CHAPTER 9

Direct drive superconducting wind generators

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There are plans for a large expansion of offshore wind energy, particularly in Northern Europe where there is limited space for onshore turbines. One means to reduce the cost of offshore wind energy is to build wind farms with fewer larger turbines, reducing the number of costly offshore foundations. The emerging next generation of HTS technology, which offers the prospect of low cost high volume HTS wire production, can be used to build compact and lightweight generators at high rating and torque. These new generators will become the enabler for very large, direct drive wind turbines in the 10 MW class. Direct drive turbines also offer an improvement in reliability and efficiency by removing the gearbox, which has been a troublesome component in many offshore wind farm projects, and replacing it with a much simpler mechanical system that is not sensitive to the misalignment or to fluctuations in the shaft torque. Reliability is particularly important in offshore turbines where access is difficult and expensive and often prevented by weather conditions. Converteam UK Ltd. are in the final stages of a project to design a direct drive HTS generator for this class of turbines, and to build and test a scaled prototype. Following on from this project will be the manufacture of a full size prototype and its demonstration on a 10 MW turbine. An economic analysis during earlier stages of the project calculated a reduction in the cost of energy of 17% from a 500 MW offshore wind farm by the use of this class of HTS direct drive turbines compared with the baseline case of 4 MW conventional DFIG turbines. This analysis did not include any additional cost reduction due to improved reliability and availability.

1 Introduction

The wind turbine market is large and rapidly growing; while at the same time there has been a trend towards larger and larger turbines. Larger turbines are attractive
to the new generation of offshore wind farms currently under construction and planning. Recently there has been a development of direct drive generators by a number of turbine manufacturers in order to simplify the mechanical drive train and avoid reliability problems with gearboxes. Direct drive generators are required to operate at the very low speed of the turbine rotor, and hence very high torque. Since it is torque rather than power that predominantly determines the size of the generator, they are significantly larger than high speed generators. To date, most commercial direct drive generators have been very large conventional synchronous machines, most notably from the turbine manufacturer Enercon, but recently there has been the introduction of permanent magnet direct drive generators that are smaller and lighter for the same rating.

During the 1990s electrical machines began to be developed using high temperature superconducting (HTS) materials, the attraction being a significant reduction in the size and weight of the machines. Recently a 36.5 MW, 120 rpm HTS propulsion motor for the US Navy was tested, with a shaft torque similar to that of existing direct drive wind turbine generators. However, the cost of HTS wire has been too high for a cost sensitive market such as wind energy. A second generation of HTS wire (sometimes known as tape) is beginning to come into commercial production, offering an order of magnitude reduction in the cost of HTS wire when produced in volume. This new type of HTS wire opens up the possibility of using HTS generators in wind turbines to make the next significant step up in turbine power rating without the additional penalty of higher mass at the top of the tower.

2 Wind turbine technology

2.1 Wind turbine market

The wind energy market has been growing rapidly since the mid 1990s, with new installed capacity growing at an average rate of 28% in the years 1997–2004, and an average of 34% in the years 2005–2007 [1]. Total installed capacity stood at 93 GW by the end of 2007, and the wind industry expect this to increase to between 490 and 2400 GW by 2030 [2].

Along with this growth in installed capacity there has been a growth in the size and rating of wind turbines, with the largest turbines now being installed (2008) rated at 5 MW. Larger turbines are under development, with Clipper Windpower Plc developing the 7.5–10 MW Britannia turbine in the UK for the offshore wind market [3].

The UK, like many northern European countries is densely populated, so the number of acceptable sites for onshore wind farms is limited. However, the UK is surrounded by large areas of shallow sea with some of the best wind resource in the world. European countries are committed to increasing the share of renewables in energy consumption to 20% by 2020 [4]. In the UK and many other northern European countries, a large proportion of this energy is planned to come from offshore wind, and it is the UK government’s intention to install up to 33 GW of offshore wind power to meet the 2020 target [5].
The requirements of the offshore market differ from those of the onshore market. Since the installation cost, and the cost of access for maintenance is significantly higher for offshore turbines, there is a preference for fewer higher power turbines in order to reduce the number of installations. The higher towers would also result in higher average hub height wind speed. Most of the offshore wind farms put into service around the UK to date have used 2, 3 or 3.6 MW turbines. The cost of turbine foundations is a significant proportion of the offshore wind farm, and since the mass of the nacelle has a significant impact on the cost of the most common monopole foundation, a low nacelle mass is important.

Due to the cost and limited availability of access to offshore turbines, reliability is most important. If a failure occurs in a turbine in the North Sea in the winter, the time of maximum energy production, it may be weeks or months before a suitable weather window provides access to enable major equipment repair.

2.2 Case for direct drive

Early wind turbines had low power ratings (100 kW or less) and typically used a fixed speed induction generator (a standard industrial induction motor), driven though a speed increasing gearbox. The turbine power was limited in high wind speeds by progressive aerodynamic stall of the blades. As turbine ratings increased to more than a few hundred kilowatts, the advantages of using a variable rotor speed with blade pitch control became apparent. The most popular solution was the doubly fed induction generator (DFIG), in which the stator is directly connected to the grid, and the rotor power (30–50% of the total power) is fed to and from the grid through sliprings and a variable frequency power converter [6]. This arrangement had the advantage of a smaller power converter at a time when the cost of power electronics was high. With turbine ratings of 2 MW or more, and with wind energy beginning to contribute a significant proportion of the grid generating capacity in some countries and the falling cost of power electronics, the fully fed generator became attractive. The DFIG began to be replaced with either a cage induction generator or a synchronous generator, and all of the power was transferred to the grid via a variable frequency converter. This system offered a number of advantages: the generator no longer had slip rings that required regular maintenance, and the fully fed converter made it easier to implement ride through grid fault capability and continue generation once the fault had cleared – essential for the security of power supply when wind contributes a significant proportion of generating capacity. Unlike the directly connected stator windings of the DFIG, the converter isolated the fully fed stator windings from the grid, so offered greater protection from grid faults for the generator, as well as the turbine mechanical components.

The speed increasing gearbox is a complex mechanical system requiring good mechanical alignment for reliable operation. It also has lubrication and cooling systems requiring maintenance. Gearboxes have been responsible for reliability problems in many wind turbines in the past. One investigation [7] found that gearbox development had not kept pace with the increasing size of wind turbines, results in more reliability problems with the newer larger turbines. The 2006 annual
report for the Kentish Flats offshore wind farm in the UK [8] reported that one-third of turbines were unavailable during that period due to gearbox problems.

There have been a number of studies on gearbox reliability Ribrant and Bertling [9] studied the cause of turbine failure in Sweden over the period from 1997 to 2005. They found that, while the gearbox was not the most common cause of failure, the long time to repair meant that it was responsible for the largest proportion of down time. There have been a number of studies looking at how to improve gearbox reliability. Musial et al. [10] have embarked on a long-term study to systematically investigate gearbox reliability problems. In the meantime problems continue. Figure 1 shows the proportion of turbine lost hours as a result of problems with specific components for turbines in Germany during the third quarter of 2008, data from [11].

A logical result of these problems is that a number of wind turbine manufactures and several independent studies have looked to direct drive where the generator rotates at the same speed as the turbine blades. By their nature, these generators also have fully fed converter system to connect to the grid. Polinder and van der Pijl [12] made a comparison study between wind turbines with direct drive synchronous, direct drive permanent magnet, single stage geared with both permanent magnet and DFIG, and three-stage geared systems with DFIG generators.

2.3 Direct drive generators

A direct drive generator for a wind turbine is characterized by having a very low rotational speed, and hence very high torque for a given power. Torque in an electrical
machine is related to a magnetic shear stress in the airgap of the machine given by the following equation:

\[ \sigma_g = \frac{\tau}{2\pi r_t^2 l_r} \]  

(1)

where \( \sigma_g \) is the airgap shear stress, \( \tau \) is the motor torque, \( r_t \) is the rotor radius, and \( l_r \) is the rotor core length [7]. The shear stress is effectively the mean value of the tangential component of the Maxwell stress tensor over the surface of the rotor, which is dependant on the square of flux density, as shown in eqn (2). This defines the Maxwell stress tensor in the cylindrical coordinate system for the magnetic field, assuming that the components due to electric fields can be ignored:

\[ \sigma_{rt} = \frac{1}{\mu_0} B_r B_t - \frac{1}{2\mu_0} B^2 \delta_{rt} \]  

(2)

where \( r \) is the radial direction, \( t \) is the tangential direction, \( \sigma_{rt} \) is the Maxwell stress tensor at a point, \( B \) is the magnetic flux density, \( \mu_0 \) is the permeability of free space and \( \delta \) is the Kronecker’s delta. For this reason machines with a higher airgap flux density are capable of higher shear stress. A comparison of the shear stress obtainable in various types of electrical machine, including HTS, is given in [13].

If the torque exceeds the maximum overload shear stress capability of the generator then the machine will ‘pull out’ and cease to generate. The magnetic flux density in the airgap is limited to approximately 1 T in conventional machines by saturation in the iron magnetic circuit. Hence, for a given airgap flux density, the size of any given type electrical machine is largely determined by its torque rather than power. For this reason direct drive wind generators are large compared to their high speed geared equivalents. For a given wind speed and blade efficiency, the power obtainable from a wind turbine is proportional to the swept area of the rotor. Therefore, increasing the power of a wind turbine means increasing the diameter of the rotor, and since the blade tip speed is maintained within a certain limit for either mechanical or environmental (noise) reasons, this means a proportionally lower rotational speed and even higher torque as turbine power increases.

Wind turbines are commercially available with direct drive conventional synchronous generators, and turbines with direct drive permanent magnet generators (PMGs) are now beginning to appear, which have significantly greater torque density and hence smaller size and lower mass compared to conventional generators.

In 2008, Converteam UK Ltd. delivered a prototype direct drive PMG to Siemens Windpower in Denmark. This generator has been demonstrated on the Siemens 3.6 MW turbine at a test site in Denmark. Figure 2 shows this generator leaving the Converteam factory in Rugby, UK.

Converteam UK Ltd. are also in the process of producing a 5 MW direct drive PMG for the DarwinD offshore turbine.
3 Superconducting rotating machines

3.1 Superconductivity

Superconductivity is a phenomenon where electricity is conducted with zero resistance and zero loss, hence current in a loop of superconducting wire would continue forever. Superconductivity was discovered by H.K. Onnes in 1911 when he cooled mercury below 4.2 K (the boiling point of liquid helium) [14]. Temperatures in the fields of cryogenics and superconductivity are normally quoted using the Kelvin absolute temperature scale, where absolute zero is 0 K = −273.16°C. As temperature decreases the resistance of metals generally decreases. In the case of non-superconducting metals such as copper, a residual resistance value is reached and further temperature reduction does not result in any more reduction in resistance. Superconducting materials, on the other hand, have a critical temperature below which the resistance suddenly decreases to zero. When in the superconducting state the material has a critical current which increases as temperature decreases, above which superconductivity ceases, and also a critical magnetic field above which superconductivity ceases. Hence, the current carrying capacity of a superconductor is a function of temperature and magnetic field strength. They also exhibit a phenomenon, known as the Meissner effect, where all magnetic flux is excluded from within the superconductor when in the superconducting state [15].

The earliest superconducting materials (known as Type I Superconductors) were pure metals and had too low critical magnetic field to be of practical use. Later, another class of superconducting materials was discovered, consisting of metal alloys and known as Type II Superconductors, which were able to tolerate much higher magnetic fields. These materials allowed penetration of magnetic flux, which was then trapped within them by a mechanism known as “flux pinning”.

Figure 2: The 3.7 MW, 14 rpm PMG.
The critical temperature of these materials can be up to around 25 K, but all need to be cooled to 4.2 K for practical use. The materials have been developed into practical wire products and are now commonly used in magnets for particle accelerators and in the commercial market for MRI scanners. A summary of the properties and manufacture of these low temperature superconductors (LTS) can be found in [16, 17].

Many studies were made into the use of these LTS materials for the field windings (magnets) of rotating machines [19], particularly in the 1960s and 1970s. The high magnetic field strength for superconducting magnets results in much smaller machines, and higher efficiency due to the zero loss in the field winding. However, the practicality and cost of cooling the field on the rotor of these machines using liquid helium meant that they never became a commercial proposition.

### 3.2 High temperature superconductors

Only small increases in the critical temperature of these LTS materials were achieved from their discovery in 1911 up until the 1980s. Then, in 1986 a material was discovered by Bednorz and Muller that became superconducting at a temperature of around 30 K [18], and very shortly afterwards (Fig. 3) many more materials were discovered with ever increasing critical temperature, although after 1990 this trend considerably slowed.

These discoveries brought the operating temperature of the superconductors into the range of liquid nitrogen, which is two orders of magnitude cheaper than the liquid helium used to cool LTS coils. All HTS materials are Type II Superconductors.

![Figure 3: Development of the critical temperature of superconductors.](image)
One common characteristic of these materials is they were all complex copper oxides and, more significantly, all ceramic materials. While it was relatively easy to manufacture such materials in bulk form, the technology to produce flexible wires that would be of use in electrical machine windings proved to be a considerable challenge. After considerable effort, the HTS material Bi$_2$Sr$_2$Ca$_2$Cu$_3$O$_x$ (more commonly referred to as BSCCO-2223) was successfully manufactured into practical wires during the 1990s.

### 3.3 HTS rotating machines

Rotating machines utilizing HTS materials have been under development for nearly 20 years, following the discovery of HTS materials in the late 1980s. HTS machines can use either HTS wires [19], or bulk HTS material [20], or even a combination of both [21]. Various types of HTS rotating machine topology have been proposed, including synchronous, homopolar [22] and induction [23]. Most large HTS machines projects to date have used a topology similar to conventional large synchronous machines, with a DC field winding on the rotor wound with HTS wire, and a copper AC stator winding at conventional temperature, as in [19].

The largest HTS machine that has been built and tested so far is a 36.5 MW, 120 rpm ship propulsion motor designed by American Superconductor (AMSC), and manufactured by AMSC, Northrop Grumman Corporation and Electric Machinery (now part of the Converteam group) for the US Navy [24]. This motor completed full load testing in January 2009. It has a rated torque of 2.9 million Nm, comparable to that of a 4 MW wind turbine. The 36.5 MW machine was the follow-on from a scaled prototype 5 MW, 230 rpm machine design and manufactured by AMSC and ALSTOM Power Conversion Ltd. (now Converteam Ltd.). The 5 MW machine was tested at full torque at ALSTOM, Rugby, UK [25], and at full load under simulated ship at sea conditions over a period of 1 year in the C.A.P.S. facility at Florida State University [26].

### 4 HTS technology in wind turbines

#### 4.1 Benefits of HTS generator technology

HTS technology allows rotating machines to be constructed with significant increases in power density compared to conventional or permanent magnet machines. This advantage becomes greater as the size of the machine increases [27]. High power density is the result of the high current density that can be obtained in HTS coil, reducing the space required for the rotor field coils. The copper coils in a conventional machine typically operate with a current density between 3 and 5 A/mm$^2$, while the current density in the wire in a HTS coil can operate at 200 A/mm$^2$ or more. In HTS wire this is known as the ‘engineering current density’ which is the current density in the full cross section of the wire, but as the HTS material only forms a small proportion of the cross sectional area of the wire, the current density in the HTS material itself is much higher, up to 20,000 A/mm$^2$. Additionally, the ability to place many Amp-turns of field winding
in a small volume, way beyond that which could be achieved using copper without unacceptable losses, can be used to increase the airgap flux density, allowing the airgap shear stress to increase. This offers the advantages of a direct drive generator at increasingly large turbine ratings without encountering practical difficulties due to the ever increasing size and mass of the generator. This reduction in mass of the largest turbine ratings is particularly important for the offshore wind market. A smaller, lower mass generator also enables the nacelle to be transported and lifted to the tower in one piece. The current generation of dedicated offshore wind turbine installation vessels have a lift capability of typically around 300 tonnes. The nacelle mass of some of the larger turbines currently available exceeds this. Lifting heavier components is possible, but becomes very expensive. The assembly of nacelle components at the top of the tower at an offshore location, particularly in a climate such as that in the North Sea, would be prohibitively expensive. An HTS direct drive generator of 6 MW or more would be approximately 20% of the mass of an equivalent conventional direct drive wound pole synchronous generator such as a rim generator design, or 50% of the mass of an optimized permanent magnet direct drive generator. Hence an HTS generator can make a direct drive feasible, with a similar nacelle mass to the traditional geared high speed generator, at very large turbine power ratings (>6 MW), where conventional or PMGs would become impractically large. HTS generator technology, therefore, can make very large turbines (8–10 MW or more) viable, resulting in a reduction in cost of offshore wind energy.

HTS generators also offer efficiency advantages at full load and particularly at part load when it is important to extract as much energy from the wind as possible. The value of efficiency in a wind turbine could be questioned, since the source of energy is free. However, a more efficient generator will generate more sales revenue from the same power at the turbine blades. There is an economic balance between the amount of energy generated by the turbine over its lifetime against the capital cost of the turbine. However if an efficiency gain, resulting in greater output for the same mechanical equipment, can be obtained without a corresponding increase in the capital cost of the turbine, it offers an advantage. A conventional machine has significant losses in the generator rotor, which, apart from a relatively small power requirement for the cooling system, the HTS machine does not have. The permanent magnet machine also has virtually no loss in the rotor and no power requirement for the cryogenic cooling system, but the airgap flux density is limited by the permanent magnet material and saturation in the iron magnetic circuit. In an HTS machine the increased flux density induces more e.m.f. per unit length in the stator copper coil, hence for a given copper section, and a given airgap diameter, the HTS generator output will be greater with same loss, hence higher efficiency.

A direct drive generator eliminates the gearbox, resulting in reduced maintenance requirements and increased reliability. Unlike a DFIG, but like the PMG, the HTS generator can have no sliprings requiring maintenance. A DFIG or conventional synchronous generator contains insulated windings on the rotor which are subject to elevated temperature and to thermal cycling whenever the load on the generator changes. This is a known source of failure on conventional generators [28]. In contrast, the rotor field winding of an HTS generator is maintained at a
constant low temperature, except for periods of prolonged shutdown, and therefore does not see continuous thermal cycling [29]. Moreover, the operating temperature is such that the chemical processes that are responsible for the ageing of the electrical insulation have all but ceased.

The HTS windings need to be cooled by a closed loop cryogenic cooling system, with a cryocooler providing the cooling power. Cryocoolers with a suitable power rating are available as off-the-shelf commercial products. The present generation of cryocoolers do require periodic maintenance with intervals similar to those of many other turbine components; however in Europe there are projects working on the development of low maintenance or maintenance free cryocoolers. Converteam Ltd. is involved in one of these projects.

4.2 Commercial exploitation of HTS wind generators

In order for an HTS generator to be commercially competitive in the wind turbine market, a number of prerequisites must be met.

4.2.1 HTS wire

* It must be possible to manufacture HTS wire in large volume at low cost.

The volume of HTS wire required for a viable HTS wind market is many times greater than the present HTS production capacity. The production process of the previously commercially available BSCCO-2223 wire would not be scaleable to the required volume at the required cost. HTS wind generators will rely on the development of the 2nd generation (2G) of HTS wire described below.

The cost of HTS wire is normally stated as the cost of the wire needed to carry an amount of current over a certain distance, typically in $/kAm – the cost to carry 1000 A over 1 m. There is a further complication in that the current carrying capacity of the wire depends on its operating temperature and the operating magnetic flux density, therefore it is conventional to use the current carrying capacity at 77 K (boiling point of liquid nitrogen) with no applied magnetic field. In 2008 the cost of HTS wire was around 130 $/kAm. In order to be cost effective in HTS generators for wind turbines the cost needs be in the range 10–20 $/kAm.

4.2.2 Generator design

* The generator design must be optimised for low cost volume production.

The majority of cryogenic design experience has been with low volume specialist applications where cost is much less important. The exception to this has been the MRI scanner market using LTS magnets, which manufacture moderately high volumes. Design for manufacture techniques, and careful selection of materials and components, must be used to obtain a volume manufacture generator design.

4.2.3 Cooling system

* The cryogenic cooling system must be reliable with extended maintenance intervals.
Commercially available cryocoolers are designed for the laboratory or hospital environment, and would require some ruggedisation to be suitable for an off-shore wind turbine environment. The coolers of the temperature range and power required for the HTS generator use either the Gifford-McMahon cycle, or Stirling cycle. Maintenance intervals are presently 9–18 months, which would need to be extended for offshore wind power applications. Zero maintenance has already been addressed for very small cryocoolers – there a large number small Stirling cycle coolers on spacecraft that have operated without maintenance or failure for up to 16 years. Newer cooler technology such as pulse tubes, which have no moving cold parts [30], and free piston Stirling cycle coolers [31], which have no wearing seals, are beginning to become viable in the larger power ratings required for HTS machines.

5 Developments in HTS wires

HTS generators cannot be a commercial success in the wind market without low cost volume production of HTS wire. All HTS wire produced to date has been more than an order of magnitude too costly to be considered. However, a new class of HTS wires have been developed and are currently at the early stage of commercialisation. These wires have the potential to meet the volume and cost requirements for the HTS wind generator. These new wires have become known as 2G HTS wire and the earlier wire as 1G.

5.1 1G HTS wire technology

Until very recently (2006) all commercially available HTS wire was based on BSCCO and manufactured using the ‘Powder in Tube’ method. The HTS precursor powder was placed inside a machined silver tube which was the drawn out until reduced to about 1 mm diameter. This was then cut into short lengths and a large number of these, typically 80–100, placed inside another silver tube, and drawn out again until about 1 mm diameter. This wire was then rolled flat to about 4 mm wide by 0.2 mm thick. The final process was a controlled heat treatment in a controlled atmosphere to produce the superconductor material inside the filaments. The resulting wire structure can be seen in Fig. 4.

This was an inherently costly process, requiring a large floor space for the drawing process. Early wire was priced at around 1000 $/kAm, with prices in 2008 around 130 $/kAm. The ultimate minimum price in volume for this wire is

![Figure 4: Composition of 1G BSCCO wire.](image-url)
estimated to be more than 50 $/kAm, which may be acceptable in niche rotating machine markets, but too expensive for the wind market.

5.2 2G HTS wire technology

The new 2G wires are based on the superconducting material YBa$_2$Cu$_3$O$_x$ normally referred to as YBCO-123 or simply YBCO. The structure and manufacturing method of 2G HTS wire is very different from that of 1G wire. YBCO was one of the first HTS materials to be discovered and is easily made in bulk form by growing a crystal in a similar manner to silicon. Development of YBCO-based wire began in the 1990s by attempting to deposit a crystal of YBCO onto a metal substrate tape. This technique has now been extensively developed by several manufacturers using a number of different processes. The wire structure consist of a substrate, typically a Nickel-Tungsten alloy, a very thin buffer layer onto which is deposited the YBCO superconductor to a thickness of 1–5 µm. Often an outer copper layer is added for stability. The overall wire thickness is between 0.1 and 0.2 mm thick depending on the manufacturer and product. The coatings are deposited on a wide strip of the substrate and then slit to the required tape width. This gives flexibility in the final width and current carrying capacity of the HTS tape, the most common being 4 mm for compatibility with 1G HTS materials, and 12 mm for higher current carrying capacity. A simplified wire structure is shown in Fig. 5, some processes introduce additional buffer layers. It is also possible to join two of these tapes back to back to produce a symmetrical duplex tape.

This type of HTS wire has the potential for volume production at low cost. It does not require the large floor space the 1G wire need for the drawing process, since the 2G process can be reel to reel, and once the correct process parameters are set up production remains almost entirely automated.

HTS materials are intrinsically anisotropic, and their sensitivity to magnetic field depends on the direction of the field relative to the surfaces of the HTS tape. It has been necessary to develop methods in the manufacturing process that minimise the effect of this anisotropic behaviour [32].

![2G HTS wire structure]

Figure 5: Simplified 2G wire structure – thickness scale exaggerated.
A number of different manufacturing processes are used to produce HTS wire of this composition. Superpower Inc., for example, use a vacuum deposition process [33], others use a mixture of chemical and vacuum processes. Zenergy Power Plc has been developing an all chemical deposition process, which they believe offers the potential for the lowest cost volume production [34]. Other manufacturers have also begun to look at all chemical processes.

### 5.3 HTS wire cost trends

HTS wire prices for 1G wire fell rapidly from the mid-1990s. Since 2004 the price of 1G wire has fallen more slowly as manufacturers have ceased production to concentrate on commercialisation of 2G wire.

2G wire first became commercially available in 2006–2007, although at a high cost, and with performance inferior to 1G wire. By the end of 2008 the performance of 2G wire was beginning to approach that of 1G, but with prices still higher. In 2009 the performance of the best 2G wire is expected to exceed that of 1G and the price to be comparable.

The historic and forecast prices are shown in Fig. 6, in which forecast prices were obtained from data supplied by a number of HTS wire manufacturers. The forecast shows that commercial viability for HTS technology in wind turbines is expected to occur after 2013.

### 6 Converteam HTS wind generator

In 2004 Converteam Ltd. (then ALSTOM Power Conversion Ltd.), undertook a feasibility study into a direct drive wind generator based on the use of low cost 2G HTS wires, expected to become available in commercial quantities and at an

![Figure 6: HTS wire price trend.](image-url)
economic cost in the 2010–2015 time scale. This feasibility study resulted in a project to design and de-risk a full scale direct drive HTS wind turbine generator. The project is scheduled to complete in 2010, and will be followed by a program to prototype and industrialize a full size generator. It is partly supported by a grant from the U.K. Department of Trade and Industry (now Technology Strategy Board), and includes A.S. Scientific, a specialist cryogenic engineering company in Abingdon, U.K. and the University of Warwick, U.K., for their expertise in materials and volume manufacturing methods, as project partners.

6.1 Generator specification

The generator specification was based on the rating of the largest offshore turbines expected to be in production in 5–10 years time. The rating was chosen to be 8 MW at 12 rpm, which would be used on a turbine with a rotor diameter of around 160 m, and a blade tip speed optimised for far offshore application. This gives the generator a shaft torque of 6500 kNm, the largest torque of any HTS rotating machine project to date.

6.2 Project aims

The project was originally planned to extend over a period of 3 years although this was subsequently extended to 4 years to permit work on two other HTS projects concurrently. It was divided into three principle tasks:

1. The conceptual design of the full size generator during the first year of the project, followed by a gate review.
2. The detailed design, with cost and performance modelling, of the full size generator.
3. In parallel with the detailed design, a scaled model generator having a rated torque of up to 200 kNm, to be designed, manufactured and tested, employing the technology that will be used in the full scale design.

6.3 Conceptual design

The first stage of the project, involved the conceptual design of the full size generator, and was completed in November 2006. The resulting generator design was 5 m diameter with an overall length (excluding shaft extensions) of 2.2 m, and a mass of just over 100 tonnes. This stage of the project examined the technical, economic and market feasibility of the HTS generator, and aimed to provide a baseline design and one or more solutions to the technical challenges that could be used in the detailed design stages to follow. The completed concept design, with the rotor shown separately is shown in Fig. 7.

A preliminary study examined many of the synchronous HTS machine topologies, in order to determine the optimum design basis for the HTS wind generator. The design of HTS machines involves a broader range of skill than those that are
necessary to design a conventional electrical machine. In addition to skills in the fields of electromagnetic and mechanical engineering needed for conventional machine design, skills are also required in the fields of cryogenics and vacuum technology. There are more options open to the designer of an HTS synchronous machine compared to a conventional machine. Since conventional electrical machine design tools are not applicable to some of these topologies, it is necessary to rely heavily on electromagnetic finite element analysis (FEA) for the design process. The limited magnetic circuit in most HTS machine designs give no defined path for the magnetic flux, which means that 3D electromagnetic FEA must be used. This is an order of magnitude more time consuming than 2D analysis.

The HTS synchronous machine can be classified into a number of different types with different characteristics, advantages and disadvantages:

1. Conventional stator with iron teeth and HTS rotor with magnetic pole bodies which can be either warm or at cryogenic temperature. The electromagnetic layout of this type is shown in Fig. 8 (components without an electromagnetic function are not shown). This type does not offer much improvement in size or mass compared to a conventional machine, but offers gains in efficiency due to almost zero rotor loss.

2. Conventional stator and HTS rotor with non-magnetic pole bodies (Fig. 9). The advantages are similar to type 1, but it requires more HTS wire to produce the necessary stator flux density. It avoids potential high cost cold magnetic materials or complex thermal isolation.

3. Airgap stator winding and HTS rotor with magnetic pole bodies (Fig. 10). This construction allows the flux density at the airgap significantly beyond what is possible with a conventional stator. The rotor iron can operate very highly saturated, since the flux is predominantly DC. This allows significant reductions in size and mass of the HTS machine. Since most ferromagnetic materials become

![Figure 7: The conceptual 8 MW generator design.](image-url)
very brittle at low temperature the choice of material is limited. Nickel-based alloys have satisfactory properties but are expensive.

4. Airgap stator winding and HTS rotor with non-magnetic pole bodies (Fig. 11). This construction also allows significant reduction in size and mass. It requires more HTS wire than type 4, but does not require expensive cold iron components since it is relatively easy for the rotor core to be warm and thermally isolated from the cold HTS field system.
The above options were studied for the direct drive wind generator, for which cost and low mass are important (size less so, apart from transport considerations). Types 3 and 4 offered the advantage of lowest mass. The cost balance between these two types to a large extent depended on the relative cost of HTS wire against other materials. Based on the predicted volume pricing for 2G HTS wire, type 4 was chosen for the Converteam HTS machine.
6.4 Design challenges

The direct drive wind generator presented a number of design challenges, which were identified as risks or potential stumbling blocks at the start of the project. However, the conceptual design stage identified solutions to all of them. A number of these challenges are described below.

6.4.1 Rotor torque transmission

The very high rated torque of this generator needs to be transmitted from the HTS coils at cryogenic temperature to the shaft at near to ambient temperature, without conducting an unmanageable quantity of heat from the warm parts to the cold parts. A typical cryocooler that can extract 100 W at 30 K would require in input power to the compressor at approximately 10 kW, although cryocooler efficiency is expected to improve over the next decade.

The conceptual design used a torsion rod system that could transmit rated and fault torque with only a little over 20 W of heat conduction to the cold parts.

6.4.2 Managing mechanical forces

The generator is a large machine, with a very high rated torque, operating at high magnetic flux density (>4 T in parts of the HTS coils). The large physical size means that stresses due to differential thermal contraction must be carefully modelled and managed to prevent excessive stress in rotor components, particularly in the HTS coils where excessive strain in the HTS wire could lead to a reduction in the critical current of the wire, which could lead to a quench, when the wire returns to its non-superconducting state.

The high operating current density in the HTS coils in combination with high magnetic flux density, leads to very high Lorenz ($J \times B$) forces acting on the HTS wire. Although the generator torque acts on the coil by this force, it represents only 10% of the total Lorenz force on the HTS wire, the remainder due only to applying rated field current. The force density on the HTS coil for this condition is shown in Fig. 12.

![Figure 12: Force density on the surface of the HTS coils.](image-url)
A coil geometry and support structure was chosen that met the criteria to control the mechanical forces, while minimising the flux density in the HTS wire, taking into account the anisotropic characteristics of the wire. Converteam has been supported by its superconducting partner Zenergy Power in develop the coil manufacturing process.

6.4.3 Wind turbulence

Wind does not blow at a constant speed, so a wind turbine is subjected to constantly changing wind speeds and load. The amount of turbulence is dependant on the site location and the wake effects from other turbines, with background turbulence much higher onshore than offshore. This results in a wind turbine generator being subjected to constantly changing speed and torque, which can induce eddy currents in the electrically conducting cold components, creating losses and hence unwanted heating of the cold parts. It can also result in fluctuating flux density at the HTS coils, causing AC loss in the superconductor.

A simulation was carried out on the conceptual design using a level of wind turbulence at the high end of what may be expected for an offshore location, as shown in Fig. 13.

A two-dimensional non-linear time stepping electromagnetic finite element (FE) simulation was carried out over a simulated time period of 10 min using Vector Fields Opera software. The model included an external circuit (outside of the FE mesh) which was continually varied to simulate the turbine control system. The solution was post processed to obtain eddy current loss in individual rotor parts and flux density variation in the HTS coil. The simulation included the effect continuous blade pitch control in the turbine to attempt to maintain the power supplied to the grid constant whenever possible, allowing the generator speed and torque to vary. A similar control method is described in [35]. The simulation also included blade pitch control compensating for the periodic torque variations due to wind.

![Typical Wind Turbulence](image-url)

Figure 13: Wind velocity.
shear giving different wind velocity between a blade at the top and bottom of its rotation and also of the effect of blades passing the tower. The resulting generator speed (top trace), output kW (middle trace) and torque (bottom trace) is shown in Fig. 14. The resulting eddy current losses in the rotor cold parts and the warm electromagnetic shield surrounding the rotor are shown in Fig. 15.

Although there is high instantaneous loss at the instant of sudden changes, the average loss is low, requiring negligible additional cooling power. The fluctuations in flux density in the HTS were also found to be small. AC components of current and magnetic flux density are known to induce losses in the HTS wire (known as AC loss), which was not included in the analysis. AC loss in superconductors is
difficult to calculate and has been extensively researched. However, nearly all of
this research was for AC current applications such as HTS power cables and trans-
formers, where the HTS wire current and magnetic flux density is purely AC, and
small relative to the DC critical current value, such as in [36]. In this situation there
will also be hysteresis losses in the magnetic substrate of the 2G HTS wire. The
2 MW generator in [37] has a permanent magnet field and pure AC current in the
HTS stator winding. In the Converteam HTS generator the HTS wire is operating
with a DC current and in a very high DC magnetic flux density, not far from the
wire critical current, with a very small (compared to the pure AC studies, and even
slammer compared to the DC component) AC component superimposed. The 2G
wire magnetic substrate would be fully saturated in this case, and would not expe-
nience hysteresis loss, but these will still be losses due to the changes in trapped flux
within the superconductor (also known as hysteresis) and due to eddy currents in the
wire substrate. Converteam Ltd. have commissioned the University of Cambridge,
UK to carry out a theoretical analysis of AC loss for wire under these conditions
backed up by tests using a variable temperature insert in a 5 T LTS magnet.

6.4.4 Cooling of HTS coils

It is essential that during operation the HTS coils are maintained at a temperature
such that there is sufficient margin between the operating field current and the
critical current of the wire. In order to minimise the power input to the cryocooler
and make best use of its cooling capacity a temperature difference as small as pos-
sible between the cryocooler and the HTS coils is desirable.

Past HTS motor projects have used either closed circuit helium gas circulation
[38], or phase change neon cooling systems. The neon-based systems, such as
described in [39] condense the neon gas at the cryocooler at its boiling temperature
of 27.2 K. Liquid neon is then supplied to the rotor and allowed to evaporate,
removing heat from the rotor in the process, and returning to the cryocooler as a
gas. This type of system has the advantage that it is a very effective cooling pro-
cess and can operate as a thermosiphon, with no mechanical assistance to the cir-
culation. One disadvantage to such a system is that the cryocooler cold head
temperature varies with heat load, and it is necessary to introduce a heater to the
system to prevent the temperature from dropping to 24.6 K and freezing the neon,
wasting cryocooler power. A second disadvantage is that the coolant temperature
is fixed at 27 K, and it is expected that with 2G HTS wire, that the operating tem-
perature could be considerably higher, probably in the range 40–60 K. A third
disadvantage is that cooling will be non-uniform when the rotor is stationary. This
could cause undesirable stresses in coils and their support structure.

A helium gas circulation system was chosen for the HTS wind generator. While
this had the disadvantage of requiring assisted circulation, it offered complete flex-
bility in the choice of operating temperature. Heat was transferred between the
HTS coils and the cold helium in the rotor cooling circuit by conduction. In order
to calculate the heat flow and to determine the coil operating temperature, it was
necessary to use detailed computational fluid dynamics (CFD) and thermal FE
models that also had to take into account the larger (order of magnitude) variation
in material properties such as thermal conductivity and specific heat capacity with temperature.

6.4.5 Airgap stator design

In a conventional stator the radial and tangential forces act on the iron teeth, where the stator conductors only see a small force due to leakage flux, but in an airgap winding these forces act directly on the stator conductors. The stator coils not only have to withstand these forces, but the forces also have to be transferred from the coils using non-magnetic, non-conducting materials, since magnetic materials would saturate leading to high losses due to AC flux, and high eddy current losses would be induced in conducting materials. These forces are also cyclic, so the stator teeth are subject to high cycle fatigue loads. Even when the total generator torque is steady, each individual coil side sees a force fluctuating at 2\times the stator fundamental frequency with a pattern rotating around the machine with the rotor field. In fault conditions the patterns are continually changing in time as well as space, involving complex mechanical time stepping modelling techniques. An example of an electromagnetic and mechanical time stepping simulation of a short circuit fault is shown in Fig. 16, where the graph show the force on individual stator teeth against time, with mechanical FE output of the deflection. A number of composite materials have been investigated, and some glass-based materials have been found to offer acceptable properties.

The modelling produced a design with acceptable stress and deflection using composite material support structure. Further prototyping and fatigue testing is planned.

The high power density that is possible with HTS machines also means that careful design must be given to stator cooling. Due to the cost sensitive nature of

![Stator mechanical model during a short circuit](image)

**Figure 16**: Force and deflection of stator coils.
the wind generators it was desirable to avoid complex liquid cooled systems. Extensive thermal and CFD modelling showed that the stator could be easily cooled by forced air ventilation.

6.4.6 Stator iron losses
The stator design contains a laminated iron core located radially behind then airgap winding. This serves three purposes:

1. It provides a means of mechanical support and rigidity close to the coil supports.
2. It shields external components from stray flux.
3. It provides an easy circumferential path for the flux passing behind the airgap winding, reducing the amount of HTS wire required.
4. It enhances the field in the active region of the stator winding.

A fully airgap design (type 4 above) machine has a significant component of magnetic flux in the axial direction near to and outside of the straight length of the machine. This can cause eddy currents to flow in the radial and tangential direction in the laminations, causing a high concentration of loss at the ends. The low frequency of the generator (<2 Hz) was expected to reduce these losses, but the phenomenon was still seen as a potential risk at the start of the project.

The conceptual design was modelled using Vector Fields Opera 3D electromagnetic FE software. The original design had a total end loss due to eddy currents of 55 kW, which may have been possible to remove by cooling, but would have had a detrimental effect on the efficiency on a machine of only 8 MW rating. Careful design of the stator core geometry and further modelling resulted in a design with this loss reduced to 6 kW.

6.5 The cost-benefit study
In order to justify the business case for the development of the HTS generator, Converteam Ltd. commissioned the independent wind turbine consultants BVG Associates Ltd. to analyse the cost/benefit of very large offshore turbines employing HTS direct drive generators and medium voltage power converters [40]. This study involved the design of a complete, notional, 8 MW, 12 rpm rotor wind turbine, with appropriate foundations by Sheffield Forgemasters, and turbine blade design, control and structural integration by Garrad Hassan Ltd.

Comparisons were made for a typical UK Crown Estate Round 2 offshore wind farm of 504 MW containing 4 MW geared conventional DFIG turbines (the baseline), 8 MW geared turbines, 8 MW direct drive PMG turbines, and 8 MW direct drive HTS turbines. To ensure consistent analysis, the study found first that on monopile foundations, conventional and PMG 8 MW turbines actually increased the cost of electricity from the wind farm compared to the baseline 4 MW turbines. Benefits of the Converteam design, low mass, 8 MW HTS generator resulted in an identical cost of energy compared to the baseline, even at pre-series volume costs.
Then, retaining the successful 8 MW HTS design, the foundation was replaced with an alternative more suited to such large turbines in relatively deep water. With this configuration, the 8 MW HTS turbines resulted in a 17% reduction in the cost of energy relative to the baseline, in the same pre-series volumes. The analysis included the efficiency benefits of HTS generators, but only at part load, since at wind speeds greater than the minimum required for full load output only part of the kinetic energy is extracted from the wind and the benefit of increased generator efficiency is limited to reducing the load on the mechanical components. Work is progressing with a wind turbine manufacturer towards the design and cost analysis of a new giant turbine, in serial volumes, prior to demonstrator deployment.

6.6 Model generator

Following the completion of the concept design, work started on the design of the scaled demonstration ‘Model Generator’. Apart from the use of 1G HTS wire rather than 2G, due to the limited availability and performance of 2G at the time of the wire purchase, the model generator uses scaled components of the same type as in the full size generator. The rating of the machine was constrained by the project budget for HTS wire, and was chosen to be 500 kW at 30 rpm. At the time of writing (December 2008) the design of the major components has been completed, and manufacturing was in progress. Manufacturing and testing of this generator is expected to be completed in 2010.

6.7 Material testing and component prototypes

An important part of the de-risking process for new technology is the manufacture and test of prototype components. A test facility was established at the University of Warwick with a cryostat to enable mechanical and thermal testing of small components at room temperature and down to a temperature of 30 K. Other tests included material properties for the support teeth for the airgap stator winding. Figure 17 shows a carbon fibre cold-to-warm torque link for the model generator, prior to mechanical testing. It was also considered essential to manufacture and test smaller versions of the HTS coils. During the concept design phase, three HTS coils were made to a design similar to the model generator and full size coils, which were tested in a

![Figure 17: Torque link.](image)

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simulated magnetic circuit in a small cryostat. These coils were successfully tested up to an operating current of 230 A, compared to the 140 A operating current in the model generator.

Following on from these tests Converteam opened a cryogenics laboratory in their Rugby facility to support all HTS projects, with a large cryostat (8 m$^3$ vacuum space) capable of accommodating the coils for the full size wind generator, shown in Fig. 18 during the setting up of a test.

6.8 The full scale detailed design

Following discussions with a wind turbine manufacturer, the rating of the full size generator was changed to 10 MW at 11.5 rpm, to suit their planned turbine development. The 10 MW design was scaled from the 8 MW concept design, resulting in a slight increase in diameter to 5.4 m, an increase in length to 2.6 m, and a mass of less than 140 tonnes.

The design is based on the expected performance of the best HTS wire in 2010, the earliest time when wire will need to be ordered for the full size prototype generator. This is expected to require an operating temperature of 40 K. The helium gas cooling system used in the design permits the operating temperature to be easily changed when future improvements in HTS wire performance permit.

7 The way forward

The next logical step will be the manufacture and test of a full size prototype, followed by its demonstration on the 10 MW turbine. In parallel with this the supply chain development and engineering of the manufacturing process for production manufacturing will take place before the start of commercial volume production, which could begin by 2015.

Figure 18: Large cryostat with a prototype HTS coil in a magnetic circuit at Converteam Ltd., Rugby.
As the performance of the HTS wire improves over the lifetime of the product, it is expected that the design will evolve. The improvement in wire performance could be used to increase in the operating temperature of the HTS coils, possibly to as high as 65 K, thereby considerably reducing the cooling power required. Alternatively the improvement in performance could be used to reduce the amount of HTS wire by operating at a higher current, although this change would require careful mechanical analysis of any resulting increase in forces on the coils.

Further developments are also expected in cryocooler technology. Pulse tube cooler, with no cold moving parts, are beginning to reach the power levels at the temperatures required in the HTS wind generator. Pulse tube will offer cooler with less maintenance and greater reliability, with the potential to locate the entire cryogenic cooling system on the rotor, removing the need to transfer cold fluid through a rotating seal.

8 Other HTS wind generator projects

In 2007 AMSC announced the start of a $6.8 million project to design a 10 MW class HTS direct drive wind generator. AMSC are working in partnership with TECO Westinghouse and with partial funding from NIST. The 30-month project, like the Converteam project, is also targeting the offshore wind power market. The project scope is similar to the concept and full size detailed design stages in the Converteam project.

A design study examining HTS direct drive wind generators at ratings of 2 MW, 21 rpm and 8 MW, 12 rpm was carried out in Japan [41]. Many conclusions were similar to those in the Converteam study. The HTS generator designs were reported as 1/3 to 2/3 of the size on non-superconducting machines, with efficiency gains of 1% at full load to 10% at part load. The optimum pole number was found to be between 16 and 20.

9 Conclusions

The new generation of HTS wire coming to the market is predicted to be available in volume at a cost low enough to make HTS motors and generators cost competitive with conventional copper and PMGs. The significant size and mass advantages make direct drive HTS generators an enabling technology for the very large 10 MW class turbines that will help reduce the cost of offshore wind energy.

Leading players have substantial developments completed and in demonstration, and wind power system developers and operators are being invited to appreciate the great potential in superconducting generators.

References


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