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THE ELECTRICAL CONVERSION SYSTEMS AND FUNDAMENTALS OF WIND TURBINE OPERATION

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Abstract

This article provides a synopsis of wind turbine electrical conversion technologies. A brief overview of the electric system's needs is followed by a review of the fundamentals of wind energy conversion using wind turbines. Up next, we'll go over the pros and drawbacks of the three traditional conversion methods: constant speed, variable speed with a doubly-fed induction generator, and variable speed with a direct-drive generator. We will quickly go over the power electronic converters that are used in this context. We wrap off by talking about some of the latest developments and alternate generation methods. The use of systems with variable speeds is becoming more common. More and more systems that use doubly-fed induction generators have the ability to ride through grid faults. Compared to electrically stimulated synchronous generators, radial flux permanent-magnet synchronous generators are more efficient and cost-effective for direct-drive turbines. Generator voltages are anticipated to rise to levels of 5 kilovolts.

Introduction

The main factor which has stimulated the use of renewable energy is environmental protection. The cost disadvantage of renewable energy has resulted in numerous efforts to reduce its cost. For wind turbines, this has resulted in a continuously increasing power, as appears from Fig. 1 [1].

The goal of this paper is to give an overview over different electrical conversion systems for wind turbines. First, the basic requirements for the drive system are discussed from some basic wind turbine relations. Next, the paper describes the three classical generator systems with their strengths and weaknesses. Subsequently, the applied electric converters are shortly addressed. Finally, alternative generator systems and trends are discussed.

Basic relations

Power from wind

The power that can be captured from the wind with a wind energy converter with effective area A_r is given by [2]

$$P = \frac{1}{2}\rho_{air} C_p A_r v_w^3 \quad (1)$$

where ρ_{air} is the air mass density [kg/m^3], v_w is the wind speed and C_p is the so-called power coefficient which depends on the specific design of the wind converter and its orientation to the wind direction. Its theoretical maximum value is 16/27 = 0.593 (Betz limit). For a wind turbine with given blades it can be shown that the power coefficient C_p basically depends only on the tip speed ratio λ, which equals the ratio of tip speed v_t [m/s] over wind speed v_w [m/s] and the so-called blade pitch angle θ [deg]. This pitch angle is defined as the angle between the cord of the blade and the plane of the wind rotor. So, for a wind rotor with radius r, (1) can be rewritten as:

$$P = \frac{1}{2}\rho_{air} C_p(\lambda,\theta)\pi r^2 v_w^3 \quad (2)$$

As an example, Fig. 2 shows the dependency of the power coefficient C_p on the tip speed ratio λ and the blade pitch angle θ for a specific blade. For this blade maximum energy capture from the wind is obtained for $\theta = 0$ and λ just above 6. To keep C_p at its optimal value for varying wind speed, the rotor speed should be proportional to the wind speed.

In practice both constant λ (variable speed) and constant speed operation is applied.

For on shore turbines, the blades are designed such that the optimal tip speed is limited to roughly 75 m/s. This is done because the blade tips cause excessive acoustical noise at higher tip speeds. For offshore turbines, the noise does not play an important role, and higher speeds are used leading to slightly higher optimal values of C_p.

The relation between wind speed and generated power is given by the power curve, as depicted in Fig. 3. The power curve can be cal-

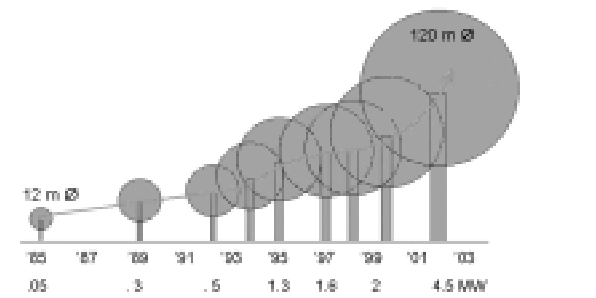

Fig. 1: Development of power and size of wind turbines at market introduction [1]

* This paper has been designated as outstanding paper of NORPIE 2004

culated from (2) where the appropriate value of λ and θ should be applied. In the power curve, four operating regions can be distinguished, that apply both to constant speed and variable speed turbines:

– no power generation due to the low energy content of the wind;
– less than rated power generation. In this region, optimal aerodynamic efficiency and energy capture is aimed at; the wind speed at the boundary of region 2 and 3 is called the rated wind speed and all variables with the subscript rated refer to design values at this wind speed;
– generation of rated power, because the energy content of the wind is enough; in this region, the aerodynamic efficiency must be reduced, because otherwise the electrical system would become overloaded;
– no power generation: because of high wind speeds the turbine is closed down to prevent damage.

Aerodynamic power control

In region 3 (and 4) the shaft power should be less then the available power from wind to prevent overloading of components. There are two main methods for limiting the aerodynamic effi- ciency in high wind speeds. With the first method one takes advantage of the aerodynamic stall effect. When the angle, at which the wind hits the blade ('angle of attack'), is gradually increased, then at a certain angle the airflow will no longer flow along the blade, but will become loose from the blade at the back side. Large eddy's will be formed that result in a drastic reductionof C_p (see Fig. 4).

If a turbine is operated at constant speed and the wind speed increases, then automatically the angle of attack increases. At a certain wind speed the angle of attack will reach the value where stall occurs. Here it is assumed that the pitch angle θ is not changed. With so-called stall controlled turbines the blades are designed such that the stall effect just starts at the rated wind speed. Due to the stall effect, the power is more or less constant above rated wind speed, as indicated by the dotted curve in Fig. 3 [4]. No active control systems are used to achieve this, which also implies that the blade does not need to be pitchable.

With variable speed (constant λ) wind turbines the angle of attack is independent of the wind speed so that the stall effect does not occur. To reduce the power above the rated wind speed the blades are pitched towards the vane position by hydraulic or electric actuators resulting in a reduction of C_p. Above the rated wind speed the variable speed turbines are normally operated at constant speed, where power (so torque) is controlled by the pitch angle. This results in a flat power curve above the rated wind speed (solid line in Fig. 3). From above it will be obvious that stall control is mainly used with constant speed turbines and pitch control with variable speed wind turbines.

Energy yield

The annual energy yield E of a wind turbine depends on its power curve $P(v_w)$ and the probability density distribution function $u(v_w)$ of the wind speed at the turbine site:

$$E = \int_0^\infty P(v_w)\cdot u(v_w)\,\mathrm{d}v_w \qquad (3)$$

Fig. 5 shows schematically a power $P(v_w)$, a distribution function $U(v_w)$ and the power density distribution (= $P.U$) as a function of wind speed. The figure shows that on an annual base there is hardly any energy contained in the wind range above 13 m/s because of the low occurrence of high wind speeds. This clarifies why the system is normally designed for a power rating that is much less than the power that would be available at the maximum operational wind speed of the turbine (25 m/s in Fig. 3). The choice of the rated power is obtained from a trade-off between investment costs to increase the power rating of components and the value of non-captured energy.

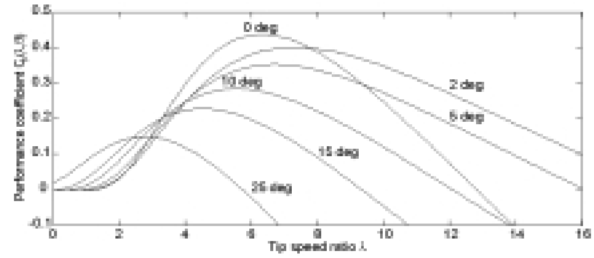

Fig. 2: Power coefficient C_p as a function of tip speed ratio λ and pitch angle θ for a specific blade [3]

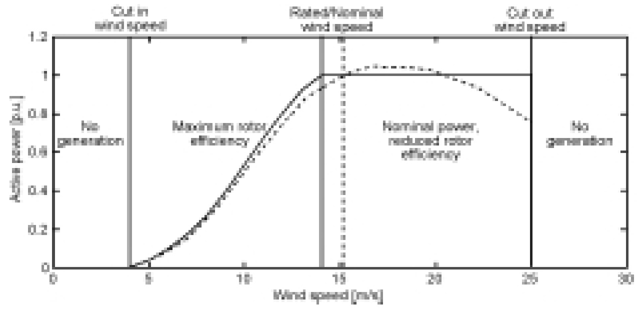

Fig. 3: Typical power curve of a constant speed stall (dotted) and a variable speed pitch (solid) controlled wind turbine [4]

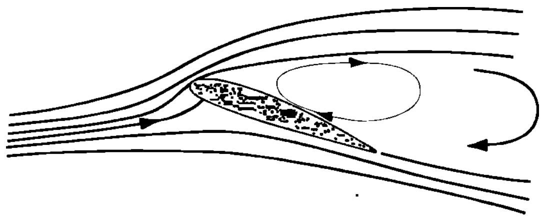

Fig. 4: Stalled flow around an aerofoil

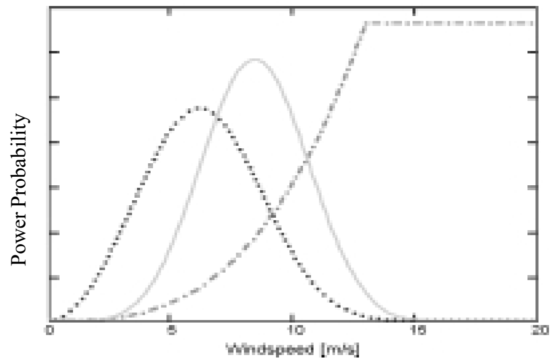

Fig. 5: Power P (dashed), probability density U (dotted) and power density distribution (solid) as a function of wind speed (arbitrary units)

Scaling laws

As stated before, the rated tip speed should be limited to about 75 m/s. If the rated tip speed v_{trated} is assumed independent of the size of the wind rotor, then the rotational speed of the rotor is inversely proportional to radius of the wind rotor. With (2) this results in a rated speed inversely proportional ($\propto$) to the square root of the rated power:

$$N_{rated} = \frac{60}{2\pi}\frac{v_{trated}}{r} \propto \frac{1}{\sqrt{P_{rated}}} \quad (4)$$

For the torque this implies that:

$$T_{rated} = \frac{P_{rated}}{\omega_{rated}} \propto P_{rated}^{3/2} \quad (5)$$

The size of the generator is related to the torque to be developed. The force density (the force per square metre of active air gap surface area) in electrical machines is a quantity that is rather constant over a wide range of machine powers. For the conventional generators used in wind turbines, the air gap force density is in the order of

$$F_d = 25 - 50 \text{ kN/m}^2 \quad (6)$$

This force density is rather constant because it is the product of air gap flux density, which is limited because of magnetic saturation, and current loading, which is limited because of dissipation. By using forced liquid cooling, this force density can be increased, but at the cost of reduced efficiency.

Based on this force density, a very fast and rather good estimate of the generator dimensions can be made. The power produced by a machine is given by

$$P = \omega T = 2\omega\pi r_s^2 l_s F_d \quad (7)$$

where ω is the mechanical angular frequency, r_s is the stator bore radius, and λ_s is the stator stack length. From this, the rotor volume of a generator can be estimated as

$$V_r = \pi r_s^2 l_s = \frac{P}{2\omega F_d} \quad (8)$$

If we further assume that the rated tip speed is independent from rated power, then for direct-drive wind turbines, according to (5), this reduces to:

$$V_r \propto \frac{P_{rated}^{3/2}}{2F_d} \quad (9)$$

Electrical system

Currently used generator systems

As stated before two types of wind turbines can be distinguished namely variable speed and constant speed turbines. For constant speed turbines one applies induction generators that are directly connected to the grid. For variable speed turbines a variety of conversions systems is available. The three most commonly used generator systems applied in wind turbines are depicted in Fig. 6 and discussed below. Table I lists a number of wind turbine manufacturers with their products, which contains some more systems than shown in Fig. 6.

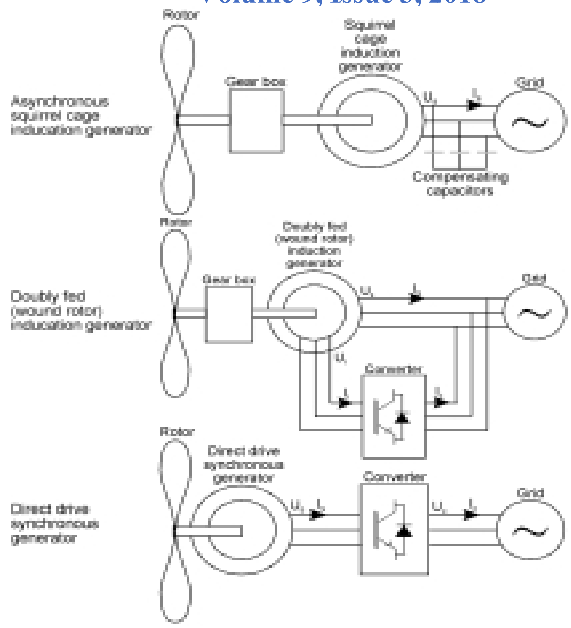

Fig. 6: The three commonly used generator systems

Table I: Wind turbine manufacturers, currently used concepts and power ranges, compare [4]

Manufacturer	Concept	Power range
Siemens / Bonus (DK)	CT/CS CT/AS	600 kW 1 – 2,3 MW
Dewind (UK/D)	VTDI	600 kW – 2 MW
Ecotecnia (SP)	CT/CS VTDI	750-1300 kW 1670 kW
Enercon (D)	VTDD	300 kW – 6 MW
GE Wind Energy (US/D)	CT/CS VTDI	600 kW 900 kW – 3,6 MW
Jeumont (F)	VTDD	750 kW – 1,5 MW
MADE (ES)	CT/CS VTSGP	660 kW – 1,3 MW 2 MW
Vestas / NEG Micon (DK)	CT/CS CT/AS VTDI	600 kW – 1,5 MW 1,5 – 2 MW 2,75 – 4.2 MW
Nordex (D)	CT/CS VTDI	600 kW – 1,3 MW 1,5 – 2,5 MW
Repower Systems (D)	CT/CS CT/AGP VTDI	600 – 750 kW 1050 kW 1,5 – 5 MW
Vestas (DK)	SVT/OSP VTDI	660 kW – 2,75 MW 850 kW – 3 MW
Zephyros (NL)	VTDD	1.5 – 2 MW

CT/CS: fixed speed, classic stall (fixed blade angle)
CT/AS: fixed speed, active stall (negative variable blade angle, 3-5 degrees)
VTDI: variable speed (+ pitch), doubly-fed induction generator
VTDD: variable speed, direct drive synchronous generator combined with pitch (Enercon + 1.5 MW Jeumont) or combined with classic stall (Jeumont J48 (750 kW))
VTSGP: variable speed/pitch combined with (brushless) synchronous generator
CT/AGP: nowadays unusual combination of fixed speed/pitch with directly connected asynchronous generator
SVT/OSP: semi-variable speed/pitch combined with OptiSlip (maximum +10% variation in nominal speed)

Constant speed wind turbine with squirrel cage induction generator (CT)

Between the rotor and the generator, there is a gearbox so that a standard (mostly 1500 rpm) squirrel cage induction generator can be used. The generator is directly connected to the 50 Hz or 60 Hz utility grid. Mostly, the power is limited using the classic stall principle: if the wind speed increases above the rated wind speed, the power coefficient inherently reduces, so that the power produced by the turbine stays near the rated power. Sometimes active stall is used: negative pitch angles are used to limit the power. There are a few variants:

– pole changing generators with two stator windings with different numbers of pole pairs so that the turbine can operate at two constant speeds in order to increase energy yield and reduce audible noise,
– generators with electronically variable rotor resistance in order to reduce mechanical loads by making larger speed variations possible: the semi variable speed wind turbine.

Variable speed wind turbine with doubly-fed (wound-rotor) induction generator (VTDI)
Between the rotor and the generator, there is a gearbox so that a standard (mostly 1500 rpm) doubly-fed induction generator can be used. The stator is directly connected to the utility grid. The rotor is connected to a converter. A speed range from roughly 60 % to 110 % of the rated speed is sufficient for a good energy yield, that is achieved by using the variable speed capability to keep the tip speed ratio λ at the value resulting in optimal energy capture. If the gearbox ratio is chosen such that the synchronous speed of the generator just falls in the middle of the speed range (in this case at 85 % of rated speed), then the lowest converter power rating is obtained. A converter rating of roughly 35 % of the rated turbine power is sufficient, particularly when star-delta switching at the rotor winding is applied. At wind speeds above the rated wind speed, the power is reduced by pitching the blades.

Variable speed wind turbines with direct-drive synchronous generator (VTDD)

In this system, no gearbox is necessary, because the generator rotates at very low speed, typically 10 to 25 rpm for turbines in the MW range. Standard generators can therefore not be used and generators have to be developed specifically for this application. As can be concluded from equations (6) and (8), these generators are very large because they have to produce a huge torque. The total turbine power goes through a converter that converts the varying generator frequency to the constant grid frequency. At wind speeds above the rated wind speed, the power is again reduced by pitching the blades.

Comparison of the three systems

Table II gives an overview of the characteristics of the three different systems. The criteria for comparison are discussed below [5].

Cost, size and weight

Squirrel cage induction generators are roughly 25 % cheaper than doubly-fed (wound-rotor) induction generators.

The converter for a doubly-fed induction machine is smaller and cheaper than for a direct-drive generator.

Direct-drive generators are much more expensive because they are large and heavy and have to be specially developed. However, direct drive turbines do not need a heavy gearbox.

Table II: Comparison of the three Wind Turbine Concepts, +: Strength, - Weakness

		CS	VTDI	VTDD
Cost, size and weight		+	+/-	-
Suitability for 50 and 60 Hz grid frequency		-	-	+
Audible noise from blades		-	+	+
Energy yield	Variable speed	-	+	+
	Gearbox	-	-	+
	Generator	+	+	-
	Converter	+	+/-	-
Reliability and Maintenance	Brushes	+	-	- (PM: +)
	Gearbox	-	-	+
	Mechanical loads	-	+	+
	Complexity	+	-	-
Power quality	'Flicker'	-	+	+
	Grid *V&f* control possible	-	+	+
	Harmonics	+	-	-
Grid faults	Fault currents	+	+	+/-
	Restoring voltage	-	+	+

Suitability for 50 and 60 Hz grid frequency

Turbines with generators that are directly coupled to the grid (CT and VTDI) need different gearboxes for different grid frequencies. This is not the case when a converter decouples the two frequencies.
Audible noise from blades
In a well-designed wind turbine, the blades are the main sources of audible noise. In variable speed wind turbines, the rotor speed is low at low wind speeds, and so is the audible noise. This is not the case in constant speed wind turbines. At higher wind speed the noise from the blade tips drowns in the wind noise caused by obstacles more close to the observer. However, in a wind turbine that is not properly designed, mechanical resonances can also cause other audible noise.

Energy yield

In order to capture the maximum energy from the wind, the rotor speed has to be proportional to the wind speed in region 2 of Fig. 3. Therefore, the energy yield of variable speed wind turbines is larger than of constant speed wind turbines. Especially in part load, gearboxes and power electronic converters have limited efficiencies.

Low-speed direct-drive generators have lower efficiencies than standard 1000 or 1500 rpm induction machines because direct-drive generators have to produce much higher torques at much lower speeds.

Reliability and maintenance

Brushed synchronous generators and doubly-fed induction generators have brushes, which need regular inspection and replacement. Permanent magnet (PM) and squirrel cage induction generators don't have this problem.

Gearboxes are widely used, well-known components with many of applications. However, in wind turbines, gearboxes show a reliability record that is rather negative [6].

In constant speed wind turbines, wind gusts immediately lead to torque variations, while in variable speed wind turbines, wind

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gusts lead to variations in the speed without large torque variations. Therefore, constant speed wind turbines suffer from heavier mechanical loads, which may result a decrease in reliability and an increase in maintenance.
Generally, more complex systems suffer from more failures than simple systems.

Power quality

Fig. 7 depicts measurements of wind speed sequences and the resulting rotor speeds, pitch angles and output powers for the three most used generator systems at wind speeds around the rated wind speed. It appears that the power output of variable speed wind turbines is much smoother (less 'flicker') than constant speed wind turbines because rapid changes in the power drawn from the wind are buffered in rotor inertia. The fast power fluctuations in constant speed wind turbines are caused by variations in wind speed, but also by the tower shadow.

If the converter rating is large enough, variable speed wind turbines also can be used for voltage and frequency (*V&f*) control in the grid (within the limits posed by the actual wind speed) [7], which is not possible with constant speed wind turbines.

Power electronic converters produce harmonics that may need to be filtered away.

Grid faults

The three concepts behave differently in case of a grid fault causing a voltage dip. In case of a fault, constant speed wind turbines can deliver the large fault currents, necessary for activating the protection system. However, when the voltage comes back, they consume a lot of reactive power and thus impede the voltage restoration after the dip. In addition both the fault and the reconnection results in large torque excursions that may damage the gear box.

In case of a grid fault, the rotor currents in a doubly-fed induction generator increase very rapidly and without a special protection system, the turbine should be disconnected from the grid within milliseconds in order to protect the converter. In grids with a high fraction of wind power disconnecting all wind turbines leads to problems with the power balance (the generated power must be equal to the consumed power at any time), which is essential for a correct functioning of a power system. After the fault has been cleared and the conventional power stations have restored the voltage, the wind turbines can be reconnected.

In Table II, it is assumed that the VTDI's are equipped with additional hardware to enable ride through of the turbine during faults [15]. In addition this system enables the generation of reactive power during the fault to support the grid voltage restoration.

In case of a fault, turbines where all power goes through a converter could stay connected [8, 18]. The converter can limit the current to rated values during dips, and continue to deliver power and reactive power at reduced voltage levels [15,18]. Therefore, these turbines may help the conventional power stations in rebuilding the voltage after grid failures.

More information about modeling wind turbines for power system simulations and about the impact of wind power on the power system dynamics can be found in [17].

Converter systems

Variable speed turbines require conversion from variable frequency AC to constant frequency AC, where at the same time the input voltage is changing more or less proportional with the input frequency. Nowadays this conversion is mostly implemented with back-to-back connected voltage source converters. The generator-side voltage source converter can provide the voltage step-up function that is needed at when the input voltage is low, such as at low speed of a direct drive generator. Further both converter stages can provide reactive power. On the generator side this may be needed for magnetisation or control (VTDI) and on the grid side it may be used to support voltage control of the grid [7, 16, 17].

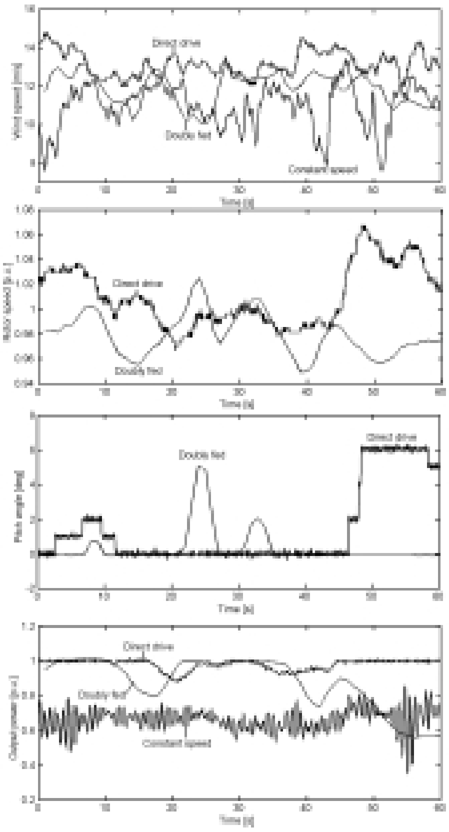

Fig. 7: Measured wind speeds and resulting rotor speeds, pitch angles and output powers for the three different generator systems.

For cost reasons the voltage source converter on the generator side is sometimes replaced by a diode rectifier in turbines with direct-drive generator. In that case a boost converter should be inserted between the rectifier and grid-side converter to boost the voltage at low speed.

Static operation

For constant speed turbines with grid connected squirrel cage induction generator the static operation point is automatically reached, while for variable speed turbines active control of the torque is needed.

For constant speed wind turbines the operation point corresponds to the point of intersection of the respective torque speed curves of the electric machine and the wind turbine. Because the squirrel cage induction machine is operating in generator mode the operational speed is slightly above its synchronous speed and varies only little with wind speed. Note that the wind rotor has a different torque speed curve for each wind speed.

With variable speed wind the torque needs to be controlled actively to reach the proper operating point. The kinetics of the system is governed by the following relation:

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$$J\frac{d\omega}{dt} = T_{aero} - T_{em} \quad (10)$$

where J is the effective inertia of the rotating system, T_{aero} is the aerodynamic torque developed by the wind rotor (prime for transformation through gearbox) and T_{em} is the electro magnetic torque. If T_{em} is larger than the available wind torque T_{aero} than the turbine will eventually stop. If T_{em} is too small, the turbine will speed up to a tip speed ratio λ above the optimal value, resulting in a reduction of the power coefficient C_p and the torque T_{aero}. Eventually the turbine will reach a stable operation point that is above the optimal speed and below the optimal torque. For variable speed turbines the control is mostly based on space vector torque control, where the set point for torque is mostly derived from the power curve. From the torque the needed stator current vector can be calculated if the air gap flux vector is known. With direct-drive generators the rotor position is measured and used to determine the position of air gap flux. Based on this position a voltage space vector is applied at the terminals that will results in the required stator current vector. Because the control is based on space vectors, automatically the applied voltage will have the proper electrical frequency.

Alternatives and trends

Alternative generator systems

Variable speed with squirrel cage induction generator

A few manufacturers have produced variable-speed wind turbines with squirrel cage induction generators with a converter carrying the full power. Compared to the doubly-fed induction generator this system has the following advantages:

– the generator is cheaper;
– the generator has no brushes;
– the system is often used as a standard industrial drive;
– it can be used both in 50 Hz and 60 Hz grids
and the following disadvantages:
– the converter is larger and more expensive (100 % of rated power instead of 35 %);
– the losses in the converter are higher because all power is carried by the converter.

From the fact that this solution is known and rarely applied, it can be concluded that its disadvantages are more important than the advantages.

Variable speed with geared synchronous generator

Recently, the Spanish manufacturer Made developed a geared wind turbine with a brushless synchronous generator and a full converter (VT/SGP in table I). Compared to the doubly-fed induction generator, this generator system has the following advantages:

– the generator has a better efficiency;
– the generator is cheaper;
– the generator can be brushless;
– it can be used both in 50 Hz and 60 Hz grids
and the following disadvantages:
– larger, more expensive converter (100 % of rated power instead of 35 %);
– the losses in the converter are higher because all power is carried by the converter.

It is possible that the steady decrease in cost of power electronics (roughly a factor 10 over the past 10 years) will make this an attractive system in the near future.

Trends in geared generator systems

As appears from Table I, the first trend to be mentioned is the fact that in recent years, many wind turbine manufacturers changed from constant speed to variable speed systems for the higher power levels for reasons mentioned above in the comparison.

The doubly-fed induction generator systems have been made suitable for grid fault ride-through. A next step might be that the turbine has to be made suitable to assist in the voltage and frequency (V&f) control of the grid, which is in theory possible, but should be implemented in practice.

The generators used in geared wind turbines are more or less standard off-the-shelf electrical machines, so that major development steps were not necessary.

Trends in direct-drive generator systems

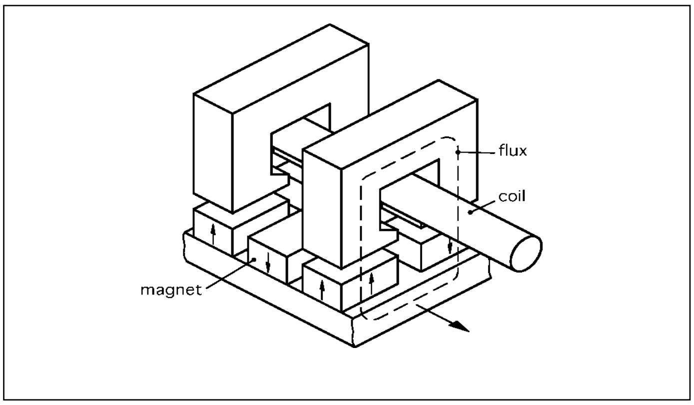
Most of the current direct-drive generators are electrically-excited synchronous generators (Enercon). Some manufacturers work on permanent-magnet synchronous generators (Zephyros, Jeumont, Vensys). Enercon and Lagerwey started developing direct-drive generators in the early nineties, when permanent magnets were too expensive. Although magnet prices dropped by roughly a factor of 10 over the past 10 years, Enercon seems to stick to it successful, well-known and proven solution.

The advantages of permanent-magnet excitation when compared to electrical excitation are lower losses (no excitation losses), lower weight (roughly a factor 2 in active generator material) and lower cost. A disadvantage is that the excitation can not be controlled. As early as in 1996, it was stated in that permanent-magnet generators were more attractive than electrically-excited synchronous generators [9,10]. Since then, the permanent-magnet generator has only become more attractive due to the decreasing magnet prices.

Direct-drive generators are not standard off-the-shelf machines. Therefore, it is worthwhile to study the use of alternative generator topologies which offer the possibilities of further weight and cost reduction.

Axial flux generators as used by Jeumont generally are smaller, but also heavier and more expensive than radial flux machines [11,19]. This is because in axial flux machines the force density introduced in (6) is not optimal for all radii, and because the radius where the force works is not everywhere maximum.

The use of transverse flux generators (see Fig. 8) has been investigated for application in wind turbines [12,19] because in literature, very high force densities are claimed for this machine type



[13, 14]. However, this high force density disappears when the machine has a large air gap, which generally is the case in large direct-drive generators [19]. An advantage of transverse flux generators is the simple stator winding geometry, which offers possibilities to apply high voltage insulation. Disadvantages are the very low power factor and the complex construction, which may result in mechanical problems and audible noise. In the TFPM machine with toothed rotor proposed in [12, 19], some rotor construction problems have been solved.

One of the issues related to cost of direct-drive turbines is transportation. The 1.5 or 2 MW generator of Zephyros has an outer diameter of roughly 4 m, so that it can be transported by regular means. The 4.5 MW Enercon generator with a diameter in the order of 10 m is made in segments that can be transported separately.

Trends in voltage levels

Until a few years ago, wind turbine manufacturers mainly used voltage levels of 400 V and 700 V. However, in the nineties of the last century, ABB came with the wind former, a medium voltage generator. In the past few years, a few wind turbines operating with higher voltage levels have been introduced: Vestas and Made use 1 kV, Zephyros uses 3 kV, and NEG-Micon even uses 6 kV for the stator winding.

In principle, the voltage level does not matter for the electromagnetic design of the generator. By doubling the number of turns in a slot and halving the cross-section of these turns, the voltage level can be doubled while the amount of copper in the slot remains the same. However, at low voltage levels, huge cables are necessary between the generator terminals and the transformers. At voltage levels above several kV, the conductor insulation takes more space, the amount of copper in the slots is reduced and larger generators are necessary to convert the same power. Even the voltage levels of very large turbo generators (500 MVA) in power stations normally do not exceed 20 kV. Besides, power electronic converters for voltage levels in the order of several kV have become available. Therefore, an increase of the voltage levels to several kV can be expected, but we do not expect voltage levels far exceeding 6 kV.

Offshore

The two most important reasons to situate wind energy offshore are:

– especially in densely populated regions such as the Netherlands, there is hardly space for wind energy on shore;
– offshore wind speeds are higher than on shore wind speeds, so that higher energy yields can be expected.

The most important difference between the requirements for onshore and offshore wind energy is that for offshore wind turbines it is much more important that they are robust and maintenance-free. This is because it is extremely expensive and difficult and under certain weather conditions even impossible to do offshore maintenance and reparations.

Further, an offshore environment is rather aggressive both for insulation materials that deteriorate and for steel and if applicable permanent magnets that may corrode. Therefore, special corrosion protection and the use of conditioned air should be considered.

There are several facts that make permanent-magnet direct-drive generators suitable for offshore wind turbines: they do not need maintenance requiring brushes and gearboxes and the large size is not a real disadvantage offshore.

To improve the availability of offshore wind turbines, condition based maintenance and condition based control can be considered. However, this should be done in such a way that the turbine can remain in operation when the sensors fail.

Summary

This paper first reviews the basics of wind energy conversion with wind turbines. The requirements with respect to the electric system are considered. Next, the paper describes the three classical conversion systems with their strengths and weaknesses: constant speed, variable speed with doubly-fed induction generator and variable speed with direct-drive generator. Then, the applied electric converters are shortly addressed. Finally, alternative generator systems and trends are discussed. There is a clear trend towards variable speed systems. Doubly-fed induction generator systems are increasingly equipped with grid fault ride through capabilities. For direct-drive turbines, the radial flux permanent-magnet synchronous generator probably is cheaper and more efficient than the electrically excited synchronous generator. It is expected that the voltage level of generators will increase up to values in the order of 5 kV.

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