The attraction of simplicity

Permanent magnet machines are here to stay

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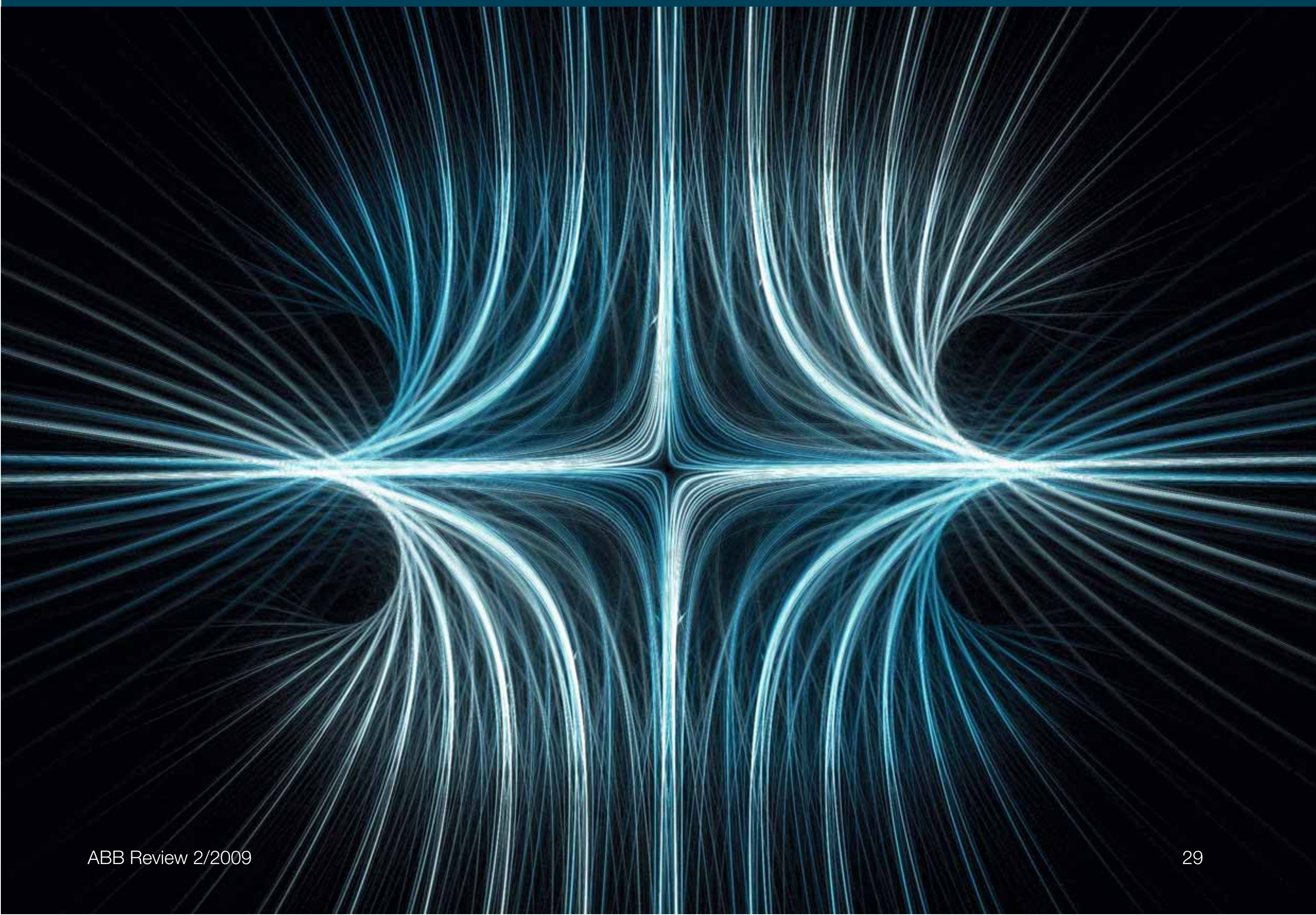
It is interesting to consider that many system components that we take for granted started off as workarounds. Not long ago, most readers would have taken it for granted that a large electric motor needed a gearbox to convert its speed and torque, and also an excitation system to provide the magnetic fields.

Sometimes, a redesign can help eliminate these workarounds and reduce the system to elegant simplicity. Progress with magnetic materials means that low-speed high-torque drives can now be realized with permanent magnets, permitting the elimination of both the excitation and the gearbox.

This approach is permitting energy saving and manifold other advantages in applications such as industrial drives, Azipod marine propulsion systems and wind turbines.



The concept of using permanent magnets (PM) for excitation in electric machines has been around for a long time. During the last 10 years, however, PM technology has advanced to be a technically and economically feasible solution, especially for slow speed high torque direct drives.

PM technology has some clear advantages over other excitation methods for electrical machines. Its widespread application has only become feasible recently, however, thanks to improvements in permanent magnet technology and decreases in their costs. ABB has developed PM technology-based products, especially for low-speed high-torque applications, as are found, eg, in process industries, ship propulsion and wind power.

During the last 10 years, PM technology has advanced to be a technically and economically feasible solution.

Further gains can be made by adopting all-electric direct drive technology, eliminating the gearbox and its accessories 1. The removal of these features leads to lower losses and better reliability of the drive as a whole. A three-stage gearbox in a 3 MW wind turbine decreases overall efficiency by about three percent. Additionally the elimination of the gearbox and jackshaft saves space on the factory floor.

A PM machine can be made as robust and simple as the equivalent squirrel-cage induction motor. When such a PM machine is used with an ABB direct torque control (DTC) variable-speed converter, there is no need to use a speed encoder to provide feedback of the rotor speed. The elimination of this potentially unreliable component further increases the reliability of the PM direct drive solution. Such a drive can offer a better availability than other presently available technologies in the low-speed, high-torque range. Thanks to this increased availability, the life-cycle costs can also be reduced.

PM machines in direct drive technology

ABB has been producing permanent magnet (PM) machines for almost 10 years now. A PM machine is a synchronous machine. It normally has three or more stator phases in the stator winding. Permanent magnets mounted in the rotor create a practically constant flux in the air gap. This "locks" to the rotating flux created by the stator windings. The PM machine thus runs in synchronism.

The shaft height of the machines delivered varies from 280 mm motors to 2,500 mm wind generators. The M3BJ, AMZ and AMG permanent-magnet machine product series have proven themselves as mature products.

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Electrical machines with a low number of poles, designed for a higher rated speed, can be operated at low speeds if they are supplied with a low frequency. However, such an application is not efficient as the converter's output frequency is much lower than its rated frequency range. At such a low frequency, the power switches have to be over-dimensioned in order to withstand the resulting switching losses. Therefore, machines with a high number of poles are generally preferable for low-speed applications.

Induction machines designed to run at 750 to 3,000 rpm are not particularly well suited for low-speed direct-drive operation as their efficiency drops with the reduction in speed. They may also be unable to deliver sufficiently smooth torque across the lower speed range.

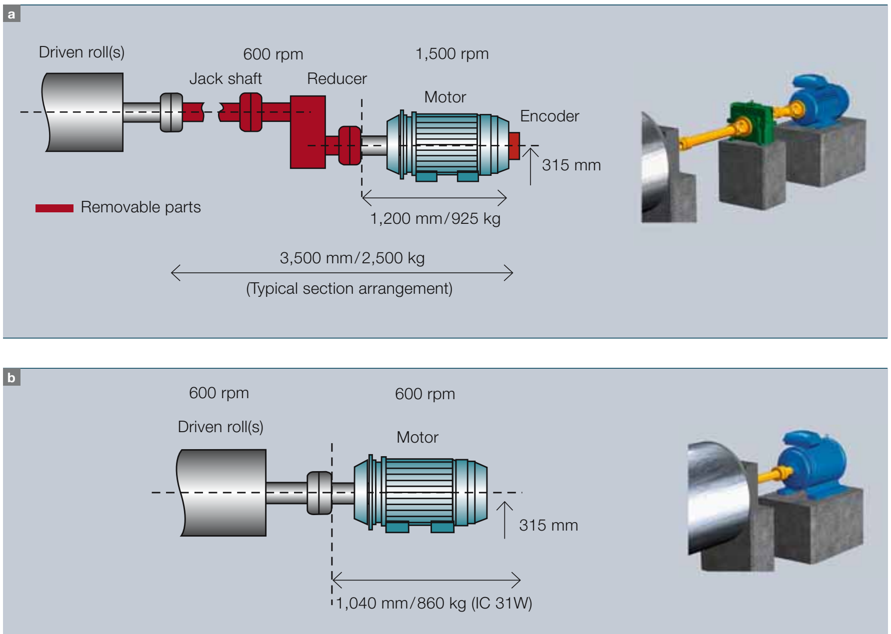
The power factor of an induction machine also drops with higher pole numbers (due to the increased leakage inductance). Therefore, induction machines with high pole numbers are not really suitable for low-speed direct drives.

These problems explain why gearboxes were added for such applications, permitting the machines to run more comfortably at higher speeds. The superior performance of PM machines in low-speed high-torque applications changes this, and permits the gearbox to be eliminated.

Reduced losses

One notable advantage of using per-

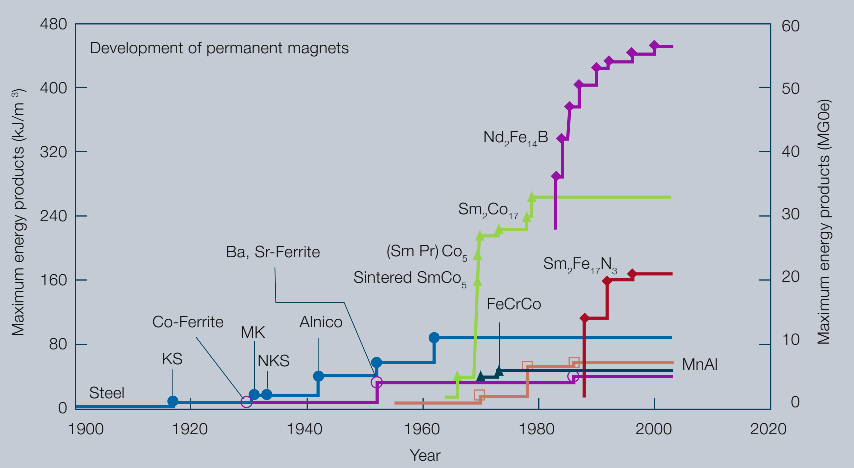
1 Drive configurations with conventional induction motor drive, gear and jackshift a, and the direct drive b



manent magnets for excitation is that there is no need to deliver excitation power from the grid through the converter to the machine, and thus the power required for excitation is saved. Also, converter losses are reduced, as the reactive current of excitation power is avoided. This gives some extra margin of load capacity for the inverter compared to a drive for an induction machine of the same output power.

The superior performance of PM machines in low-speed high-torque applications permits the gearbox to be eliminated.

2 Development of the energy product of permanent magnets



Source: Masato Sagawa, NdFeB magnets: Past, Present and Future, Prizztech Seminar on Advanced Magnetic Materials and their Applications 10.–11. 10. 2007 Pori

Energy product is a measure of the strength of a magnet, expressed as the product of its flux, B (measured in Gauss) and field intensity, H (measured in oersteds or amps per meter). The units for energy product are megagauss-oersteds (MGOe) or kJ/m³.

Harmonic components of the inverter voltage cause eddy currents on the surface of the PM rotor and magnets. These can be significantly reduced through suitable design methods and constructions. Most of the losses of the PM machine are generated in the stator windings and stator core. As a result, the temperature of the PM rotor in load conditions is quite low compared with electrically excited machines. Consequently, the temperature of the bearings is often lower. Lower bearing temperatures result in longer life of both the lubricant and the bearing itself.

DTC without encoders

Low-speed high-torque direct-drive applications usually demand control of torque and speed. The speed of a synchronous machine, such as a PM motor, can only be controlled with a variable-speed drive. Furthermore, the PM machine control must be specifically developed for permanent-magnet flux control. ABB's direct torque control (DTC) method has been enhanced for variable-speed PM machine drives.

Low-speed direct-drive applications often come with high demands on controllability and dynamics. These can be met by using ABB's DTC drive technology. When using a PM machine, it is possible to obtain the required high-performance operation without a speed encoder, as accurate calculation of the angle position and speed of the rotor are possible without such a device.

Currently ABB has low-voltage ACS800 and medium-voltage PCS6000 drives capable of supplying PM machines with DTC control.

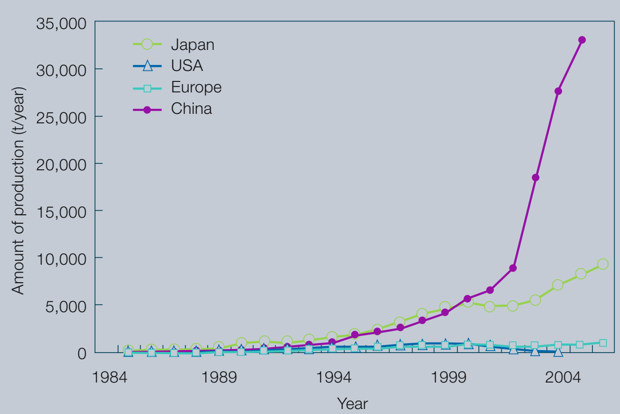
Higher system efficiency and availability

It has already been mentioned that the PM machine direct-drive solution can have higher overall system efficiency than a conventional jack shaft, gearbox and electric machine combination, because the associated losses are avoided. The efficiency advantages do not end here, however.

The construction of a PM machine can be as simple and robust as that of a cage induction machine. The absence of a gearbox, associated accessories, jack shaft, extra couplings and speed encoder means PM direct drives have a minimum amount of rotating parts and a minimum need of maintenance. This leads to high system efficiency when compared with other currently available technologies.

All these factors lead to increased availability, energy savings and minimized life cycle costs.

3 Development of production of sintered NdFeB magnets

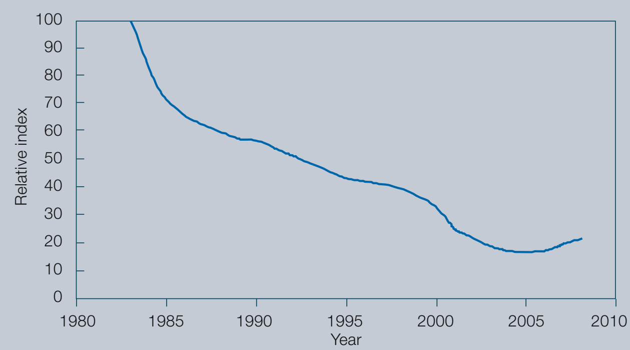


Source: Masato Sagawa, NdFeB magnets: Past, Present and Future, Prizztech Seminar on Advanced Magnetic Materials and their Applications 10.-11.10.2007 Pori)

Development of permanent magnets

Since 1960 the development of permanent magnets has advanced at a rapid pace 2. Permanent magnets see widespread use in low-power motor drives such as in hard disk drives and in consumer electronics. The use of permanent magnets in electrical machines has not been common until last two decades. This was primarily due to the relatively high price

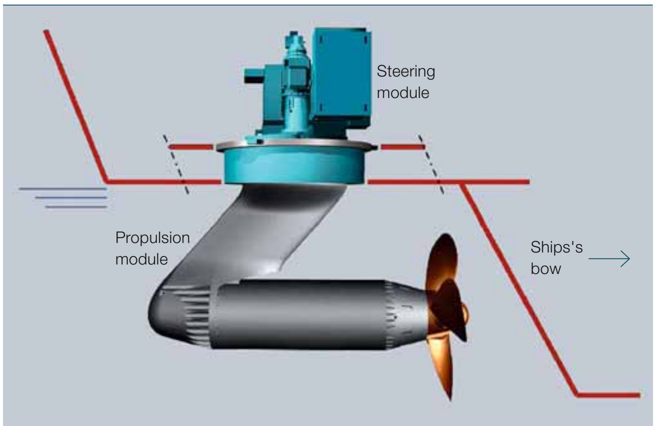
4 Development of relative price of sintered NdFeB magnets



The price of 1983 is used as a base value

Source: Magnews Summer 2008

5 ABB's Compact Azipod uses a permanent magnet motor

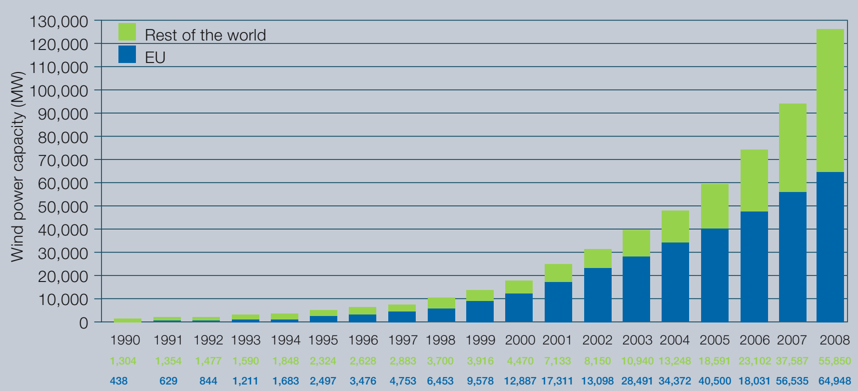


and manufacturing costs of magnet material.

Neodymium (Nd) Iron (Fe) Boron (B) magnets were invented in 1987. NdFeB is now the newest and most powerful magnetic material on the market. NdFeB has high values of flux density at very high values of magnetization. It is also extremely resistant to demagnetization. Furthermore, NdFeB is less costly and brittle than samarium cobalt, another rare earth material, that was used widely in the 1980s. Hence NdFeB magnets are normally used in ABB PM machines.

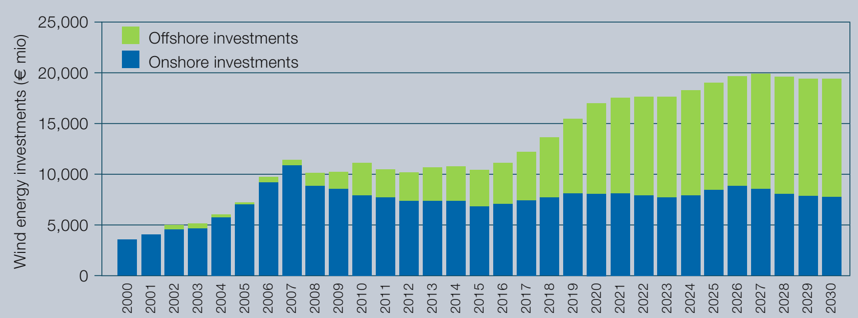
Rare earth metal production started in China in the mid 1980s. Strong market penetration caused the prices of the rare earth metals used in the production of permanent magnets to collapse 3. NdFeB is currently the most important permanent magnet material. In addition to Nd, Dysprosium (Dy) and Terbium (Tb) are also needed. The price of NdFeB magnets 4 has decreased significantly since the 1980s, but now after a bottom touch, the prices are increasing again; however at a reasonable rate.

6 Growth opportunity: Global cumulative wind power capacity 1990–2008



Source: EWEA, Wind Energy Scenarios up to 2030

7 Scenario of wind energy investments in the EU up to 2030



Source: EWEA, Wind Energy Scenarios up to 2030).

The higher availability of the PM direct drive has the additional advantage that it permits a reduction in inventory costs as fewer spare parts are needed.

The cost of NdFeB magnets of a large 2 to 4 MW direct-drive wind turbine PM generator is about 15 to 30 percent of the total material costs of the generator. The reduction in prices of NdFeB magnets at the beginning of the first decade of the 2000s has made large PM machines more attractive than ever before for low-speed direct-drive solutions.

PM motors in the process industry

High-accuracy low-speed drives are widely used in process industry. PM direct-drive technology can be used to eliminate gearboxes across a wide range of industries. For example, there are tens of rolls in a paper machine driven by a conventional solution: Every variable-speed drive with a normal-speed induction motor in such an application has a pulse encoder, jack shaft and gearbox. The PM direct drive solution without these extras is particularly beneficial in the paper industry, where poor reliability of feedback devices is a cause of unplanned production breaks. The higher availability of the PM direct drive has the additional advantage that it permits a reduction in inventory costs as fewer spare parts are needed.

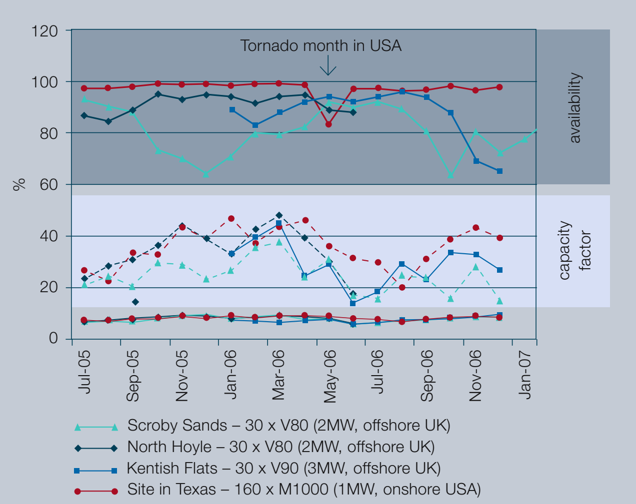
PM technology in propulsion

The ABB podded electric machine propulsion concept "Azipod" for ships has been on the market for 20 years now. During that time, in addition to being fitted to large cruise vessels, Azipod has rapidly gained popularity in other types of vessels such as cable layers, dredgers, shuttle tankers, chemical and product tankers, support vessels, motor yachts, drill ships and semi-submersible rigs.

In Azipod technology, the electrical motor is mounted in a bulb, which is attached to the hull of the ship, and these together form the main propulsion system. The speed of the motor and direction of the propulsion force is controlled in relation to the ship. The typical power range of these motors is 400 kW to 20 MW. One ship is normally equipped with between one and three propulsion units, and rigs equipped with dynamic position systems may use up to 10 units. Azipod allows excellent ship maneuverability, low vibration and noise levels, high efficiency, low emission and passenger comfort.

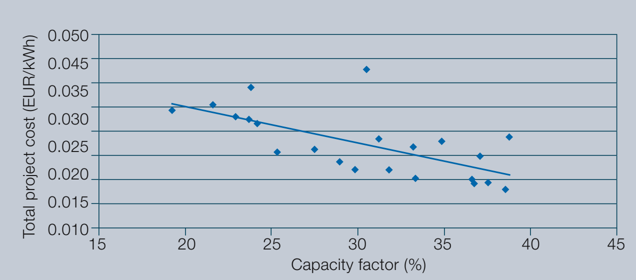
Permanent magnet motor technology has been used in the development of a highly standardized modular concept known as "Compact Azipod" 5, which has been designed for a propulsion power range of between 400 to 5,000 kW. Permanent magnets and DTC have been the main factors for improving the performance and extending the applicability of Compact Azipod.

8 Availability, capacity factor and wind speed of four wind farms



Source: Fabio Spinato, The Reliability of Wind Turbines

9 Total project cost per kWh vs. capacity factor



Source: Garrad Hassan, European Wind Farm Project Costs History and Projections 2008 Study

In PM Azipod solutions, the motor module can be cooled by the surrounding seawater, which would not be possible with high rotor losses.

There are no excitation losses in the PM rotor and hence most of the losses are generated in the stator winding and stator core, from where they can more easily dissipate. This permits PM technology to provide a higher power density. In PM Azipod solutions, the motor module can be cooled by the surrounding seawater, which would not be possible with high rotor losses. Furthermore, this approach permits the pod housing diameter to be kept small, providing improved hydrodynamic efficiency. This further increases fuel efficiency.

PM machines in wind power generation

The last 20 years have witnessed a phenomenal growth in the wind energy business 6. In this time, it has developed from experimental pioneering to mature global manufacturing. Today, wind power is the most promising source of new renewable energy.

Wind energy capacity is expected to grow much faster offshore than onshore 7. There are various reasons for this: It is easier to find space for a big offshore wind farm than for a big onshore wind farm. Offshore wind farms do not disrupt social communities in the way that onshore installations might do. It also expected that available wind resources are substantially more significant offshore than onshore.

In order to get the most energy out of available wind, the capacity factor should be high. The capacity (or load) factor of a wind turbine or wind farm is a measure of how much electricity is generated yearly compared with the installed capacity. The capacity factor is not a direct reference for the "windiness" of a particular region or site. This is because the size of the turbine rotor, the height of the tower and the availability of the turbine also have significant influence on energy capture.

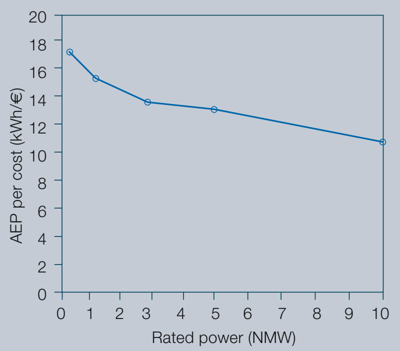
It can be seen from 8 that where the availability of offshore wind farms rises above 90 percent, their capacity factor often exceeds that of the onshore wind farms.

Availability is a function of machine reliability. A system can have a high reliability, but if appropriate maintenance is not conducted speedily, then the wind turbine can have a low availability.

Availability can be defined as a function of MTBF (mean time between failure) and MTTR (mean time to repair), so that Availability = MTBF/(MTBF+MTTR). MTBF is a measure of reliability and MTTR is measure the repair time, which is affected by availability of spare parts, personnel and equipment needed for repair and accessibility of the turbine.

The total project cost and cost of energy are affected by the capacity factor 9. A larger turbine can capture more energy out of wind, thus making the price of generated energy cheaper 10.

10 The annual energy production (AEP) per cost as a function of rated power



Source: Hui Li, Zhe Chen, Design Optimization and Comparison of Large Direct-drive Permanent Magnet Wind Generator Systems, Proc. ICEMS 2007).

There is an obvious trend to build larger and larger wind turbines and position them further offshore. However, recent studies have shown that more than one failure per turbine per year is common and reliability is lower for larger turbines [1]. Such poor reliability will be problematic in offshore installations, where more than 0.5 failures per year are not acceptable.

There are no excitation losses in the PM rotor and hence most of the losses are generated in the stator winding and stator core, from where they can dissipate more easily.

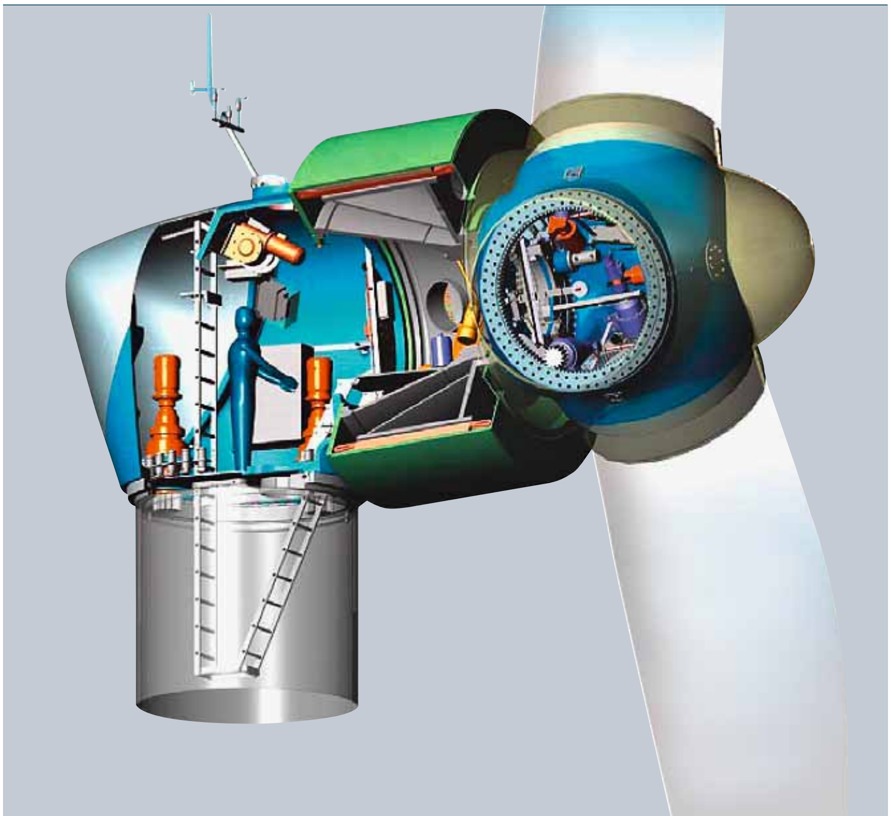
Reliability issues are mainly concentrated in the drive train and electrical subassemblies. Gearboxes for 3 MW and more are gaining in reliability, but gearbox failures do cause the most significant downtime and costs. Electrical components (except generators) cause relatively little downtime but their repair also causes high costs, especially in offshore locations.

The share of direct-drive turbines has been 13 to 15 percent of all yearly installed capacity over the last 10 years.

It may come as a surprise that the direct drive is not always intrinsically more reliable than an indirect drive. This is because the technology is still relatively new, and in some respects still developing.

Before even larger offshore wind turbines become feasible, their availability has to increase further. It is probably easier to improve the reliability of electric systems than that of mechanical systems. It is therefore expected that a permanent-magnet direct-drive wind turbine will have higher availability than a traditionally geared electrically excited one.

The Zephyros Z72 wind turbine with an ABB Direct Drive PM generator (green part)



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References

[1] **Spinato, F.** (2008). The reliability of wind turbines. PhD thesis, Durham University.