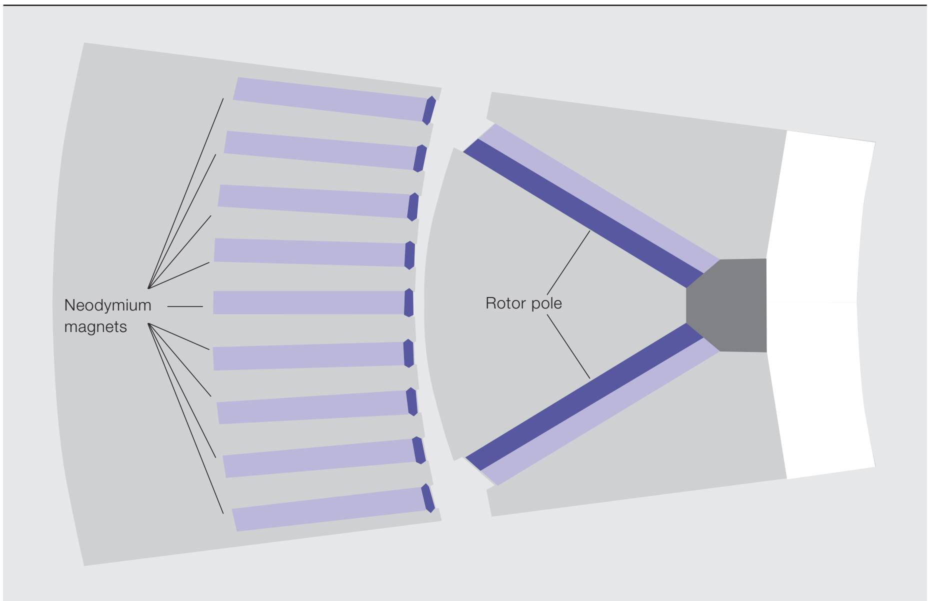
Wind of change

Design and test of a 7 MW wind turbine drivetrain

ERKO LEPA, TOBIAS THURNHERR, ALEXANDER FAULSTICH – Wind turbines are being installed at record rates around the world. With the vast capital sums being spent on this type of equipment, it is essential that the best technology is chosen. The market for wind turbine powertrains has, until now, largely been dominated by doubly-fed induction generators, but the market share of full-convertor-based concepts is increasing. Of these, it can be shown that the medium-voltage (MV), medium-speed class provide the best characteristics for utility-level applications: MV systems provide a low-current solution that minimizes cable losses, makes generator design easier and allows the use of a robust MV converter with high availability; medium speed allows a solution that is compact, lightweight and of the highest efficiency, compared with all other concepts. It pays dividends to design the components of a wind turbine carefully and this is illustrated here by the design and integration test of a 7 MW unit.

1 Rotor geometry



The doubly-fed and full converter electrical drivetrain concepts are the two prevalent in today's utility-scale wind turbines. The primary differences between them are the type and size of generator used and the function of the converter. The market has largely been dominated by the doubly-fed induction generator, but full converter concepts are now increasing their market share. There are several factors driving this shift, including grid code compliance and optimized power generation at lower wind speeds.

In the full converter concept, the converter decouples the generator and the mechanical drivetrain from the grid and all the generated power flows through the converter to the grid. The converter provides the generator's torque and speed control.

There are three types of full converter concept, each using different gearbox and generator solutions: low-speed (also known as direct drive), medium-speed and high-speed. In these, permanent magnet synchronous generators (PMSGs) and squirrel cage induction generators (SCIGs) are typically used.

Low-speed full converter type

The low-speed full converter (LSFC) type, also known as the gearless direct drive concept, uses a large diameter, low-speed (up to 30 rpm) generator. Permanent magnet or separately excited synchronous generators with a single bearing are typically used.

Medium-speed full converter type

In the medium-speed full converter (MSFC) type, either a single-stage or two-stage gearbox is used with a compact medium-speed permanent magnet generator (MS PMG). The nominal speed of the generator varies between 100 and 500 rpm. This concept causes less mechanical stress due to the lower speed and integrated gearbox solution. The integrated gearbox also results in a compact overall size.

High-speed full converter type

The high-speed full converter (HSFC) type runs at around 1,000 to 2,000 rpm, is mechanically similar to the doubly-fed induction machine and uses a normal three-stage gearbox. The overall size is small.

The main advantages are lower weight and smaller generator size.

Selecting a drivetrain

As each drivetrain type will result in different turbine weights, sizes and maintenance needs, selecting an appropriate drivetrain requires care and must take into consideration all of the turbine requirements, certification needed and grid code specifications.

Choice of voltage

The chosen speed concept does not determine the system voltage. Instead, the voltage is chosen based on the power level required. As a rough guide, for generators up to 3 MW, a low voltage is chosen (eg, 690 V). Above this, it often makes sense to choose a medium voltage (eg, 3.3 kV). This is mainly done to reduce the converter current. Lower current means the losses in the cables are lower. Additionally, design and part sourcing is simplified.

Choice of generator speed

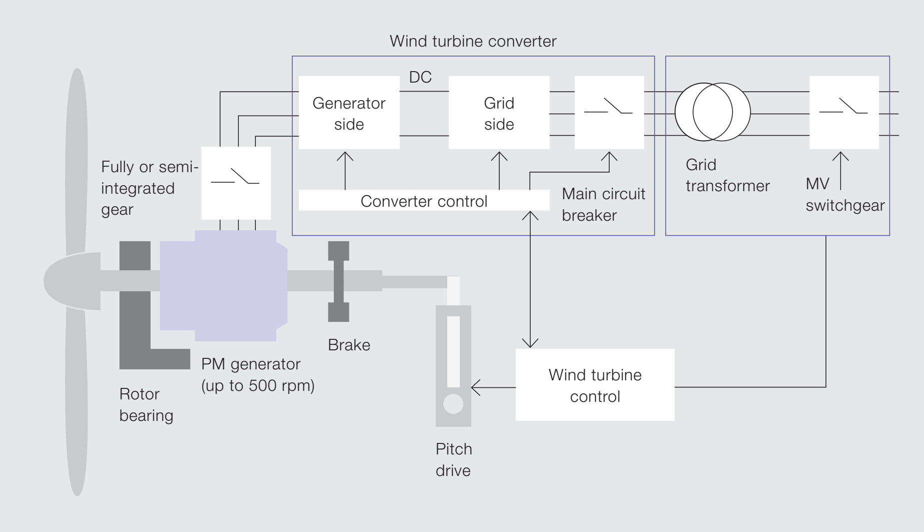
The choice of rotation speed depends on the particular characteristics of the drive components – eg, gearbox, generator, converter and transformer.

Direct investment perspective

Depending on the design, turbine power, grid requirements and market prices of the materials, the high-speed concept usually has the lowest direct investment costs. Direct drives are normally the most expensive solution, with medium-speed being slightly more expensive than high-speed solutions. However, maintenance costs, availability and annual wind distribution also contribute to lifetime costs, so only an analysis of all aspects can determine which concept delivers the most benefit.

Title picture
Choosing the right system components, such as this water-cooled, medium-speed permanent magnet generator, can bring huge benefits over the lifetime of a wind turbine. What are the critical design aspects involved?

2 ABB PCS 6000 converter schematic



3 Possible converter arrangements

Medium-speed PMSGs deliver over 98 percent efficiency – the highest of any commercial wind generator design.

Efficiency of different concepts

Calculations show that the medium-speed concept with a PMSG delivers the highest efficiency at the nominal point. In fact, medium-speed PMSGs deliver over 98 percent efficiency – the highest of any commercial wind generator design. Efficiency is also high at partial loads in low wind conditions and this enables the highest annual production of kWh. In addition, gearboxes can be smoothly integrated for a compact solution and the lower rotation speed means less wear in drivetrain components.

Choice of generator type

The power factor of an induction generator (IG) decreases as the number of poles increases and the pole pitch decreases. IGs are, therefore, competitive with synchronous generators (SGs) when their number of poles is small – ie, IGs are strongly competitive in high-speed applications. In medium-speed applications, IG efficiency is significantly lower. Generally, the greater the diameter of the generator, the higher its performance will be. As SGs can have a greater number of poles, the air gap diameter can be increased and there is greater flexibility in dimensioning the nominal frequency.

For low-speed, the only options are the PMSG or high-speed electrically excited synchronous generator (EESG). Both provide superior efficiency up to wind speeds of 8 m/s – ie, roughly 0 to 40 percent of the turbine nominal power. Above that, other concepts compete strongly.

With PMSGs the rotor is lighter, the generator efficiency is higher and the machine size is smaller, as there is no excitation system. Thus, PMSGs offer the best technical advantages in direct drive (DD) concepts.

Design of a medium-speed PMSG

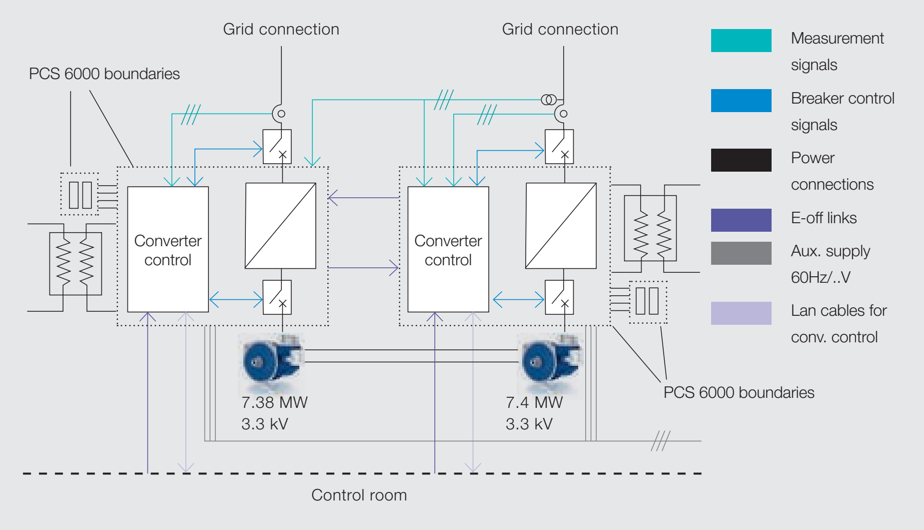
A 7 MW medium-speed PMSG and converter were designed and tested. Several design aspects are important:

- Due to the long distance from the generator to the transformer and high turbine power, a PMSG with an MV converter was selected.
- Calculations showed that 14- to 20-pole solutions were feasible from the performance and manufacturability points of view. Designs with 16 and 18 poles were quite similar, with negligible differences in losses, power factor, back-emf and active material masses. The inductances and load angle were slightly smaller in the 18-pole design, which was, consequently, chosen.
- After comprehensive calculations, optimizations and analyses, a V-type rotor pole shape was designed ➔ 1. Neodymium magnets with a high intrinsic coercivity force were chosen, based on simulations of sudden load and short-circuit conditions with different magnet properties and temperatures.
- In the design phase, it is important to identify potentially harmful resonance frequencies in the mechanical structure and provide enough damping and stiffness to tolerate the forces involved. It is equally important that the converter modulation strategy and switching frequency are adjustable. Based on experience, a change of about 50 Hz in the switching frequency will shift the excitation frequency from the resonant point and might lower the noise and vibration level significantly.

Converter design

The converter used for the 7 MW wind turbine electric drivetrain is based on a MV integrated gate-commutated thyristor (IGCT) with a three-level neutral-point

4 Back-to-back setup



clamped (NPC) topology. The IGCT combines the low conducting losses and reliability of a thyristor with full switch-off capability. The nominal converter voltage of 3.3 kV used not only means that the cabling effort and cable losses can be reduced compared with a converter with a lower output voltage, but also that fewer semiconductors are used, reducing failure points. The modular design of the ABB PCS 6000 product family converter allows a tailored mechanical arrangement of the converter components, whether the converter is placed in the tower, nacelle or a separate container outside the turbine, with different possible arrangements ➔ 2–3.

Lower current means lower losses in the cables and simpler design and part sourcing.

Integration tests

For the integration test, two generators were mechanically coupled and both were connected to the grid through a frequency converter ➔ 4. One PCS 6000 drove the connected generator as a motor, or so-called prime mover. This drove the other generator, which generated power back to the grid through the other converter. With this test setup, only the losses of the whole system have to be covered from the grid. The setup allows the generator to be run at nominal power, provided that the driving converter is able to operate with nominal turbine power and can cover the total losses in the setup.

The generator temperature rise was as calculated and converter component final temperatures remained under the component limits. The generator no-load voltage was lower than calculated and this reduced the power factor of the generator. Despite this, the generator main ratings were as calculated. The three-phase short circuit test after temperature rise demonstrated that the generator magnets were protected against demagnetization, as designed. The generator vibrations and emitted noise were measured and the values were well below the IEC criteria. The efficiency of the generator was 98.17 percent at the nominal point and exceeded expectations at other loading points.

Different switching frequencies over the whole speed range in different modulation modes were tested. The best results were achieved with a fixed pulse width modulation carrier frequency of 720 Hz or above over the whole speed range, in asynchronous mode. Asynchronous mode provided favorable results because the switching frequency and its side bands did not hit dangerous resonance points at any rotation speed.

MV delivers benefits in multimegawatt wind turbine applications when compared with LV systems. MV systems provide a low-current solution that minimizes cable losses, makes generator design easier and allows the use of a robust MV converter with high availability. The medium-speed concept with PMSG is a compact solution with low weight and the highest efficiency close to the nominal point, compared with all other concepts. Back-to-back tests of the electrical drivetrain demonstrated that the ABB generator and converter meet the requirements of the customer and IEC. Discrepancies between the calculated figures and measurements were within acceptable limits.

This combination of medium speed and medium voltage provides many significant benefits, not only for the customer – the turbine manufacturer – but also for the wind farm operator and end customer.

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