

# High-Temperature Superconducting Wind Turbine Generators

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## 1. Introduction

It is well acknowledged that wind represents a clean, renewable and reliable source of energy for electricity generation. The past two decades have seen a rapid growth in wind energy utilization throughout the world and a particular trend towards ever increasing turbine ratings. Indeed, the exploitation of wind energy has been high on many governments' and organizations' agenda. However, for onshore wind farms the interference with neighboring residents and low wind speeds may limit the number of acceptable sites available for development. On the contrary, high wind speeds and low interference make offshore wind farms attractive which are expected to be a significant growth area to bridge the energy gap, with many wind farms rated as highly as 1000 MW being currently under development. Yet, the drawbacks of the offshore installation are generally associated with the foundation of wind turbines, grid connection and maintenance. Thus, it is economically preferable for offshore wind farms to have fewer but larger wind turbines instead of many small ones. Currently, the wind turbine generators of 5-7.5 MW are commercially available in the marketplace (UK Wind Power, 2008) and these of 10 MW are under development (Windpower Engineering, 2010). When the mast-top weight of mega-watts generators exceeds 100 tonnes, installation would become increasingly difficult and costly. In fact, the existing offshore installation vessels have a lifting capability of around 300 tonnes (Scots, 2008). The nacelle mass of some large wind turbines currently available can easily exceed this (Lewis & Muller, 2007) so that it is not economically viable to develop heavier wind turbines for offshore applications. Not surprisingly, therefore, the possibility of utilizing superconductors in wind turbine generators to reduce the mass and volume has come under the spotlight, primarily aided by the continuous improvement of superconducting materials.

## 2. Development of superconductors

The phenomenon of superconductivity was first discovered in 1911 by Onnes (later won a Nobel Prize in 1913) when he observed that the resistance of the mercury dropped to zero at a temperature of 4.2 K (-269°C). Since then, earlier developed metallic low-temperature superconductors (LTS) always operated at a temperature of 4.2 K or below, which requires the employment of costly liquid helium refrigeration for cooling purposes. The first commercial LTS were developed at Westinghouse in 1962. Typical LTS materials include NbTi (at 4 K), Nb<sub>3</sub>Sn (at 4 K) and magnesium diboride MgB<sub>2</sub> tapes (at 20 K) (Gieras, 2009).

Due to the complexity and cost of liquid helium refrigeration equipment, the superconductors were rarely used in applications. A breakthrough was made in 1986 when a cuprate-perovskite ceramic material lanthanum barium copper oxide (LBCuO, or LBCO) was discovered with critical temperatures in excess of 77 K. This marked the beginning of high-temperature superconductors (HTS), paving the way for a gradual proliferation of superconductivity. Having been further explored over two decades, the family of HTS continues to expand and today includes many rare-earth ceramic materials such as bismuth strontium calcium copper oxide (BiSrCaCuO, or BSCCO) (first generation) and yttrium barium copper oxide (YBaCuO, or YBCO) (second generation). The chronological discovery of superconductors is shown in detail in Fig. 1. The 1G HTS are produced as multiple filaments in a silver matrix, involving multiple rolling processes followed by controlled heat treatment in the manufacturing. In contrast, the 2G HTS are coated on a buffer layer and substrate. Main specifications for typical BSCCO and YBCO wires are listed in Table 1.

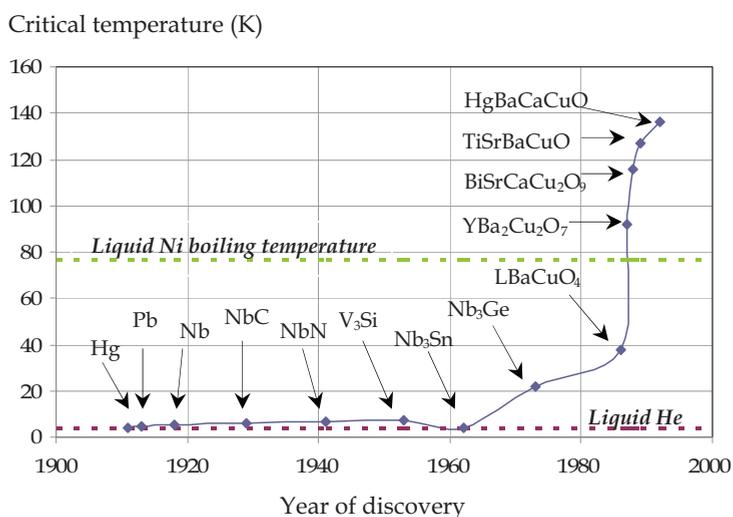


Fig. 1. Chronological discovery of superconductors

Specifications	BSCCO (Bi-2223)	YBCO (348C)
Thickness (avg)	0.19-0.23 mm	0.18-0.22 mm
Width (avg)	3.9-4.3 mm	4.70-4.95 mm
Min critical current	115 A *	≥100 A *
Min current density	135 A/mm <sup>2</sup> *	93 A/mm <sup>2</sup> *
Max stress	75 MPa **	150 MPa **
Max strain	0.15% **	0.3% **
Min bend diameter	100 mm **	30 mm **
Note	* at 77 K, self-field, 10 mV/mm ** With 95% I <sub>c</sub> retention	

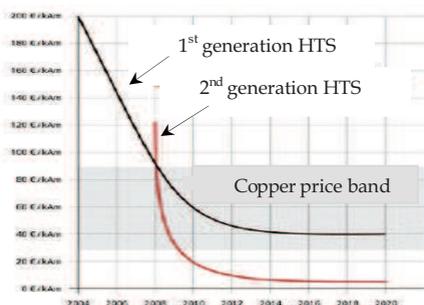
Table 1. Properties for typical BSCCO and YBCO wires (AMSC, 2008)

In principle, the HTS have neither resistance nor magnetic properties under their critical conditions. More importantly, they have non-linear  $J$ - $E$  characteristics, which are governed by the following equation.

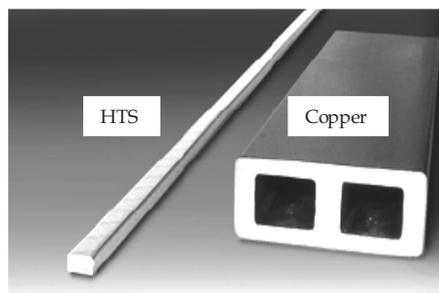
$$\vec{E} = E_c \left( \frac{J}{J_c} \right)^{N-1} \frac{\vec{J}}{J_c} \quad (1)$$

where  $E$  and  $E_c$  are the electrical field and electrical critical field,  $J_c$  is the critical current density, and  $N$  is an empirical factor chosen to match the experimental results.

In order to maintain superconductors in the superconducting state, it is required to keep their temperature, current density and magnetic field all below their critical values. Otherwise, the superconductors would return to the resistive mode, termed as “quenching”. As a whole, HTS materials are characterized by their high transition (or critical) temperatures. For example, transition temperatures for the second generation superconductors are typically between 77 K and 125 K (i.e.  $-196^\circ\text{C}$  and  $-148^\circ\text{C}$ ). This feature makes it possible to use cheap liquid nitrogen for cooling purposes. In fact, it is this refrigeration advantage that has spurred an immediate resurrection of interest in superconducting applications. At the present time, the development of HTS is nearing viable commercialization. A cost comparison between HTS and copper conductors is depicted in Fig. 2(a).



(a)



(b)

Fig. 2. (a) HTS price in €/kA over time along with copper price band; (b) Comparison of 1kA insulated HTS stack with copper bar. (Lewis & Muller, 2007)

However, the quest for higher-temperature superconducting materials or even room-temperature superconductors (RTS) (precisely, temperatures above  $0^\circ\text{C}$ ) has never ceased. A recent breakthrough was achieved in 2008 by a group of UK-US scientists who successfully identified a key component to unravelling the mystery of room-temperature superconductivity (Suchitra et al., 2008). This takes us a big step closer to the dream of RTS. The fact that HTS could transport electricity with virtually no resistance at relatively high temperatures holds vast potentials and opens many doors for applications. These include electrical machines (Bumby, 1983; Superczynski & Waltman, 1997; Ship et al., 2002; Sykulski et al., 2002; Fee et al., 2003; Fogarty, 2004; Hull & Murakami, 2004; Kalsi et al., 2004; Masson & Luongo, 2005; Snitchler et al., 2005; Nakamura et al., 2006; Al-Mosawi et al., 2007; Klaus et al., 2007; Wilke et al., 2008; Abrahamsen et al., 2009; Wen et al., 2009), transformers (Kamijo

et al., 2007; Choi et al., 2008; Liu et al., 2010), power transmission lines (Wang & Lancaster, 2006; Sasaki et al., 2007; Johnson et al., 2009), energy storages (de Andrade et al., 2005; Hirabayashi et al., 2008; Dai et al., 2010) and so forth. It becomes clear that the superconducting apparatus have to be sufficiently large to justify the costs of superconductors and the associated cooling system.

In the application of superconducting rotating machines, superconductors can be used as either HTS wires (Kalsi et al., 2004), bulk HTS materials (Hull & Murakami, 2004), or a combination of the two (Masson & Luongo, 2005). This chapter considers HT superconductors to be used as coils rather than bulks, which are commonplace in practice. In the literature, most large HTS machines are of synchronous type which uses HTS wires in the dc field winding at cryogenic temperatures and copper wires in the stator winding at ambient temperatures. The largest manufactured and tested to date is a 36.5 MW 120 rpm HTS propulsion motor for the US Navy, designed and supplied by American Superconductor Corporation (AMSC) and Northrop Grumman (AMSC, 2007).

Overall, it is estimated that the multi-MW machines would be highly efficient (over 98%) and capable of reducing the weight and volume by 50% and the capital cost by 25% in the general power application. Obviously, large wind turbine generators (with MW rating) will fit the bill perfectly.

### 3. High temperature superconducting wind turbine generators (HTSWTGs)

The ability of superconductors to increase current density allows for high magnetic fields, leading to a significant reduction in mass and size for superconducting machines. This feature is shown in Fig. 2(b) for comparison with copper bars. In the economic perspective, it is estimated that the superconducting technology could achieve an efficiency improvement of 1% in large electrical machines, which offers substantial savings to utilities and end-users. A cost comparison for 300 MW generators is given in Table 2. Another distinct feature of superconducting machines is their part-load efficiency advantages. Namely, the HTS machine efficiency at partial loads is significantly higher when compared to conventional machines, as is illustrated in Fig. 3. This is particularly relevant to wind power generation since the wind turbines operate mostly at part-load conditions. As a result, HTS wind turbine generators can extract more wind energy than other types of machines even though they have the same nominal efficiency on the nameplates.

Machine types	Efficiency (%)	Capital cost (MD)	Annual losses (MD)	Total annual costs (MD)
Conventional	98.6	880	1400	1565
HTS generator	99.7	740	280	420

(MD: millions of dollars)

Table 2. Cost comparison for 300 MW generators (Giese et al., 1992)

In wind turbine generators, there are several competing topologies. Currently the mature technology for large wind turbines is the doubly-fed induction generator (DFIG) (Pena et al., 1996; Muller et al., 2002; Pettersson et al., 2005; Ramtharan et al., 2007). Their power rating is typically between 0.5-5 MW. The prime advantage of the DFIGs is the reduced cost of the partially rated power electronic converter. However, the generator still uses brushes and

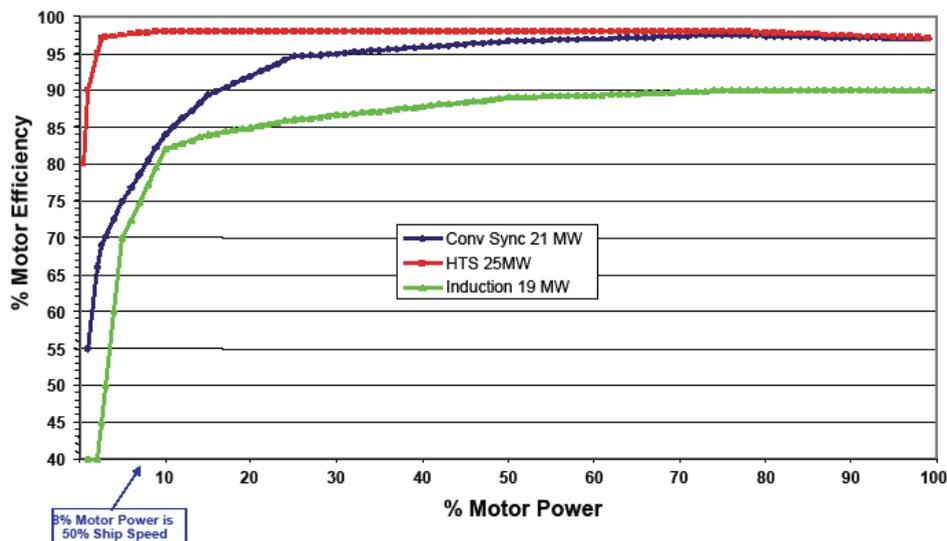


Fig. 3. Higher efficiency at full and part loads for superconducting machines (AMSC, 2010)

slip-rings which require regular maintenance. Additionally, the reactive power drawn by the machine must be compensated using power electronic converters or other measures. Nowadays, an emerging and competing technology is the permanent magnet (PM) generators. They are gradually penetrating into the wind energy market and their power rating is typically between 2-6 MW. Clearly, the use of PMs provides much promise in reduced losses and machine weight. But the flux density and power density are still limited by the existing materials (PM, copper and iron). If further improvements are demanded, superconducting generators will be an advanced technology because they eliminate conductor joule losses and provide superior performance and compactness. The likely power rating for HTSWTGs is 5-10 MW and above. Up to date a number of HTSWTG projects have been initiated worldwide. AMSC commenced a project on developing a 10 MW HTS offshore wind turbine generator in 2007 (Marsh, 2009), which is still ongoing to date. It is estimated that this machine weights around 120 tonnes and costs a US \$ 6.8 million. It can be seen that the weight is nearly a third of a similarly-rated conventional direct-drive turbine generator.

#### 4. Topologies of HTSWTGs

Since superconducting machine design is still evolving and is highly dependent on the superconducting materials used, it should not rule out any viable topology at the stage of feasibility study. In the literature, a variety of HTS machine types have been reported. These include homopolar machines (Superczynski & Waltman, 1997), induction machines (Nakamura et al., 2006) and in the majority, synchronous machines (Ship et al., 2002; Sykulski et al., 2002; Al-Mosawi et al., 2007; Klaus et al., 2007; Wilke et al., 2008).

In essence, the existing HTS are prone to ac losses when experiencing field variations. In this regard, the synchronous machine may become a natural choice of machine type since, in synchronous machines, the HTS in the rotation would see a standstill and constant field

generated from the stator winding. For the same reason, superconductors are rarely used in the stator winding. Also, it is difficult to build the stator winding by flat HTS coils for an effective use of space. Clearly a radical design of the whole superconducting arrangement (both stator and rotor) is not realistic before a new type of superconductors is developed to overcome these ac losses. As a result, a feasible design of the HTSWTG is based on the synchronous generator with the copper stator and the superconductor rotor (Bumby, 1983, Al-Mosawi et al., 2007). HTS coils are generally wound in the form of very thin race-track tapes due to their ceramic features. When installed on the rotor, they provide a constant magnetic field similar to the PMs.

Regarding the HTS synchronous machines, they can be further broken down into four different types (Lewis & Muller, 2007):

Type 1. Conventional stator and HTS rotor with magnetic pole bodies

This type offers gains in efficiency due to minimized rotor loss but does not offer substantial reduction in weight and dimension.

Type 2. Conventional stator and HTS rotor with non-magnetic pole bodies

This type offers gains in efficiency due to minimized rotor loss, and reduces costly cold magnetic materials and complex thermal isolation. However, it needs more HTS wires to establish the necessary flux density.

Type 3. Airgap stator winding and HTS rotor with magnetic pole bodies

This type produces significantly higher flux density at the airgap than a conventional stator and thus decreases the mass and size of the machine. However, the rotor iron can operate highly saturated so that the efficiency is reduced.

Type 4. Airgap stator winding and HTS rotor with non-magnetic pole bodies

This type allows significant reduction in weight and dimension, and also minimizes potential high cost cold magnetic materials. But it requires more HTS wires in use.

Since wind energy is a cost sensitive market, the capital cost is paramount in producing large machines. For offshore wind turbines, the mass saving is more important than size reduction. Therefore, the actual compromise is made between the low cost, low mass and high efficiency. For the direct-drive wind generator, types 3 and 4 both can offer the advantage of lowest mass. The cost balance between the two largely relies on the relative cost of HTS wires against other materials (cold and warm irons, copper etc). Based on the existing production pricing for iron and 2G HTS wires, type 4 may be a more cost-effective solution. Convertteam has undertaken the design of an 8 MW 12 rpm HTSWTG following type 4 topology (Lewis & Muller, 2007).

From the above analysis, a multi-MW, low speed, direct-drive HTSWTG system can be sketched, as shown in Fig. 4. The machine consists of the stator back iron, stator copper winding, HTS field coils, rotor core, rotor support structure, rotor cooling system, cryostat and external refrigerator, electromagnetic (EM) shield and damper, bearing, shaft and housing. Among all the components, key to the machine design are the arrangements for the stator, rotor, cooling and gearbox.

#### *Stator arrangements*

Although in theory the whole superconducting arrangement is possible, the excessive ac losses in the stator and physical difficulty in bending and twisting the fragile HTS to fit into the stator slots pose particular challenges. Thus it is not surprising for some designs to choose the existing stator in availability (Ship et al., 2002).

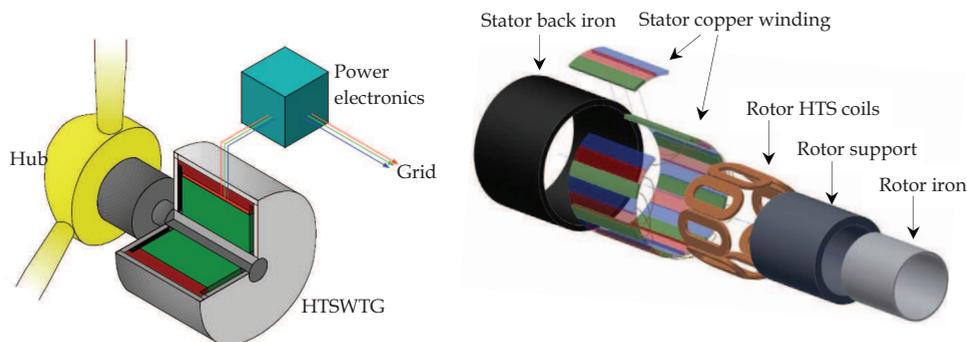


Fig. 4. Schematic of a multi-MW, low speed, direct drive HTSWTG system (Courtesy of Converteam)

In the literature, there are three different stator winding topologies reported for HTS machines. As shown in Fig. 5(a), the copper windings are placed in the slots between magnetic teeth and an iron yoke is used to guide the magnetic flux through the stator. Obviously, this configuration can take advantage of existing stator and stator winding design but has a limit on the maximum flux density in relation to the saturation of the iron teeth. The second winding topology is designed to overcome this problem by replacing the iron teeth with no-magnetic teeth (e.g. fiber reinforced plastics). Consequently, a higher level of flux density can be achieved, as well as a higher power generated from the machine. Nonetheless, replacing the magnetic teeth would change the flux distribution in the stator, giving rise to transverse flux components. In order to mitigate the resultant eddy currents, the windings should be modified using smaller-diameter insulated and transposed copper strands (Litz wires). The difference between (b) and (c) lies in the width of the non-magnetic stator teeth. The thinner teeth in (c) implies that more copper can be inserted in the slots and higher ampere-turn loading can be obtained without causing saturation in the stator teeth. But this topology is subjected to mechanical stability and cooling capability.

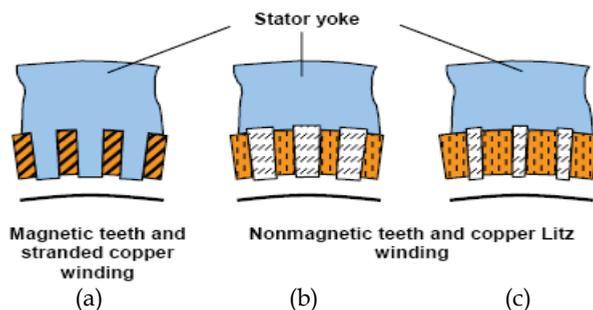


Fig. 5. Three different stator winding arrangements. (a) conventional stator, (b) high field stator, (c) high field, high magnetomotive force (mmf) loading stator (Klaus et al., 2007)

#### Rotor arrangements

In conventional copper wires, the maximum current density achieved is typically  $5 \text{ A/mm}^2$  while, in 2G HTS, this can be as much as  $135 \text{ A/mm}^2$ . The significant increase in current density leads to a much compact HTS rotor for the HTSWTGs.

In terms of magnetic characteristics, the rotor core can be either magnetic or non-magnetic. The use of magnetic irons can reduce the mmf required to establish the same field since core material forms part of magnetic circuits (much better than air). Clearly, the rotor mass would be increased accordingly and so is the rotor inertia. However, the latter does not cause problems since in direct-drive wind turbines the actual rotation speed is quite low. In practice, it is very difficult to twist the HTS coils to align with the field for the purposes of minimizing ac losses so that iron (and the flux diverters) should be used to guide the flux in the desired direction and away from the HTS. But the fact that iron saturates at approximately 2 T puts a limit on the maximum flux density.

In theory, the high current density in superconductors makes it possible to produce sufficient air-gap flux density without a rotor core. Therefore, the rotor can be of air-cored type (coreless rotor) (Ship & Sykulski, 2004; Lukasik et al., 2008). This configuration provides a significant reduction in the weight of the rotor and the associated eddy current losses. Nevertheless, it may increase the amount of superconductors used and the current level in the superconductor so as to produce the required flux density. Similarly, because there is no iron core, the support structure should be strong to transmit the high torque, which is the case of direct-drive wind turbines.

With regard to the rotor cooling arrangement, the HTSWTG can use either warm or cold rotors, as demonstrated in Fig. 6. In Fig. 6(a), only HTS coils are cooled at cryogenic temperature so that the so-called "cold mass" is low. This results in short cool-down periods and reduced eddy current losses. But the supporting structure would be complicated to hold the HTS and also to prevent heat leakage. In contrast, in Fig. 6(b), the cold rotor structure is relatively simple and the whole rotor is cooled at cryogenic temperature, requiring additional cooling capacity to remove the heat inside the rotor. Moreover, an auxiliary torque transmission element is needed to connect the rotor and the shaft. Since the two are operated at different temperatures, heat leakage arises via the intermediate element. Besides, cooling the rotor core to a very low temperature gives rise to eddy current losses when exposed to mmf harmonics. This effect can be significant and requires a careful design of the rotor EM shield to prevent the harmonics from entering the cold part. In large wind turbines, warm rotor topology may be preferred due to the minimized cooling requirement and eddy current losses.

#### *Cooling arrangements*

Cooling arrangements play a crucial role in the success of the HTS machines. When designing the cryogenic system, one should consider its ease of operation and maintenance, minimum complexity and cost, and integration with the superconducting machines. Early LTS designs used liquid helium to achieve a temperature of 4.2 K whereas the latest HTS use liquid nitrogen or even inexpensive liquid hydrogen to cool the superconductors down to 77-125 K. The cost of cryogenic cooling systems depends more on operating temperatures than anything else. Therefore, the overall cost constantly drops as the critical temperatures of HTS increase.

When the operating temperature decreases, the critical temperature and critical current in HTS wires increase. For instance, when the operating temperatures reduce from 77 K to 50 K, the critical current in the HTS is doubled but the cooling power required only increases by 15% (Jha, 1998).

The cryogenic cooling systems generally use counter-current streams for optimum economy. In this respect, the conductors with a high surface-to-volume ratio can lead to a high cooling

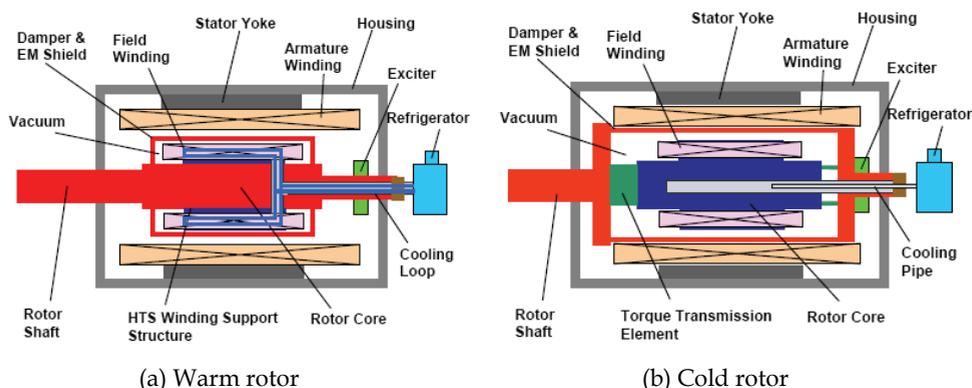


Fig. 6. Two different rotor arrangements (Klaus et al., 2007)

efficiency. It is easily understood that cooling efficiency is also dependent on the thermal insulation of HTS. In reality, to remove 1 W of heat generated at 77 K requires 10 W of electricity (Giese et al., 1992). Thus a key aspect of the cooling design is to minimize the power losses in the support structure and EM shields.

*Selection of gearbox*

Historically, gearbox failures are proven to be major challenges to the operation of wind farms (Robb, 2005; Ribrant & Bertling, 2007). This is especially true for offshore wind turbines which are situated in harsh environments and which may be realistically accessed once per year.

Obviously, direct drive configuration removes the necessity for gears, slip-rings and the associated reliability problems. A comparison of different drive train configurations is presented in Table 3. As a result, some wind turbine manufacturers are now moving toward direct-drive generators to improve reliability. However, a drawback of the direct drive is associated with the low operating speed of the turbine generator. Low speed operation implies a high torque required for a given power output, i.e., a physically large machine. As the nominal speed of the machine reduces, the volume and weight would increase approximately in inverse proportion. This may offset some of the weight savings from using the HTS. Nevertheless, the system as a whole can still benefit from reduced mass and size, taking account of savings made from removing gearboxes. For example, a direct-drive 6 MW HTSWTG is estimated to be approximately 20% of the mass of an equivalent conventional synchronous generator, half of the mass of an optimized PM direct-drive generator, and a similar mass of a conventional geared high-speed generator (Lewis & Muller, 2007).

Drive trains	Turbine speed	Gearing	Generator speed	Problems
Conventional	15 rpm	1:100 gear	1500 rpm	Heavy & problematic gearbox
Hybrid	15 rpm	1:6 gear	90 rpm	In between
Direct drive	15 rpm	No	15 rpm	Large & heavy generator

Table 3. Three types of drive train configurations

## 5. Design considerations and challenges

A good design of electrical machines should allow for better use of materials and space while meeting electrical, mechanical, thermal, economic and reliability requirements. In the design of HTSWTGs, typical optimization parameters in the consideration are: low mass and size, minimum use of superconductors, low capital cost, high efficiency, high levels of reliability and stability. However, it is highly likely that they are conflicting in practice and a compromise has to be made based on personal experiences. For instance, the working point of the machine is dictated by the critical current of the HTS coils and the maximum flux density at the conductor, which are both dependent on the operating temperature. When machine compactness is achieved by increasing the flux density, iron losses in magnetic iron parts will be increased, thus reducing the efficiency. When the operating temperature of HTS is reduced, electrical performance improves but cooling power required increases.

Without a doubt, firstly, the mechanical properties of the HTS place some constraints on the machine design. Physically, they are limited in the shape and coil arrangement. The difficulty in the cryogenic design arises from the difference in thermal contraction between the superconductors and the core, which must be taken into consideration. In the rotor design, the supporting structure must be mechanically strong to carry the loads imposed by the centrifugal forces and thermally arranged by appropriate thermal insulation to prevent the heat leak from the warm part of the rotor entering into the cryostat.

At first glance, it may be tempting to view HTS as conventional conductors with zero resistance. But this is not the case in the machine design for the  $J$ - $E$  characteristics are highly non-linear, depending on the magnetic field intensity and orientation, the temperature and current allowances for safety margin. If any one of these parameters reaches its thresholds, the superconductivity can be lost.

It is widely accepted that existing superconductors work best with dc currents and constant fields. When experiencing ac field variations, hysteresis and eddy current losses are induced in the conductors. Magnetically, the superconductors are anisotropic and particularly vulnerable to magnetic fields in perpendicular direction. When used as superconducting tapes, care should be exercised in the design to accommodate the constraints resulting from their anisotropic properties. The magnetic fields (especially perpendicular to the HTS tape's broad face) should be kept below certain limits to avoid significant power losses. Another source of power losses in the cold part of the rotor is associated with eddy currents (Sykulski et al., 2002). They can result in a significant load on the cryogenic system and therefore put a constraint on the machine design. As a consequence, electromagnetic shields should be used to protect the rotor from ac flux components. Electrically, divert rings and metal screen can also act as separate damping windings to improve the machine's transient responses.

In the stator design, a challenge is the centrifugal forces which act on the stator conductors and which are highly cycle fatigue loads. Therefore, stator copper coils need to be made from stranded Litz wire to eliminate eddy current loss and to provide physical flexibility. When the non-magnetic teeth are used, electromagnetic forces need to be transmitted to the back iron and frame via non-magnetic elements. In addition, some problems are associated with harmonic contents in the stator voltage. The output voltage harmonics are determined by the configuration of the stator winding and the air-gap flux density waveform produced by the field winding (Lukasik et al., 2008). Since HTS machines' synchronous reactance is low, the voltage harmonics have an exaggerated impact on the external circuits. It is found that the fifth harmonic is the dominant harmonic component and should be mitigated in the design of the pole face (Ship et al., 2002).

The design of a 10 kW direct-drive HTSWTG is described in (Abrahamsen et al., 2009) and the main specifications are tabulated in Table 4 for reference.

Items	Value	Items	Value
Rating	10 kW	Critical current density	110 A/mm <sup>2</sup>
Pole No.	8	Stator max flux density	0.96 T
Type of HTS	BSCCO-2223	Rotor max flux density	1.79 T
Working temperature	50 K	Stator line voltage	400 V
Stator diameter	0.32 m	Stator phase current	14.4 A
Rotor diameter	0.25 m	HTS wire length	7539 m
Rotor length	0.4 m	HTS wire weight	91 kg

Table 4. Main specifications of a 10 kW direct-drive HTSWTG. (Abrahamsen et al., 2009)

### 6. Integrating HTSWTGs into the power network

Power system stability relies on large wind turbines that remain connected when undergoing voltage surges and short-circuits at local or remote distances. Fig. 7 shows a simplified representation of the HTSWTG in a power system. Equivalent circuits for the *d*- and *q*-axis representations of superconducting generators are developed in (Liese et al., 1984), which comprise a large number of series connected *T*-networks (Kulig et al., 1984). An important feature in the modeling of the superconducting machine is the rotor EM shield, which in effect distorts the radial and tangential flux densities and affects the machine dynamic performance and output power.

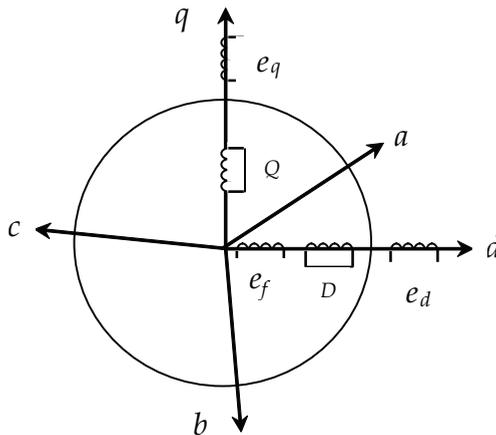


Fig. 7. Representation of the HTSWTG

When integrating large HTSWTGs into the power network, considerations of their impacts are twofold. Firstly, there is an impact of the HTSWTG on the power network and, secondly, there is an impact of the power grid faults on the HTSWTG system.

If the power network is strong, it may be able to accept more wind generation within normal power quality criteria. Nonetheless, most large wind power sites are remote where the adjacent distribution networks or substations are low in their capacity. For analysis purposes, a weak network can be represented by a short-circuit ratio (SCR) of less than 6 (Abbey et al., 2005). Calculating a local network's SCR can help optimize the wind farm design in handling the weakest point of the system. The intermittent power output of a wind farm can result in voltage fluctuations on these networks, known as "flickers". These would be significant for small numbers of large wind turbines connected at low voltages, as is the case for offshore wind turbines. Moreover, variable-speed wind turbines can also induce harmonic voltages to appear on the network, causing equipment to malfunction or overheat. Compared to the conventional wind turbine generators, HTSWTGs may have lower synchronous and sub-transient reactances. Therefore, their dynamic responses tend to be faster despite a greater L/R time constant they have. Although HTSWTGs may provide a larger dynamic stability limit, their dynamic behaviors are largely dictated by the transformer-transmission line reactance. Clearly, with the increased proliferation of wind power generation in the network, the power system may become weaker and power system stability may be of great concern.

On the other hand, it is equally important to examine the fault-ride-through (FRT) capability of the HTSWTG system responding to grid faults. Nowadays, many power network codes require wind turbines to ride through voltage sags (E.ON, 2003; Denmark, 2004; FERC, 2005; Ireland, 2007; UK, 2008). In addition to voltage fluctuations caused by varying loads connected on the network, power faults at local or remote buses of the power network are also the sources of problem. HTSWTGs may be able to provide better damping resulting from rotor electromagnetic shield and/or damping screen than conventional generators. Consequently, real power fluctuations following a grid fault should be smaller and HTSWTGs are considered to be more resistant to the transient system faults. In particular, when equipped with power electronics and low voltage ride-through-capability, large HTSWTGs may be incorporated into remote networks without compromising power system stability.

## 7. Conclusions

The implementation of superconducting technology in electrical machines offers significant reductions in mass and size, as well as superior performance and reliability, and potentially competitive costs. In the offshore wind power generation, the dominant DFIG configuration suffers from regular maintenance associated with slip-rings and gearboxes. Development of HTS materials has made superconductivity technically and economically viable to fill the gap.

This chapter has overviewed the historical development of superconductivity and considered the potential merits of applying HTS coils to large wind turbine generators. A number of machine topologies and design issues have been discussed. It is found that: 1) HTS provide potential benefits for wind turbine development in lowering the overall cost of wind energy while improving energy efficiency; 2) synchronous generators with the HTS field coils promise to be a favorable configuration for next generation wind turbine generators. This is so far a proven technology in large electrical machines and may still need some time to develop its economic competitiveness; and 3) used in combination, direct-drive arrangement can reduce the reliability problems associated with the gearbox but it comes at

a price in terms of machine size. An increase in system efficiency would have significant economic implications since the machines considered are multi-MW and above. Improved fault ride-through capacity of the HTSWTG would help minimize the need for maintenance and the likelihood of machine breakdowns. Further work is currently underway to model a 10 MW direct-drive HTSWTG using 3D finite-element tools.

Looking to the future, it would be highly desired that the next generation room-temperature superconductors be developed in commercial availability. If such a day comes, superconductivity would offer unprecedentedly significant benefits in cost saving and performance improvement, and would undoubtedly revolutionize every aspect of electrical machine design.

## 8. Acknowledgment

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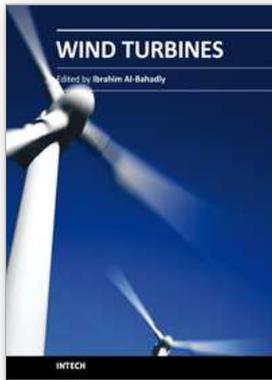
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