the conventional motor. Row 7 compares entire motor volumes, including the stator winding cooling heat exchangers. The conventional motor was assumed to have an air to water heat exchanger (air cooling the stator and rotor) while the HTS motor has a water to air cooling system (water cooling the stator winding and core). The lower loss of the HTS motor as well as the ability to employ direct water cooling of the stator winding and core results in a smaller stator cooling system package for the HTS motor so that the overall motor volume reduction is now 58%. The HTS motor will also weigh less than the conventional motor. Weight reduction values are expected to be at least as large as the volume reductions reported on line 6 of Table I. So for the 6000 hp motor example the HTS motor weight will be less than 73% of the weight of the conventional motor.

The efficiency benefits of the HTS machine span a wide range of loads as shown in Fig. 4. The efficiency values plotted account for the power required to cool the HTS coils as a loss for the HTS motor.

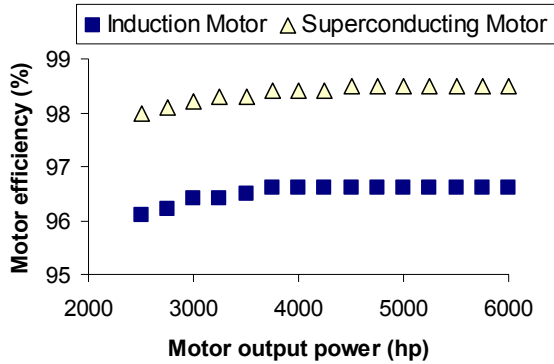


Fig. 4 Efficiency vs output power for 6000 hp, 3600 rpm, 2 pole motors at rated speed.

Efficiency advantages become less impressive for lower horsepower motors. Fig. 5 shows the efficiency versus load plot for a 1000 hp (746 kW), 1800 rpm, four pole, HTS motor compared to a conventional, high efficiency induction motor of the same rating. For this design, there is no full load loss reduction when converting to the HTS machine. The lack of loss reduction is due in great part to the fact that the HTS machine cryocooler input power does not scale with motor size. Some heat leak into the rotor is not dependent upon motor size, such as the leak through the field supply leads. Size reduction can still be obtained with the 1000 hp motor, however, as the HTS machine active volume will be about 37% of the active volume of the equivalent induction machine. For industrial motors, it appears that the lowest possible rating where size and efficiency advantages of HTS motors exist will be around 1000 hp. It is expected that the first introduction of industrial HTS motors will be in the 5000 hp rating range where size and efficiency advantages are more pronounced.

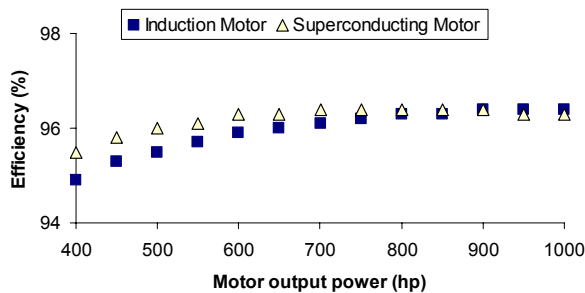


Fig. 5 Efficiency vs output power for 1000 hp, 1800 rpm, four pole motors.

III. ECONOMIC CONSIDERATIONS

A. Life Cycle Costs And First Cost

HTS based motors for industrial applications must effectively compete with high efficiency induction motors if they are to have a significant market penetration. Superconducting motor losses can be less than half the losses of an equivalent induction motor of the same rating. This results in considerable life cycle cost operating savings. For example, for the 6000 hp, HTS motor

described above an annual electric power cost savings of \$40 000 can be obtained by using the HTS motor rather than the energy efficient induction motor (based on \$0.06/kW-hr power rates, full load operation, and 85% utilization over the entire year). The HTS motor, however, will only be economically viable for a broad market if its first cost (the sell price) is such that the payback in lower operating costs due to higher efficiency is in a couple of years.

Additional benefits are obtained due to the smaller motor size which can impact the installation cost as well as the cost to maintain large motor systems. Details of these advantages will be discussed in the applications section of this paper.

The adjustable speed HTS motor / inverter package has additional advantages for fan and pump systems in the energy savings potential for part flow operation, versus mechanical damper and valve systems. Also, improved system performance, life, and reliability based on soft start and variable speed operating capabilities of the adjustable speed system can be obtained as highlighted in the applications section of this paper.

The first cost of an HTS motor, using currently available HTS wire, is strongly determined by the cost of the HTS conductor; so much so that this one material cost overwhelms the other component costs. This is a primary reason that HTS industrial motors are not being marketed today. The best performing, long length HTS wire available today is based upon the Bismuth compound (BiSrCaCuO in Fig. 1 which is commonly referred to as BSCCO or "bis-ko") and is what is called first generation HTS conductor. A new type of HTS wire, based upon the Yttrium compound (YBaCaCuO in Fig. 1 which is commonly referred to as YBCO or "why-be-see-oh") and is called second generation HTS conductor, is being developed and promises to be lower cost than the existing first generation wire.

B. First And Second Generation HTS Wire

Fig. 6 shows a cross section of first and second generation HTS wire. First generation wire is available today in long lengths and is the wire used for all HTS motor demonstrations up until 2004. The first generation HTS wire has a large percentage of silver in its cross section. The superconducting filaments are imbedded in the silver matrix through the use of a powder in tube method in which the superconducting powder is packed in silver tubes that are then packed in a larger silver tube and repeatedly drawn and repacked until fine superconducting filaments are created. The resulting round conductor is rolled flat and then processed at an appropriate temperature and atmosphere to make the wire superconducting. The combination of the high silver content and the multiple processing steps, adds cost to this conductor.

Second generation HTS wire is made up of multiple layers (see Fig. 6) in a thick film type of process. This can be done as a continuous process, reel to reel, in a controlled chamber. The materials in the buffer, substrate, and stabilizer layers are lower in cost than silver. The combination of the lower raw materials cost and lower projected manufacturing costs will ultimately make second generation wire less expensive than first generation wire. Currently, second generation wire is available in short lengths (up to 200 meters). Longer length second generation HTS wire is being developed at wire research centers across the globe. Wire lengths long enough to be used in a large hp motor are projected to be available in 2008.

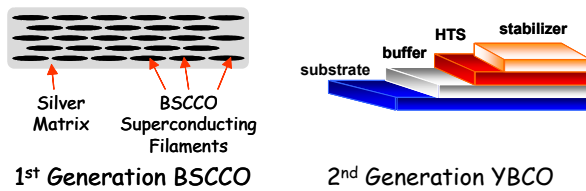


Fig. 6 Cross sections of HTS wire

The cost of the HTS wire is a key component of the total motor cost. Fig. 7 has a plot of superconducting wire cost as a percent of the motor sell price for the 6000 hp motor example of Fig. 3 and Table I. Using first generation HTS wire that is available today, the cost of the HTS wire alone exceeds 35% of the sell price of the induction motor. This high cost, for a single component of the motor, makes current HTS motors for a broad base of industrial applications not economically viable. Fig. 7 also shows that the projected future cost of first generation HTS wire will be around 8% of the sell price of an induction motor. Even at 8% of the sell price, however, the HTS wire cost content would make HTS motors a tough sell in the industrial marketplace. Second generation HTS wire projected costs, in long lengths, are about 25% of the projected first generation wire costs. This brings the HTS wire cost content to around 2% of the motor sell price. At 2% of the motor sell price, the HTS wire cost becomes a small fraction of the total motor cost and more in line with conventional material component costs for a large AC motor (like magnet wire and electrical steel) so that the cost penalty for using HTS materials becomes manageable.

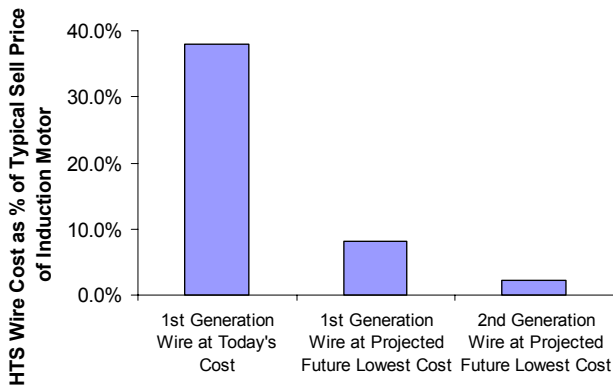


Fig. 7 HTS wire cost as a % of motor sell price for the 6000 hp motor example design

IV. HTS MOTOR PROTOTYPE HISTORY

A. Motors With First Generation HTS Coils

Development of prototype motors using first generation HTS wire has been ongoing throughout the world since the discovery of these materials and the first HTS wire development. All of the motor demonstrations have been laboratory prototypes. None have made it into industrial applications largely due to the cost

penalty for motors constructed with first generation HTS wire. Fig. 8 shows 1800 rpm HTS motor demonstrations vs time and the country of origin of these various prototypes.

B. Motors With Second Generation HTS Coils

In 2005, a small synchronous motor using second-generation HTS-wire technology was demonstrated. The objective of this small motor prototype construction and test was to show that second-generation HTS wire can be successfully employed in applications involving rotating-machinery and not to demonstrate the technology advantages that are expected to result from the second-generation HTS wire. As a result, this HTS motor was not built from “scratch”. Rather, it was based on a standard 5-hp, 4-pole, 3-phase, 1800-rpm induction motor with the HTS synchronous rotor substituted for the original squirrel-cage rotor.

Fig. 9 shows an axial cross section of the resultant motor. A salient-pole rotor configuration was chosen. The HTS coils are marked with ‘X’ and ‘O’ (to indicate current direction). The rotor outer diameter was 12 cm. The motor had four second generation HTS coils. Each coil consisted of 25 turns of 1-cm wide superconducting tape with a total length of approximately 6 m of superconductor per coil.

Fig. 9 also shows the fully assembled motor. In the foreground of the picture on the motor shaft are the slip rings through which current was supplied to the HTS field winding. Additional slip rings were used for rotor sensors. The cooling scheme for the motor is quite simple; liquid nitrogen flows into the rotor via a bayonet inserted into a hole machined into the center of the opposite drive end rotor shaft extension. The liquid nitrogen then flows out of the rotor into the air-gap, spilling over to the stator and out of the motor, ultimately forming a pool at the bottom of motor. A foam container, shown partially assembled in Fig. 9, is used to contain the liquid nitrogen. In HTS motors for industrial applications, the rotor cooling fluid would be totally contained in the rotor, transfer coupling, and cryocooler system (see Fig. 2) so that no cryogenics will be lost.

The motor was tested on a dynamometer stand driven by a variable-speed drive. Operating at a speed of 1800 rpm with a terminal voltage of 486 V and a current of 40 A in the HTS windings, the motor produced an output power of 7.5 hp (5.6 kW) during tests conducted in July of 2005. This is the largest HTS motor demonstration to date with second generation HTS wire and supercedes a two horsepower motor demonstration using this same motor hardware but lower performing second generation HTS coils that was demonstrated in 2004. Fig. 8 includes these two second generation HTS motor demonstrations.

Fig. 8 also shows the rapid progress in development of HTS based synchronous motor prototypes with first generation conductor. The size of motor demonstrations increased as the HTS wire technology improved. Second generation based HTS motors will likely follow the same pattern. As longer length second generation HTS wire becomes available, larger HTS motors will be demonstrated. This progression should be faster than with first generation conductors, since the base technology for high temperature superconducting motors has been developed through the work on first generation based HTS motors.

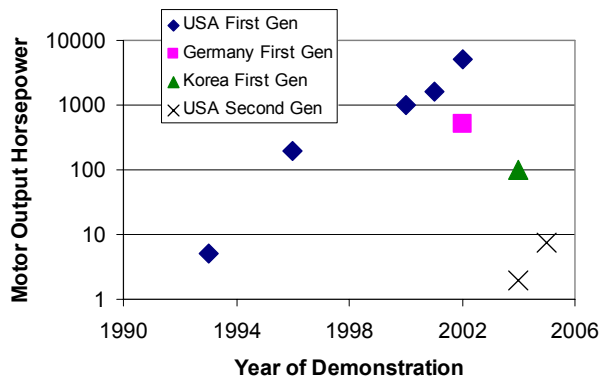


Fig. 8 1800 rpm HTS lab motor prototypes using first generation and second generation HTS wire.

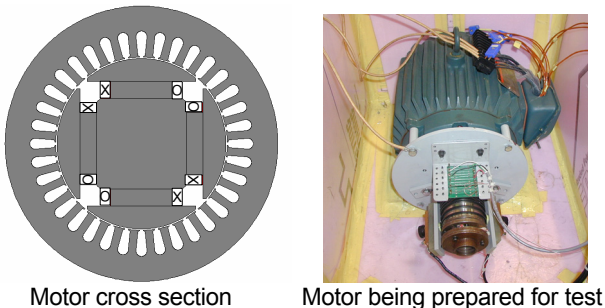


Fig. 9 HTS motor with second generation HTS field coils. (7.5 hp, 1800 rpm)

V. APPLICATION CONSIDERATIONS

Superconducting motors will offer some combination of size reduction and life cycle cost reduction (based on efficiency improvement) over that of conventional, energy efficient induction motors. Efficiency improvement related life cycle cost reduction was discussed above. Size reduction advantages for industrial applications will be discussed in this section. Advantages related to ASD operation, considered to be a requirement for the first HTS industrial motors, are also discussed.

One of the biggest issues in plant construction today is space. How do you fit all the equipment into the area allocated? Once the equipment is configured into the designated area how do you remove the components for maintenance, repair and replacement? Bigger isn't always better. The smaller size of the HTS motor provides advantages for a variety of applications. Several typical applications where the motor size can be a significant factor in both the design of the equipment and the structural support necessary to carry the motor and driven component will be discussed.

A. Vertical Pumps

Vertical pumps in many cases (depending on length of pump)

require overhead clearance equivalent to the length of the pump. The primary reason for the clearance is the requirement to remove the motor and pump for maintenance and allow for use of a lifting device (chain hoist or portable crane). Fig. 10 shows a typical installation and the overhead crane. The required overhead clearance could be substantial depending on the length of the pump. Pump removal can be a major undertaking in many instances due to space restrictions and the overall size of the unit. Large (>1000 hp) pumps can be quite difficult to remove as the motor weight (1000hp, 1800 rpm, 10 000 lbs) and height (approximately 2 m or more) becomes a substantial issue.



Fig. 10 1100 horsepower vertical circulating water pump / motor installation.

The vertical pump stand must be capable of handling the weight and dynamic loading of the motor as well as design loading from the pump. The size and mass of the motor stand is dependant on the hydraulics of the pump which dictates the hp and speed of the motor. Fig. 11 shows the motor stand for a vertical pump installation. In a typical low speed, low head (240 rpm, 6.1 m head, 1000 hp) high flow (100 000 gpm) application the synchronous motor could easily exceed 2.4 m in diameter 2.4 m in height and weigh in excess of 27 000 lbs. The massive size and weight of the motor requires a well reinforced stand to insure stable and reliable operation. This becomes very apparent when an above ground discharge is required. HTS motor size and weight comparisons that were given in previous sections related to 1800 rpm motors. These size and weight advantages will also occur for slow speed HTS motors.



Fig. 11: Motor stand for large vertical pump installation.

The support structure, as with the motor stand, must be capable of supporting the entire pump as well as the motor and associated piping. Typically a foundation for centrifugal

applications must have a minimum mass ratio of three times the mass of the machinery and five times the mass is required for reciprocating equipment. The support structure for a large vertical pump (54 000 gpm and greater) can be five times the cost of the pump and driver. The lower weight of HTS based motors will reduce the cost and size of the motor stand for these types of applications.

B. Centrifugal Pumps

Centrifugal pumps are applied to many different types of liquid services. The applications can generally be classified into three basic functions.

- Raise a liquid from one level to another
- Force a liquid into a vessel at a higher pressure by overcoming internal pressure
- Force a liquid through a pipe by overcoming piping, valve and fitting losses

The motor must be capable of providing more torque than required by the pump at each speed change from zero to full load in order to reach rated speed. Under certain conditions, such as with high specific speed pumps (axial flow, mixed flow) having high shut off head horsepower, motors with high "pull-in" torque and an ASD may be more applicable.

The start-up and shut down sequence of any pumping system is very harsh on the pump. This is due to the time it takes for the "system" to achieve hydraulic stability. In a cooling tower application where the pump and pumping system are in close proximity, the pump will generally experience only a brief hydraulic transient (if started correctly). However, in the case of a long discharge (to the destination) the hydraulic transient could last up to 30 minutes or more. This transient condition can and will reduce the pump life by as much as 50%.

It is normal practice to start vertical axial flow and propeller type pumps with high specific speeds and high shut off horsepower with the discharge valves partially open to reduce starting horsepower and thrust. The conventional start up procedure for a line start pump of this type consists of the following steps: 1) Motor Operated Valve (MOV) at pump is fully closed or 10% open based on the operator preference, 2) the valve at the source is fully closed or 10% open (operator preference), 3) the motor is started, 4) the pump is allowed to come up to speed and pressure (30 seconds to 1 minute), 5) the MOV is slowly opened (approximately 5 to 30 minutes to achieve full open position depending on the system), and 6) the MOV is positioned to the desired flow rate (this could require a partially closed valve at the pump or at the destination depending on the system).

In addition to the unavoidable damage to the pump system and valves, during the normal start-up procedure, should the operator open the discharge valve too quickly or if the system is not properly vented, water hammer can occur. This anomaly will result in severe damage to the pump and system. Typical damage can include: piping failure, broken pump shafts, motor damage, structural damage, broken pipe hangers, and/or mechanical seal failures.

The ASD pump system startup procedure is much simpler and consists of the following steps: 1) set MOV full open, 2) set valve at source full open, 3) start the motor at reduced speed, 4) slowly increase the pump speed until the line is packed, 5) adjust the pump speed to the desired flow and pressure, and 6) monitor/control the speed and flow at the Digital Control

System (DCS).

HTS motors, used in conjunction with the ASD will improve the overall reliability of the "system". The improved reliability is achieved by a more controlled start-up of the pump there-by minimizing wear and tear of the pump system. The ASD will allow the operator to control the flow and pressure without throttling the valves there-by reducing undue stress on the pump and system and saving energy. It is difficult to report "typical" savings, as the savings potential is extremely dependent upon the load profile imposed upon a motor by the equipment it drives. The load profile is the number of hours per year the motor spends at each load point.

C. Horizontal Pump Applications – Boiler Feed Pumps

The boiler feed pump is an application for HTS motors that has particular interest in several areas.

- **High Horsepower.** Recent advances in motor technology, especially 2 pole medium voltage motors, have resulted in larger electric motors being supplied for boiler feedwater pumps where steam turbines have traditionally been used in the past. This advancement has several benefits including more rapid start-up and lower installation cost. These systems also use large quantities of energy and the efficiency improvements from the HTS motor have a more substantial operating cost reduction impact at these high horsepower levels.
- **Large speed variations –** The current power generation industry has many load-following plants, which put heavy demands on constant speed boiler feed pumps when controlling them with valves. The use of variable speed has the potential to save a lot of expense during partial load plant dispatch, not only in energy cost, but in equipment maintenance expense. In fact, many of these applications are good candidates for retrofitting with HTS motors on ASD's, as the plants that used to be base load are now sometimes used as load-following, depending on demand, fuel type and cost, and dispatch requirements.
- **Intense maintenance requirements –** An additional factor that makes this application appealing is that the boiler feed pump is often located near the boiler, frequently under pipe racks or other overheads, making access difficult. The smaller, compact envelop of the HTS motor makes accessing the pump easier, as there is less hardware in the way. This is most notable in modern combined cycle units where the space is very tight near the boiler. In addition, the current motor style, like the circulating water pump motor, is frequently on the order of 10 000 lbs. or more. The smaller size of the superconducting motor makes maintenance on the pump easier.
- **Space requirements.** The variability in fuel costs has made variable speed more common in a modern combined cycle plant, however the current method to obtain variable speed is often an hydraulic coupling. This method has some significant benefits, like softer starting and reduced power consumption at part loads. However, it takes up a lot of space, frequently adding several feet to the length of the pump skid. It also requires significant cooling, which increases the demands on the plant cooling system and also requires space for several large heat exchangers. An additional complication is the fact that there are three pieces of equipment to align. The pump must be aligned

with the hydraulic coupling which must then be aligned with the motor. With the variable speed capability of the HTS motor, there is one less alignment to perform and the space required on the skid is less.

The boiler feed water system also exhibits some of the systematic behavior similar to the circulating water pumps already defined. It is critical to have the operation of the pumps programmed correctly. The soft-start nature of the ASD and HTS motor system helps to reduce the impact of these issues.

D. Forced Draft And Induced Draft Fans And Blowers

Forced draft and induced draft fans and blowers generally require some type of speed control device, usually a mechanical type requiring a fluid drive mechanism. Due to the speed control device a large foundation as well as additional space is required. The HTS motor allows for a smaller "foot print" by virtue of the reduced motor size and ASD drive capability. Operational and maintenance savings for large HTS fan systems (Fig. 12) will be obtained due to reduced substructure requirements for the HTS motor, reduced maintenance costs due to smaller motor size, and reduced energy consumption due to HTS motor efficiency advantages as well as ASD system performance improvements (over damper controlled flow systems).



Fig. 12 Large fan installation

VI. CONCLUSIONS

High temperature superconductors can be used in large industrial motors to reduce motor losses by over a factor of two and reduce overall motor weight and volume by up to a factor of two. Motors above 5000 hp in rating show particular promise in size and loss reduction, compared to high efficiency induction motors. HTS based industrial motors are expected to be adjustable speed synchronous motors with rotating HTS field windings that are cryogenically cooled through the use of an external cryocooler. A 6000 hp, 3600 rpm, 2 pole motor example showed loss reduction of 56% and active volume reduction of 41% compared to an energy efficient induction motor of the same rating.

HTS motor prototypes have been demonstrated in laboratory settings over the last decade with increasing output power as first generation HTS wire performance and lengths have increased. The largest industrial motor demonstration to date is a 5000 hp, 1800 rpm, 60 Hz motor. Second generation HTS wire promises to be lower cost than first generation wire and is key to the first cost, economic viability of HTS industrial motors. A small second generation HTS based motor, rated at 7.5 hp, is

the largest motor demonstrated to date using this technology. Rapid advancement of second generation HTS motor development is expected as long lengths of this wire become available.

HTS based electric motors offer substantial benefits to large motor customers. Efficiency improvements using this technology can result in tens of thousands of dollars in energy cost savings per year per motor. Size and weight reductions offer installation cost reductions that are also significant, when comparing to induction motors of the same rating.

Additional benefits due to the adjustable speed nature of superconducting motor systems can result in a reduction of operating costs and wear and tear of pump and fan systems.

All of these advantages of superconducting motor systems are expected to be important to large pump and fan customers as this technology moves out of the laboratory and into industrial applications over the next four to five years.

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VIII. VITA

Rich Schiferl is the Director of the Rockwell Automation, Power Systems, Advanced Technology Group. Throughout his 18 year career at Rockwell Automation he has been involved in advanced electric machinery development, including design tools, materials, and prototype development for commercial and industrial applications. Dr. Schiferl has a BEE degree from the University of Minnesota, an MSEE degree from Purdue University and a Ph. D. degree in Electrical Engineering from the University of Wisconsin, Madison where he specialized in electric motor analysis. Dr. Schiferl has been involved in the Rockwell Automation high temperature superconducting motor program from its inception in 1987 moving from electromagnetic design to program management and now to program development director. He has over two dozen publications and one patent.

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William Livoti graduated from Concordia University with a Mechanical Engineering degree in 1972. He is a member of

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