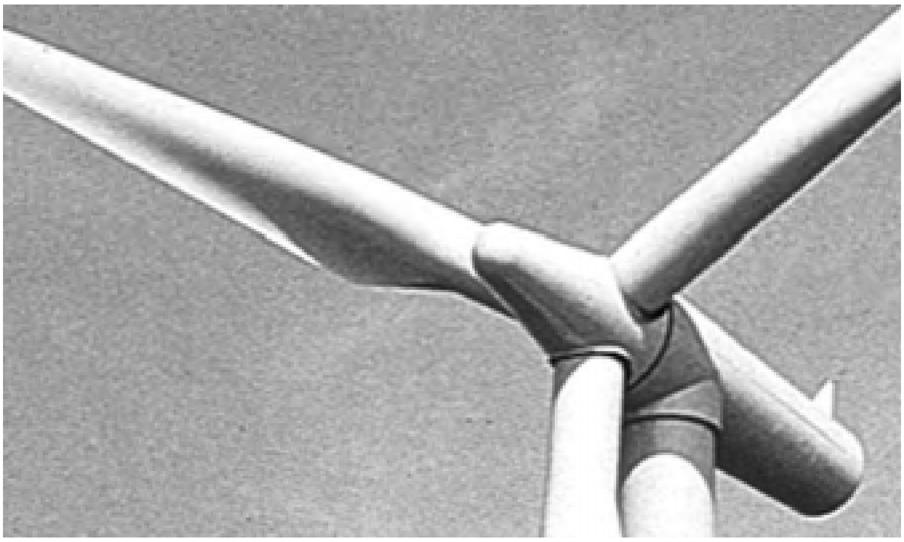
THE WIND TURBINE



COMPONENTS AND OPERATION

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Table of contents page 4

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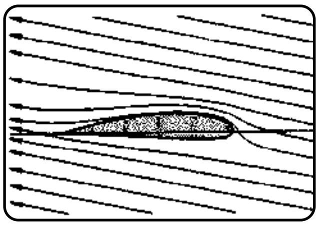
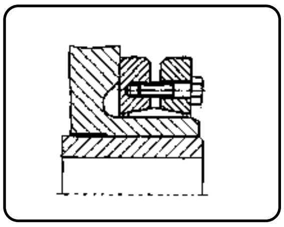
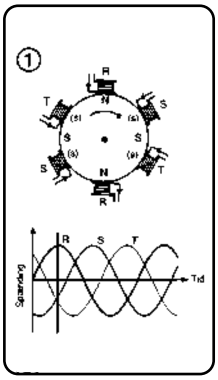
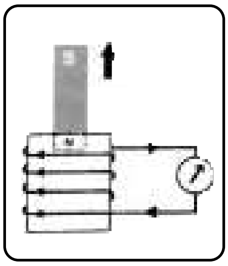
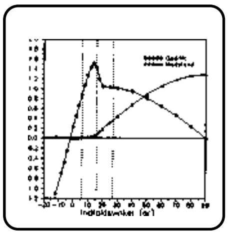
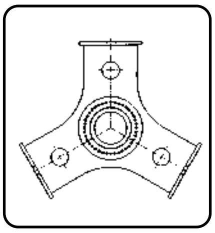
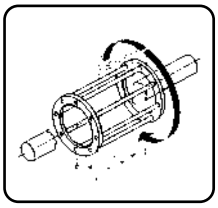
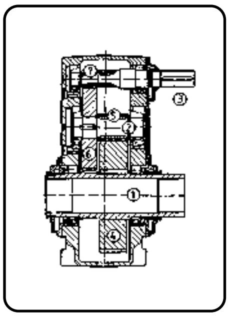
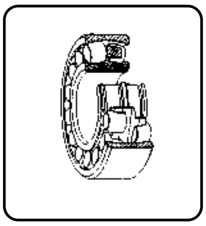
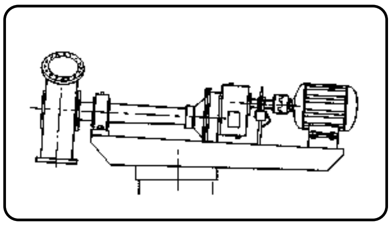
Autumn 1999




THE WIND TURBINE COMPONENTS AND OPERATION

BONUS-INFO is a newsletter for customers and business associates of the Bonus Energy A/S. This newsletter is published once or twice a year.

The first number came out in 1998, and the newsletter has now been published in four issues.

Each number has included an article on the components and operation of the wind turbine. We have received many suggestions and requests that these articles should be reprinted and published as a special single issue.

Bonus is pleased to have hereby fulfilled this request with the publication of this special issue.

Author:
Henrik Stiesdal
Responsible under the press law

Lay-out/ Production:
Claus Nybroe

Translation:
John Furze, Hugh Piggott

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BONUS ENERGY A/S
Fabriksvej 4, Box 170
7330 Brande
Tel.: 97 18 11 22
Fax: 97 18 30 86
E-mail: bonus@bonus.dk
Web: www.bonus.dk

THE WIND TURBINE COMPONENTS AND OPERATION

The Aerodynamics of the Wind Turbine 5

Basic Theory • The aerodynamic profile • The aerodynamics of a man on a bicycle • Wind turbine blades behave in the same way • Lift • The change of forces along the blade • What happens when the wind speed changes • The stall phenomena • Summary

The Transmission System 11

The hub • Main shaft • Main Bearings • The clamping unit • The gearbox • The coupling

The Generator 15

Direct current (DC) • Alternating current (AC) • Three phase alternating current • Induction and electromagnetism • The wind turbine generator as a motor • Generator operation • Cut-in • Closing remarks

Control and Safety Systems 20

Problem description • The controller • Hydraulics • Tip brakes • The mechanical brake

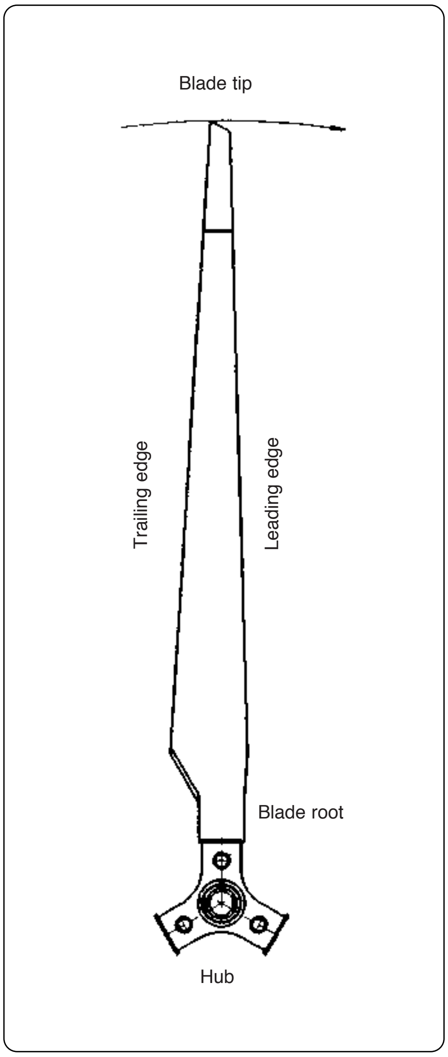
THE AERODYNAMICS OF THE WIND TURBINE

The three bladed rotor is the most important and most visible part of the wind turbine. It is through the rotor that the energy of the wind is transformed into mechanical energy that turns the main shaft of the wind turbine.

We will start by describing why the blades are shaped the way that they are and what really happens, when the blades rotate.

BASIC THEORY

Aerodynamics is the science and study of the physical laws of the behavior of objects in an air flow and the forces that are produced by air flows.



The different components of a wind turbine blade

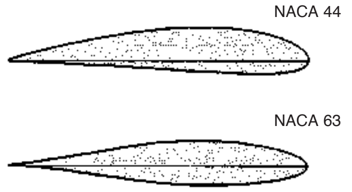
The front and rear sides of a wind turbine rotor blade have a shape roughly similar to that of a long rectangle, with the edges bounded by the leading edge, the trailing edge, the blade tip and the blade root. The blade root is bolted to the hub.

The radius of the blade is the distance from the rotor shaft to the outer edge of the blade tip. Some wind turbine blades have moveable blade tips as air brakes, and one can often see the distinct line separating the blade tip component from the blade itself.

If a blade were sawn in half, one would see that the cross section has a streamlined asymmetrical shape, with the flattest side facing the oncoming air flow or wind. This shape is called the blade's aerodynamic profile

THE AERODYNAMIC PROFILE

The shape of the aerodynamic profile is decisive for blade performance. Even minor alterations in the shape of the profile can greatly alter the power curve and noise level. Therefore a blade designer does not merely sit down and outline the shape when designing a new blade. The shape must be chosen with great care on the basis of past experience. For this reason blade profiles were previously chosen from a widely used catalogue of airfoil profiles developed in wind tunnel research by NACA (The United States National Advisory Committee for Aeronautics) around the time of the Second World War.



Blade profiles

The NACA 44 series profiles were used on older Bonus wind turbines (up to and including the 95 kW models). This profile was developed during the 1930's, and has good all-round properties, giving a good power curve and a good stall. The blade is tolerant of minor surface imperfections, such as dirt on the blade profile surface.

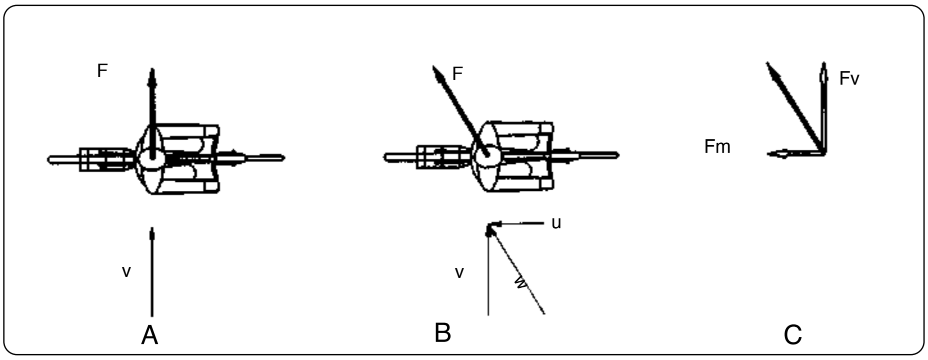
The LM blades used on newer Bonus wind turbines (from the 150 kW models) use the NACA 63 profiles developed during the 1940´s. These have slightly different properties than the NACA 44 series. The power curve is better in the low and medium wind speed ranges, but drops under operation at higher wind speeds. Likewise this profile is more sensitive with regard to surface dirt. This is not so important in Denmark, but in certain climate zones with little rain, accumulated dirt, grime and insect deposits may impair and reduce performance for longer periods.

The LM 19 blades, specifically developed for wind turbines, used on the Bonus 500 kW, have completely new aerodynamic profiles and are therefore not found in the NACA catalogue. These blades were developed in a joint LM and Bonus research project some years ago, and further developed and wind tunnel tested by FFA (The Aerodynamic Research Institute of The Swedish Ministry of Defence).

THE AERODYNAMICS OF A MAN ON A BICYCLE

To fully describe the aerodynamics of a wind turbine blade could appear to be rather complicated and difficult to understand. It is not easy to fully understand how the direction of the air flow around the blade is dependent on the rotation of the blade. Fortunately for us, air constantly flows around everyday objects following these very same aerodynamic laws. Therefore we can start with the aerodynamics of an air flow that most of us are much more familiar with: A cyclist on a windy day.

The diagrams (next page) show a cyclist as seen from above. The diagrams are perhaps rather sketchy, but with a good will one can visualize what they

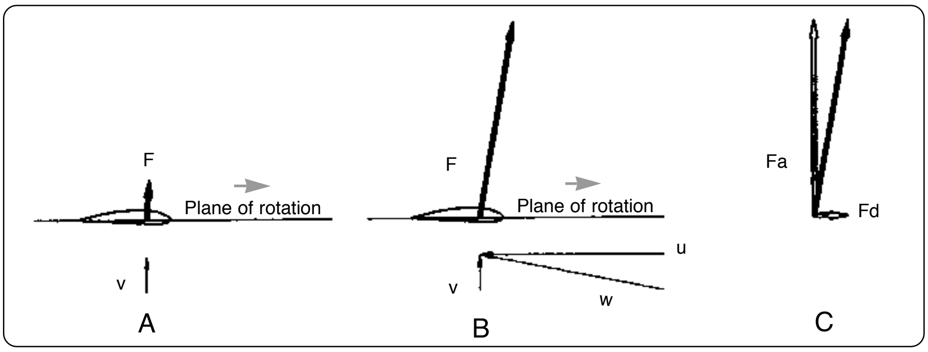


Air flow around a man on a bicycle

represent. The diagram (A) on the left, illustrates a situation, during which a cyclist is stationary and can feel a side wind "v" of 10 meters per second (m/s) or roughly 22 mph (this is known as a fresh breeze). The wind pressure will attempt to overturn the cyclist. We can calculate the pressure of the wind on the windward side of the cyclist as roughly 80 Newton per square meter of the total side area presented by the cyclist against the wind. Newton, or N for short, is the unit for force used in technical calculation. 10 N is about 1kg/force (Multiply by 0.2248 to obtain lbf.). The direction of the force of the wind pressure is in line with the wind flow. If we consider that a normal sized cyclist has a side area facing the wind of about 0.6 square meters, then the force F from the pressure of the wind will be 0.6 x 80 N = app. 50 N/m^2.

In the center drawing (B) our cyclist has started out and is traveling at a speed "u" of 20 km/hour, equivalent to about 6 meters/second, still with a side wind "v" of 10 m/s. We can therefore calculate the speed of the resulting wind "w" striking the cyclist, either mathematically or by measurement on the diagram as 12 m/s. This gives a total wind pressure of 100 N/m^2. The direction of the wind pressure is now in line with the resulting wind, and this will give a force "F" on the cyclist of about 60 N/m^2.

In the right hand drawing (C) the force of the wind pressure "F" is now separated into a component along the direction of the cyclist's travel and into another component at a right angle to the direction of travel. The right angled force "Fv" will attempt to overturn the cyclist, and the force "Fm" along the axis of travel gives a resistance that slows down the cyclist's forward motion. The size of "Fm" is about 30 N/m^2. This is the resistance force that the cyclist must overcome. A beginner, unused to cycling, may wonder why the wind has changed direction and a head wind is felt on reaching speed. This beginner might well ask " How can it be that I felt a side wind when I was at rest and standing still, could the wind have possibly changed its direction? " But no, as any experienced cyclist unfortunately knows, head wind is an integral component of movement itself. The wind itself has not turned. The head wind is a result of speed, the faster one travels the more wind resistance one experiences. Perhaps, as a famous Danish politician once promised his voters, that if elected he would insure favorable tailwinds on the cycle-paths, things may change in the future. However we others have learnt to live with the head winds resulting from our own forward movement, whether we run, cycle or go skiing.



Airflow around a blade profile, near the wing tip

WIND TURBINE BLADES BEHAVE IN THE SAME WAY

Returning to the wind turbine blade, just as in the situation for the cyclist, we can observe the aerodynamic and force diagrams in two different situations, when the wind turbine is stationary and when it is running at a normal operational speed. We will use as an example the cross section near the blade tip of a Bonus 450 kW Mk III operating in a wind speed "v" of 10 m/s.

When the rotor is stationary, as shown in drawing (A) below, the wind has a direction towards the blade, at a right angle to the plane of rotation, which is the area swept by the rotor during the rotation of the blades. The wind speed of 10 m/s will produce a wind pressure of 80 N/m^2 of blade surface, just like the effect on our cyclist. The wind pressure is roughly in the same direction as the wind and is also roughly perpendicular to the flat side of the blade profile. The part of the wind pressure blowing in the direction of the rotor shaft attempts to bend the blades and tower, while the smaller part of the wind pressure blowing in the direction of the rotation of the blades produces a torque that attempts to start the wind turbine.

Once the turbine is in operation and the rotor is turning, as is shown in the center diagram (B), the blade encounters a head wind from its own forward movement in exactly the same way as the cyclist does. The strength of head wind "u" at any specific place on the blade depends partly on just how fast the wind turbine blade is rotating, and partly how far out on the blade one is from the shaft. In our example, at the normal operating speed of 30 rpm, the head wind "u" near the tip of the 450 kW wind turbine is about 50 m/s. The "meteorological" wind "v" of 10 m/s will thus give a resulting wind over the profile of about 51 m/s.

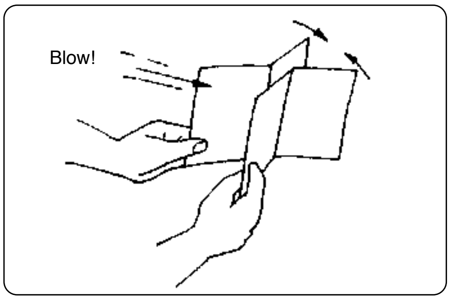
This resulting wind will have an effect on the blade surface with a force of 1500 N/m^2. The force “F” will not be in the direction of the resulting wind, but almost at a right angle to the resulting wind.

In the drawing on the right (C) the force of the wind pressure “F” is again split up into a component in the direction of rotation and another component at a right angle to this direction. The force “Fa” at a right angle to the plane of rotation attempts to bend the blade back against the tower, while the force “Fd” points in the direction of rotation and provides the driving torque. We may notice two very important differences between the forces on the blade in these two different situations and forces on the cyclist in the two corresponding situations. One difference is that the forces on the blade become very large during rotation. If vector arrows illustrating the forces in the diagrams were drawn in a scale that was indicative of the sizes of the different forces, then these vector arrows of a wind turbine in operation would have been 20 times the size of the vector arrows of the same wind turbine at rest. This large difference is due to the resulting wind speed of 51 m/s striking a blade during operation, many times the wind speed of 10 m/s when the wind turbine is at rest. Just like the cyclist, the blade encounters head wind resulting from its own movement, however head wind is of far greater importance on a wind turbine blade than for a cyclist in motion.

The other important difference between a wind turbine blade and a cyclist is that the force on the blade is almost at a right angle to the resulting wind striking the profile. This force is known as the lift and also produces a small resistance or drag. The direction of this lift force is of great importance. A cyclist only feels the wind resistance as a burden, requiring him to push down extra hard on the pedals. However with a wind turbine blade this extra wind resistance will act as a kind of power booster, at least in the normal blade rotational speed range. The reason for this difference is due to the blades streamlined profile, which behaves aerodynamically completely differently as compared to the irregular shaped profile of a man on a bicycle. The wind turbine blade experiences both lift and drag, while a cyclist only experiences drag.

LIFT

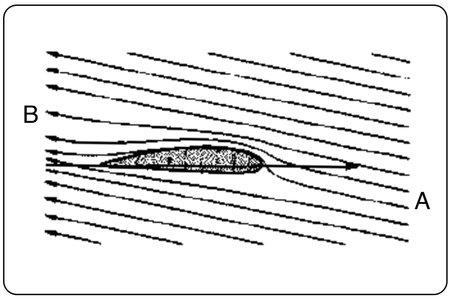
Lift is primary due to the physical phenomena known as Bernoulli’s Law. This physical law states that when the speed of an air flow over a surface is increased the pressure will then drop. This law is counter to what most people experience from walking or cycling in a head wind, where normally one feels that the pressure increases when the wind also increases. This is also true when one sees an air flow blowing directly against a surface, but it is not the case when air is flowing over a surface.



An experiment with Bernoulli’s Law

One can easily convince oneself that this is so by making a small experiment. Take two small pieces of paper and bend them slightly in the middle. Then hold them as shown in the diagram and blow in between them. The speed of the air is higher in between these two pieces of paper than outside (where of course the air speed is about zero), so therefore the pressure inside is lower and according to Bernoulli’s Law the papers will be sucked in towards each other. One would expect that they would be blown away from each other, but in reality the opposite occurs. This is an interesting little experiment, that clearly demonstrates a physical phenomenon that has a completely different result than what one would expect. Just try for yourself and see.

The aerodynamic profile is formed with a rear side, that is much more curved than the front side facing the wind. Two portions of air molecules side by side in the air flow moving towards the profile at point A will separate and pass around the profile and will once again be side by side at point B after passing the profile’s trailing edge. As the rear side is more curved than the front side on a wind turbine blade, this means that the air flowing over the rear side has to travel a longer distance from point A to B than the air flowing over the front side. Therefore this air flow over the rear side must have a higher velocity if these two different portions of air shall be reunited at point B. Greater velocity produces a pressure drop on the rear side of the blade, and it is this pressure drop that produces the lift. The highest speed is obtained at the rounded front edge of the blade. The blade is almost sucked forward by the pressure drop resulting from this greater front edge speed.



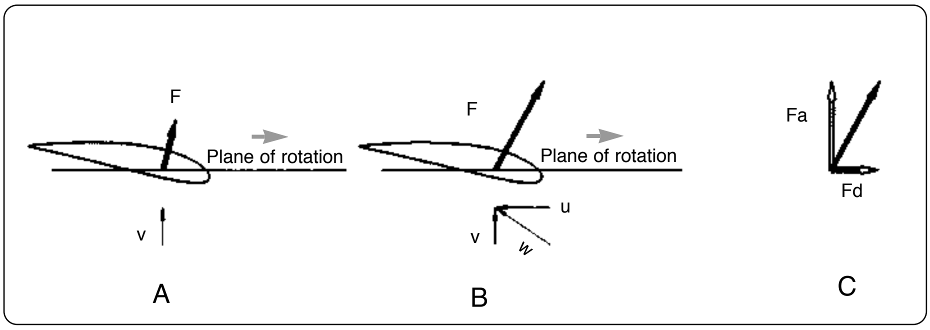
Air flow around an aerodynamic profile

There is also a contribution resulting from a small over-pressure on the front side of the blade.

Compared to an idling blade the aerodynamic forces on the blade under operational conditions are very large. Most wind turbine owners have surely noticed these forces during a start-up in good wind conditions. The wind turbine will start to rotate very slowly at first, but as it gathers speed it begins to accelerate faster and faster. The change from slow to fast acceleration is a sign that the blade’s aerodynamic shape comes into play, and that the lift greatly increases when the blade meets the head wind of its own movement. The fast acceleration, near the wind turbine’s operational rotational speed places great demands on the electrical cut-in system that must “capture and engage “ the wind turbine without releasing excessive peak electrical loads to the grid.

THE CHANGE OF FORCES ALONG THE BLADE

The drawings previously studied, mainly illustrate the air flow situation near the



Air flow around a blade profile near the blade root

blade tip. In principle these same conditions apply all over the blade, however the size of the forces and their direction change according to their distance to the tip. If we once again look at a 450 kW blade in a wind speed of 10 m/s, but this time study the situation near the blade root, we will obtain slightly different results as shown in the drawing above.

In the stationary situation (A) in the left hand drawing, wind pressure is still 80 N/m^2. The force "F" becomes slightly larger than the force at the tip, as the blade is wider at the root. The pressure is once again roughly at a right angle to the flat side of the blade profile, and as the blade is more twisted at the root, more of the force will be directed in the direction of rotation, than was the case at the tip.

On the other hand the force at the root has not so great a torque-arm effect in relation to the rotor axis and therefore it will contribute about the same force to the starting torque as the force at the tip.

During the operational situation as shown in the center drawing (B), the wind approaching the profile is once again the sum of the free wind "v" of 10 m/s and the head wind "u" from the blade rotational movement through the air. The head wind near the blade root of a 450 kW wind turbine is about 15 m/s and this produces a resulting wind "w" over the profile of 19 m/s. This resulting wind will act on the blade section with a force of about 500 N/m^2.

In the drawing on the right (C) force is broken down into wind pressure against the tower "Fa", and the blade driving force "Fd" in the direction of rotation.

In comparison with the blade tip the root section produces less aerodynamic forces during operation, however more of these forces are aligned in the correct direction, that is, in the direction of rotation. The change of the size and direction of these forces from the tip in towards the root, determine the form and shape of the blade.

Head wind is not so strong at the blade root, so therefore the pressure is likewise not so high and the blade must be made wider in order that the forces should be large enough. The resulting wind has a greater angle in relation to the plane of rotation at the root, so the blade must likewise have a greater angle of twist at the root.

It is important that the sections of the blade near the hub are able to resist forces and stresses from the rest of the blade. Therefore the root profile is both thick and wide, partly because the thick broad profile gives a strong and rigid blade and partly because greater width, as previously mentioned, is necessary on account of the resulting lower wind speed across the blade. On the other hand, the aerodynamic behavior of a thick profile is not so effective. Further out along the blade, the profile must be made thinner in order to produce acceptable aerodynamic properties, and therefore the shape of the profile at any given place on the blade is a compromise between the desire for strength (the thick wide profile) and the desire for good aerodynamic properties (the thin profile) with the need to avoid high aerodynamic stresses (the narrow profile).

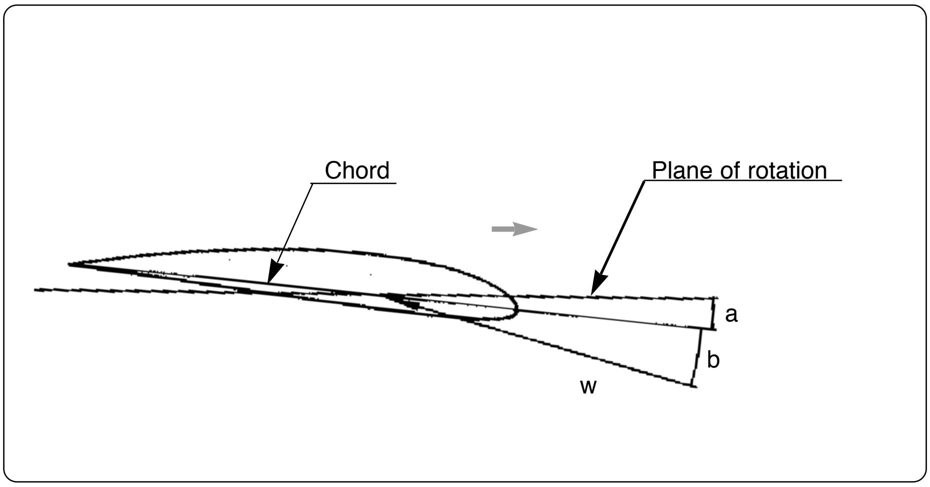
As previously mentioned, the blade is twisted so that it may follow the change in direction of the resulting wind. The angle between the plane of rotation and the profile chord, an imaginary line drawn between the leading edge and the trailing edge, is called the setting angle, sometimes referred to as "Pitch".

WHAT HAPPENS WHEN THE WIND SPEED CHANGES?

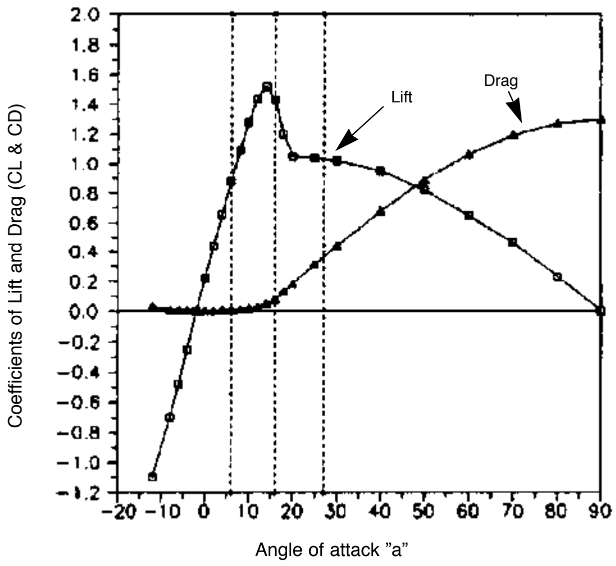
The description so far was made with reference to a couple of examples where wind speed was at a constant 10 m/s. We will now examine what happens during alterations in the wind speed.

In order to understand blade behavior at different wind speeds, it is necessary to understand a little about how lift and drag change with a different angle of attack. This is the angle between the resulting wind "w" and the profile chord. In the drawing below the angle of attack is called "a" and the setting angle is called "b".

The setting angle has a fixed value at any one given place on the blade, but the angle of attack will grow as the wind speed increases.



The angles of the profile



Relationship between lift and drag coefficients and the angle of attack

The aerodynamic properties of the profile will change when the angle of attack "a" changes. These changes of lift and drag with increasing angles of attack, are illustrated in the diagram above used to calculate the strength of these two forces, the lift coefficient "CL" and the drag coefficient "CD". Lift will always be at a right angle to the resulting wind, while drag will always follow in the direction of the resulting wind.

We will not enter into the formulas necessary to calculate these forces, it is enough to know that there is a direct connection between the size of "CL" and the amount of lift.

Both lift and drag abruptly change when the angle of attack exceeds 15-20 degrees. One can say that the profile stalls. After this stalling point is reached, lift falls and drag increases. The angle of attack changes when the wind speed changes.

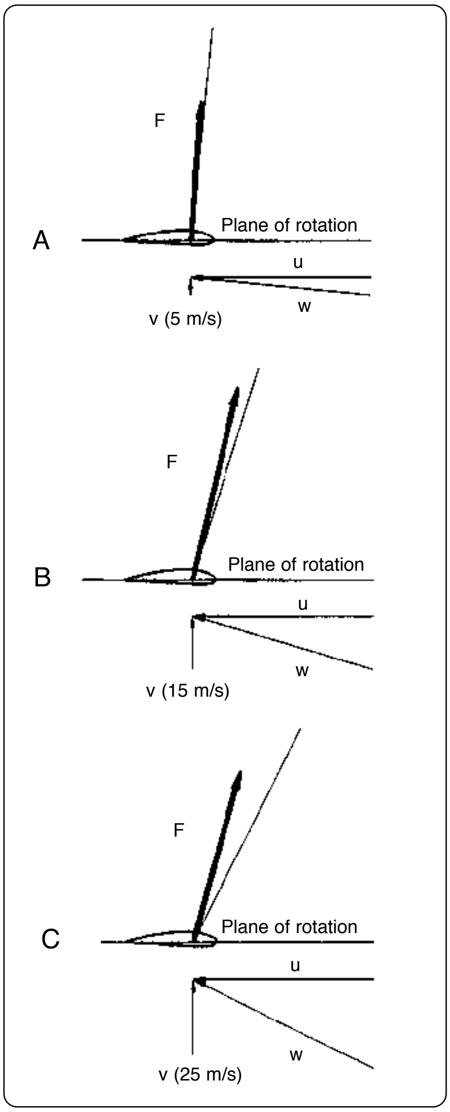
To further study these changes, we can draw diagrams, shown to the right, illustrating three different wind speeds "v" (5, 15 and 25 m/s) from our previous cross section, this time near the blade tip of a 450 kW wind turbine. This situation is rather convenient as the setting angle "b" near the wing tip is normally 0 degrees.

The head wind from the movement "u" is always the same, as the wind turbine has a constant rotational speed controlled by the grid connected generator (in these situations we do not consider the small generator used on certain small wind turbines). The free air flow "v" has three different values and this gives three different values of the resulting wind "w" across the profile. The size of "w" does not change very much, from 50 m/s at a wind speed of 5 m/s to 52 m/s in a 25 m/s wind. The reason for this relatively minor change is due to the dominating effect of the head wind.

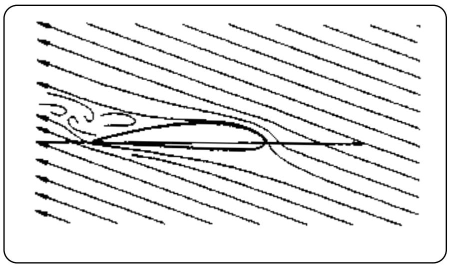
However, the angle of attack "a" between the resulting wind and the chord of the blade changes from 6 degrees at a wind speed of 5 m/s to 16 degrees at 15 m/s to 27 degrees at 25 m/s. These changes are of great importance for determining the strength of the aerodynamic forces.

Studying the diagram showing the lift coefficient "CL" and the drag coefficient "CD" we may note the following:

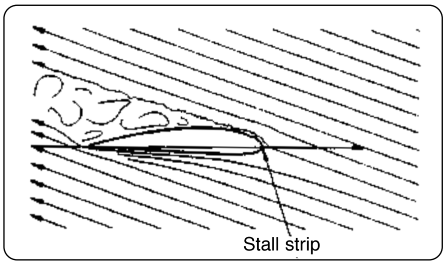
- At a wind speed of 5 m/s (A), the angle of attack is 6 degrees. The lift coefficient is 0.9 and the coefficient of drag is 0.01. Lift is therefore 90 times greater than drag, and the resultant force "F" points almost vertically at a right angle to the mean relative wind "w".
- At a wind speed of 15 m/s (B), the profile is almost about to stall. The angle of attack is 16 degrees. The lift coefficient is 1.4 and the coefficient of drag is 0.07. Lift is now 20 times drag.
- At a wind speed of 25 m/s (C), the profile is now deeply stalled, the angle of attack is 27 degrees, the lift component is 1.0 and the component of lift is 0.35. Lift is now 3 times greater than drag. We can therefore note the following:
- During the change of wind speed from 5 to 15 m/s there is a significant increase in lift, and this increase is directed in the direction of rotation. Therefore power output of the wind turbine is greatly increased from 15 kW to 475 kW.
- During the change of wind speed from 15 to 25 m/s, there is a drop in lift accompanied by an increase in drag. This lift is even more directed in the direction of rotation, but it is opposed by drag and therefore output will fall slightly to 425 kW.



Situations at three different wind speeds



Seperation of the air flow at the profile trailing edge



Interference in the stall process (stall strip)

THE STALL PHENOMENA

The diagrams showing the components of lift and drag illustrate the result of stall. Lift diminishes and drag increases at angles of attack over 15 degrees. The diagrams however do not illustrate the reasons for this stall phenomena.

A stall is understood as a situation during which an angle of attack becomes so large that the air flow no can longer flow smoothly, or laminar, across the profile. Air looses contact with the rear side of the blade, and strong turbulence occurs. This separation of air masses normally commences progressively from the trailing edge, so the profile gradually becomes semi-stalled at a certain angle of attack, but a full stall is first achieved at a somewhat higher angle. From the diagram showing the lift and drag components, one can estimate that the separation at the trailing edge starts at about 12 degrees, where the curve illustrating lift starts to fall. The profile is fully stalled, and the air flow is separated all over the rear side of the blade at about 20 degrees. These figures can greatly vary from profile to profile and also between different thicknesses of the same profile.

When the stall phenomena is used to restrict power output, as in all Bonus wind turbines, it is important that blades are trimmed correctly. With the steep lift curve, the angle of attack cannot be altered very much, before maximum output also changes, therefore it is essential that the angle of the blade is set at the correct value.

One cannot alter the different angles on the blade itself, once the form, shape and blade molding has been decided upon and fabricated. So we normally talk about calibrating the tip angle. Not because the blade tip has any special magical properties, but we can place a template at the tip, which allows us to make measurements using a theodolite. Adjusting of the tip angle can therefore be understood as an example of how the angle of the total blade is adjusted.

Of importance for power output limitation is also the fact that in practice lift and drag normally behave exactly as would be expected from the theoretical calculations. However this is not always the case. Separation can often occur before expected, for instance due to dirt on the leading edges, or it can be delayed if the air flow over the profile for some reason or other, is smoother than usual. When separation occurs before expected, the maximum obtainable lift is not as high as otherwise expected and therefore maximum output is lower. On the other hand, delayed separation can cause continuous excessive power production output.

Accordingly profile types chosen for our blades have stable stall characteristics with little tendency to unforeseen changes. From time to time, however, it is sometimes necessary to actively alter the stall process. This is normally done by alteration to the leading edge, so that a small well-defined extra turbulence across the profile is induced. This extra turbulence gives a smoother stall process.

Turbulence can be created by an area of rougher blade surface, or a triangular strip, fixed on the leading edge. This stall strip acts as a trigger for the stall so that separation occurs simultaneously all over the rear side.

On a wind turbine blade, different air flows over the different profile shapes, interact with each other out along the blade and therefore, as a rule, it is only necessary to alter the leading edge on a small section of the blade. This altered section will then produce a stall over the greater part of the blade. For example, the Bonus 450 kW Mk III turbine, is usually equipped with a 0.5 meter stall strib, which controls the stall process all over the 17 meter long blade.

SUMMARY

The main points as described in this article can be shortly stated in the following:

- The air flow around a wind turbine blade is completely dominated by the head wind from the rotational movement of the blade through the air.

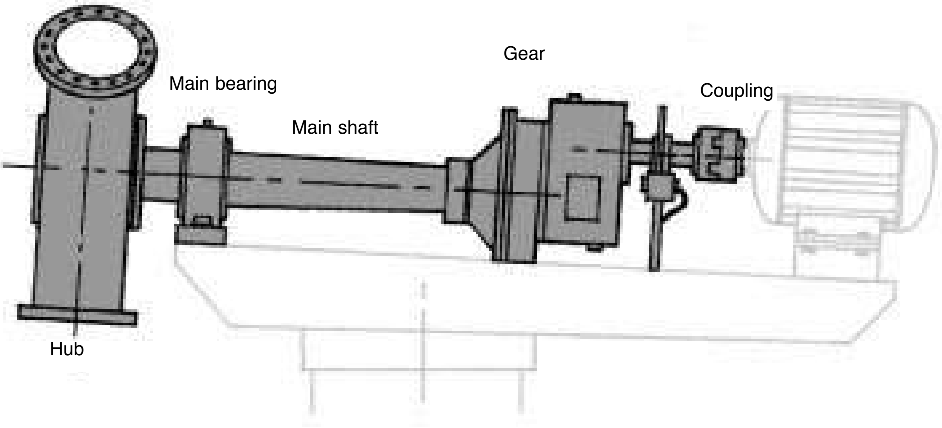
- The blade aerodynamic profile produces lift because of its streamlined shape. The rear side is more curved than the front side.

- The lift effect on the blade aerodynamic profile causes the forces of the air to point in the correct direction.

- The blade width, thickness, and twist is a compromise between the need for streamlining and the need for strength.

- At constant shaft speed, in step with the grid, the angle of attack increases with increasing wind speed. The blade stalls when the angle of attack exceeds 15 degrees. In a stall condition the air can no longer flow smoothly or laminar over the rear side of the blade, lift therefore falls and drag increases.

THE TRANSMISSION SYSTEM



The link between the wind turbine blades and the generator

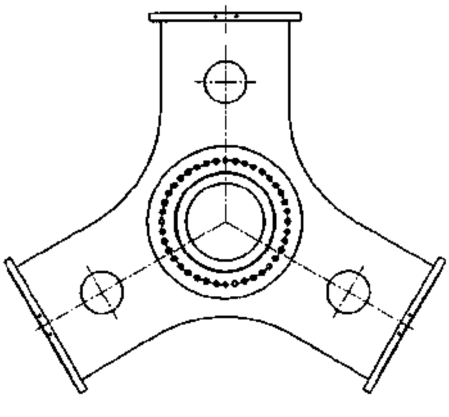
Just how much of a wind turbine that belongs to the transmission system is a matter of definition. In this chapter we will include the components that connect the wind turbine rotor to the generator.

THE HUB

The blades on all Bonus wind turbines are bolted to the hub. Older Bonus wind turbines (up to and including the 95 kW models) with Aerostar blades, have a flange joint, where the glass fiber is molded out in a ring with steel bushes for the bolts. The newer wind turbines (from the 150 kW models) have threaded bushes glued into the blade root itself. In both cases bolts from the blade pass through a flange on the cast hub. The flange bolt-holes are elongated, enabling the blade tip angle to be adjusted.

The hub is cast in a special type of strong iron alloy, called "SG cast iron". Because of the complicated hub shape which is difficult to make in any other way, it is convenient to use cast iron. In addition the hub must be highly resistant to metal fatigue, and this is difficult to achieve in a welded construction.

In contrast to cast iron of the SG type, normal cast iron has the disadvantage of being rather fragile and often can fracture under blows. This unfortunate quality is due to the high carbon content of cast iron. High carbon content enables the cast iron to melt easily and thus easily flow out into the casting form. When cast iron solidifies, carbon exists as graphite flakes suspended in the pure iron. These flakes form weak zones in the material, easily prone to zig-zag fissures from flake to flake. These weak zones are only important, if forces attempt to pull the material apart. Graphite has great compressibility strength, and is therefore not easily compressed. Normal cast iron has the same compressibility strength as steel, but its tension resistance level is only 10% of steel tension resistance.



Wind turbine hub

For many uses these strength qualities are more than sufficient, however in constructions subject to heavy usage, properties such as low tension resistance and weakness under blows are not desirable. For this reason special SG cast iron with tension resistance equal to that of steel has been developed during the past 50 years.

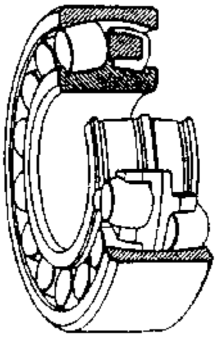
In producing SG cast iron several special materials, mainly silicium, are added during casting. After casting has taken place, it is further heat treated for about 24 hours, thereby changing the free carbon from their usual flakes into small round balls. The name SG cast iron is also short for Spherical Graphite cast iron (latin: Sphere = ball).

This round ball shape binds the necessary carbon in a more compact form. The graphite is not a hindrance for the binding structure in the metal itself, and there is likewise a better structure between the crystals of iron. Thereby achieving the higher strength qualities necessary for a wind turbine hub. On account of the extra heat treatment, SG cast iron is somewhat more expensive than normal cast iron.

MAIN SHAFT

The main shaft of a wind turbine is usually forged from hardened and tempered steel. Hardening and tempering is a result of forging the axle after it has been heated until it is white-hot at about 1000 degrees centigrade. By hammering or rolling the blank is formed with an integral flange, to which the hub is later bolted.

The shaft is reheated a final time to a glowing red, following the forging process, and then plunged into a basin of oil or water. This treatment gives a very hard, but at the same time rather brittle surface. Therefore the axle is once again reheated to about 500 degrees centigrade, tempering the metal and thereby enabling the metal to regain some of its former strength.



Spherical roller bearing • (Niemann)

MAIN BEARINGS

All modern wind turbines, including the Bonus models, have spherical rolller bearings as main bearings. The term spherical means that the inside of the bearing's outer ring is shaped like a cross section of a ball. This has the advantage of allowing the bearing's inner and outer ring to be slightly slanted and out-of-track in relation to each other without damaging the bearing while running. The maximum allowable oblique angle is normally 1/2 degree, not so large, but large enough to ensure that any possible small errors in alignment between the wind turbine shaft and the bearing housing will not give excessive edge loads, resulting in possible damage to the bearing.

The spherical bearing has two sets of rollers, allowing both absorption of radial loads (across the shaft) from the weight of the rotor, shaft, etc. and the large axial forces (along the shaft) resulting from the wind pressure on the rotor.

The main bearings are mounted in the bearing housings bolted to the main frame. The quantity of bearings and bearing seats vary among the different types of wind turbines: “ Small ” wind turbines up to and including 150 kW have two bearings, each with its own flanged bearing housing. The 250/300 kW wind turbines have only one main bearing, with the gearbox functioning as a second main bearing. The 450 kW, 500 kW and 600 kW wind turbine models have two main bearings, using the hub as a housing. Each bearing arrangement has advantages and disadvantages, and the evaluation of these properties have provides each individual type with its own setup.

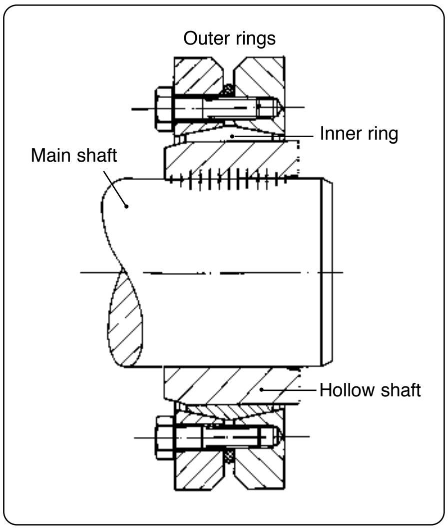
The main bearings are always lubricated by greasing, no matter which bearing arrangement is selected. Special grease having viscose properties even in hard frost is used.

Sealing of the bearing housing is insured by the use of a labyrinth packing. No rubber sealing is used, the labyrinth with its long and narrow passageway prevents grease from escaping. Water and dirt are prevented from entering from the outside by the long passageways filled with grease, which is constantly and slowly trying to escape from the bearing. This may appear to be a rather primitive arrangement, but labyrinth packing is a much used method where there is great risk of pollution by water and dirt. It is more expensive to use than a rubber sealing, because the labyrinth is complicated to fabricate on machine tools, however the seal is not subject to wear, and under normal conditions it is a safe method to keep out the pollutants that otherwise in a short time could ruin roller bearings.

THE CLAMPING UNIT

By the means of a clamping unit the main shaft of the wind turbine is coupled to the gearbox. The gear has a hollow shaft that fits over the rear end of the main shaft. Torque between the two components is transferred by friction between the two.

A clamping unit, normally composed of an inner ring and two outer rings with conical facings, is placed on the outside of the gear's hollow shaft. When the main shaft is placed inside the hollow shaft during the assembly of the wind turbine, the conical facings of the clamping unit are loosely positioned on the hollow shaft. Following control of the correct alignment of the gear and the main shaft, the rings are tightened by the means of a large number of bolts. The outer rings are thereby pressed together, while the inner ring, positioned on the hollow shaft is pressed inwards under the tightening of the bolts. The inner ring now presses so hard against the hollow shaft that the inner part of the hollow shaft is in turn pressed hard against the main shaft. It is because of this pressure that the torque is

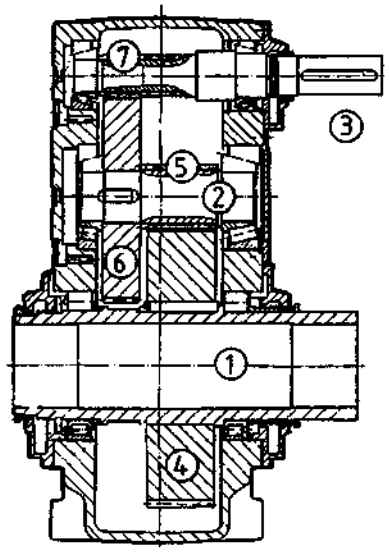


Clamping unit • (TAS Shäfer)

transferred from the main shaft to the wind turbine gear hollow shaft. One might also say that the hollow shaft is shrink-fitted on the main shaft as a result of pressure from the clamping unit.

Transferred torque is dependent upon friction between the main shaft and the hollow shaft. Therefore it is vital that the components are carefully cleaned and completely dry, before they are assembled. If they are at all greasy, they could slip in relation to each other during high loads, for example during the cut-in process in strong wind conditions.

Many know of the parallel key method, often used in assembling a shaft to a hub. The main shaft's torque is transferred by forces across the parallel key (a parallel key is often called a wedge, even though it is not wedge shaped). This assembly method is not often used with a large shaft, there being too great a risk that in time the different parts could loosen, unless they fit uncommonly well together. If the parallel key junction assembly method is used for large shafts, parts must fit so well together, that in practice one is unable to dismantle them in the field, should it be necessary during possible replacement in case of damage or repair.

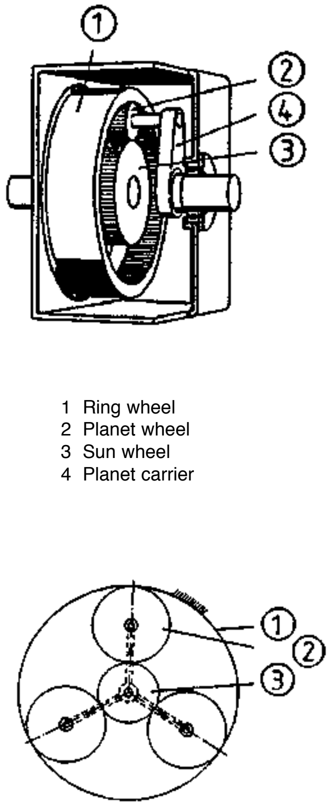


1 Hollow shaft
2 Intermediate shaft
3 High speed shaft
for the generator

Slow set
4 Large toothed wheel
5 Small toothed wheel

High speed set
6 Large toothed wheel
7 Small toothed wheel

Flender SZAK 1380 2-trins gear



1 Ring wheel
2 Planet wheel
3 Sun wheel
4 Planet carrier

Planetgear • /DIN 686/Niemann)

THE GEARBOX

One of the most important main components in the wind turbine is the gearbox. Placed between the main shaft and the generator, its task is to increase the slow rotational speed of the rotor blades to the generator rotation speed of 1000 or 1500 revolutions per minute (rpm).

Without much previous experience with wind turbines, one might think that the gearbox could be used to change speed, just like a normal car gearbox. However this is not the case with a gearbox in a wind turbine.

In this case the gearbox has always a constant and a speed increasing ratio, so that if a wind turbine has different operational speeds, it is because it has two different sized generators, each with its own different speed of rotation (or one generator with two different stator windings).

As an example of a gearbox construction, we can study a Flender SZAK 1380 gear for a 150 kW wind turbine. This gear has two sets of toothed gear wheels, a slow speed stage and a high speed stage. In the slow speed stage the large gear wheel is mounted directly on the gear's hollow shaft, while the smaller gear wheel is machined directly on the intermediate shaft.

The difference in the size of the wheels is 1:5. The intermediate shaft therefore turns 5 times every time the hollow shaft makes one complete revolution. The large gear wheel in the high speed gear stage is also mounted on the intermediate shaft, while the small gear wheel in the high speed gear stage is machined on the generator shaft itself. Here the difference in size is also about 1:5, so that the output shaft to the generator shaft turns 5 times for every one rotation of the intermediate shaft.

When the two ratios are combined, the output shaft will turn 25 times for every rotation of the hollow shaft and the main shaft of the wind turbine combined One can say that the gear has a gear ratio of 1:25.

Normally the ratio in every set of gear wheels is restricted to about less than 1:6. The 150 kW wind turbine has a rotor rotational speed of 40 rpm and with a generator speed of about 1000 rpm, the gearbox must have a total gear ratio of 40/1000 or 1:25. This is possible using a two stage gearbox. A 300 kW wind turbine has a rotor rotational speed of 31 rpm and a generator with a rotational speed of 1500 rpm. It therefore requires a gearbox with a gearbox ratio of 31/1500 or 1:48. This is not possible using a gearbox with only two stages, so the 300 kW wind turbine gearbox has an extra intermediate shaft, giving in all a three stage gearbox.

Wind turbines, from 450 kW and larger, have an integrated gearbox with a planet gear and two normal stages. The planet gear is a special version of the toothed gear. This type of gear is of great delight to gearbox technicians, as it can be combined in countless different complicated variations, each one carefully calculated with its own special inner logic. The form of planet gear used on wind turbines is however always of the same basic design: An interior toothed gear wheel (ring wheel), three smaller toothed gear wheels (planet wheels) carried on a common carrier arm (the planet carrier) and finally a centrally placed toothed gear wheel (the sun gear wheel). It is this construction, with three smaller gear wheels orbiting a centrally placed common gear wheel that has given this type of gear its name of planet gearbox.

The ring wheel itself is stationary, while the planet carrier is mounted on the hollow shaft. When the planet carrier rotates with the same rotational speed as the rotor blades, the three planet wheels turn around inside the inner circumference of the ring wheel and thereby also greatly increase the rotational speed of the centrally placed sun gear wheel. One can usually obtain a gear ratio of up to about 1:5. The sun gear wheel is fixed to an shaft driving the two normal gear stages placed at the rear end of the gearbox.

The fact that there are always three gear wheels supporting each other and that all gear wheels are engaged at the same time, is one of the advantages of the planet gear. This means that it is possible to construct rather compact planet gearboxes, because the larger ring wheel does not need to be as large as a gear wheel in a traditional type of gearbox. In principle it only needs to be about a 1/3 of the size. However in reality it not quite so simple. If a gear is needed to transfer heavy loads, it is often somewhat cheaper to use a planet gear.

However it is in the very nature of things that trees do not grow up into heaven, and also planet gears have their own special disadvantages. The compact construction, very practical for the design and construction of the rest of the machine, can be in itself a disadvantage. The compact construction makes it difficult to effectively dissipate excess heat to the surroundings. A gear is not 100% effective, and as a rule of thumb it is estimated that roughly 1% of the power is lost at each stage. A 600 kW gearbox running at full capacity, must therefore dispose of about 18 kW of waste heat. This is equivalent to nine normal household hot air blower-heaters operating at full blast. This waste heat should preferably be radiated by surface cooling and of course the less gearbox surface area, the higher the temperature must be inside the gearbox to transfer the necessary, unavoidable excess waste heat.

Another disadvantage of the planet gear is that they normally cannot be constructed with bevelled machined teeth. Bevelled teeth are always used in normal gearboxes in order to reduce the noise level. When the teeth are set at an angle, the next tooth will start to engage and take up the load before the previous tooth has slipped contact. This results in a quieter, more harmonious operation. For interior gear wheels bevelled teeth can only be machined using special machine tools that up until now have solely been used for the machining of very large turbine gears for use in ships. Therefore planet gears have always straight machined teeth, unfortunately however, resulting in a higher noise level. By combining a planet gear stage and two normal gear stages, one obtains an acceptable compromise of the advantages and disadvantages with the two different types of gear.

No matter what type of gear is used, the shape of the teeth in the different gear stages are adapted to the special conditions for wind turbine operation, especially those that are related to the noise level. Teeth as a rule are case-hardened and polished. Case-hardening is a method of giving surface strength to a specific material. During this process, the inner material maintains its previous strength, which can often be lost in normal steel hardening processes.

Hardening can only take place under conditions where there is a carbon content in the steel. The gear wheels are made of a special low carbon chrome-nickel steel. The teeth are first machined, and following the machining process, the gear wheels are packed into large boxes full of bone flour or some other form of high carbon-content powder. The boxes are placed in an oven and heated for about 24 hours to a red glowing temperature. During this baking process some of the free carbon will be transferred from the surrounding carbon-rich powder in the boxes to the gear wheel teeth surfaces. This is described as the method of hardening the teeth in boxes or cases, and therefore from this process comes the descriptive name of case-hardening.

The increased carbon content of the teeth surface allows the top edges of the gear wheel teeth to become harder, so following case hardening, the gear wheel is lifted out, still red hot, and lowered into an oil bath. This completes the process of hardening, and the gear wheel now has a hardened surface, while the inner material still has ductile and not hardened properties. The hardening process slightly deforms the material, so it is necessary to finish the process by grinding.

THE COUPLING

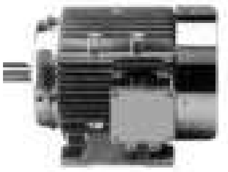
Coupling• (Flender BIPEX)

The coupling is placed between the gearbox and the generator. Once again it is not possible to consider the coupling as the same as a clutch in a normal car. One cannot engage or disengage the transmission between the gearbox and the generator by pressing a pedal, or in some other such way. The transmission is a permanent union, and the expression “coupling” should be understood as a junction made by a separate machine component.

The coupling is always a “flexible” unit, made from built-in pieces of rubber, normally allowing variations of a few millimeters only. This flexibility allows for some slight differences in alignment between the generator and the gearbox. This can be of importance under assembly and also during running operation, when both gearbox and generator can have tendencies for slight movement in relation to each other.

THE GENERATOR

The wind turbine electrical system



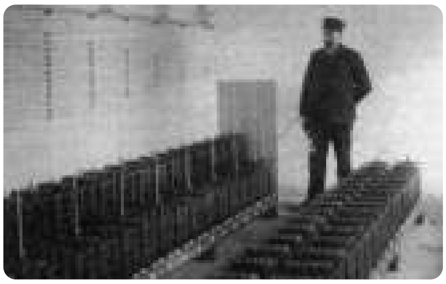
The generator is the unit of the wind turbine that transforms mechanical energy into electrical energy. The blades transfer the kinetic energy from the wind into rotational energy in the transmission system, and the generator is the next step in the supply of energy from the wind turbine to the electrical grid.

In order to understand how a generator works, it is necessary to first of all understand the deeper principles in the electrical system to which the generator is connected. Therefore we will first discuss the electrical systems based on Direct Current (DC) and those based on Alternating Current (AC).

DIRECT CURRENT (DC)

During the first use of electricity for lighting and power in the previous century, systems based on direct current were used. In DC systems the voltage is at a constant level. This could be 1.5 Volts (V) as in a modern alarm clock, 12 V as in a car or 110 V as in the first proper electrical grid.

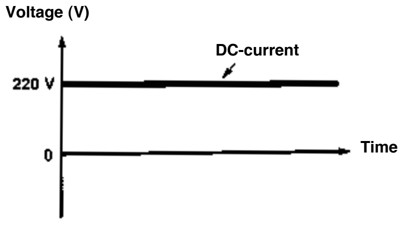
DC has the advantage that batteries can be connected, enabling a continual supply of electrical power even if the generator at the power station ceases operation and shuts down. Therefore the first power stations had large store rooms full of long rows of batteries. Such systems were well adapted to the use of wind turbines as a main power source, for with such large stocks of batteries, power could still be supplied even in calm periods.



The battery store room of a wind power plant at the beginning of the 1900´s • (H.C.Hansen: Poul la Cour)

In spite of the advantages of battery energy storage, DC is no longer used in larger grid electrical supply systems. This is due to some important disadvantages of direct current, while on the other hand the competing electrical system alternating current offers important advantages.

One of the big disadvantages of DC is the strong electrical arc produced, when the electrical current connection from supply to user is cut at higher voltages. For example, in larger installations with connections to electrical motors DC switches are both large and complicated. Therefore in practice DC systems can be rather inconvenient.



DC-system

Another "disadvantage" is that the advantages of battery energy storage do not in reality exist with the electrical grid systems in common use today. This is because our present-day energy consumption greatly exceeds the capacity of this technology.

A typical Danish family has an energy consumption of about 5.000 kWh per year, or about 13.7 kWh per day. A normal car battery has a capacity of about 60 Ah (Ampere-hours). This means that a car battery can supply an electrical current equal to 1 Ampere for about 60 hours at a battery voltage of 12 Volts. The energy in a fully charged battery can be calculated by the use of a simple formula:

$$E = 60 \text{ Ah} \times 12 \text{ V} = 0.72 \text{ kWh}$$

Therefore less than 1 kWh is stored in a fully charged car battery. A typical Danish family with a daily requirement of 13,7 kWh kWh per day will thus need 19 fully charged batteries just to cover the power consumption of a single day without a supply from the power station grid network.

Another example: In a good high wind period a 600 kW wind turbine can typically produce about 10.000 kWh per day. This is enough to charge about 14.000 car batteries per day, were it is not possible to supply this energy production for the direct consumption or use by the owner, or for supply to other consumers connected to the grid.

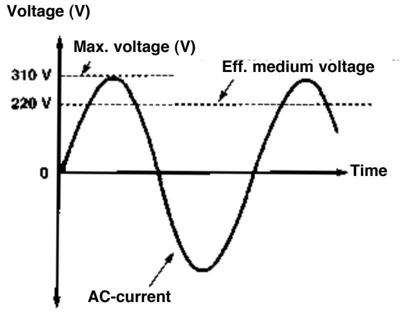
In connection with such large quantities of energy, storage in batteries is not feasible, and the storage possibilities offered by the use of DC systems are not really practically relevant.

ALTERNATING CURRENT (AC)

The voltage of the current constantly varies around zero in an AC electrical system. The maximum voltage must be somewhat higher than a DC system in order to give the same power. One can speak of an effective medium voltage as a kind of average of the voltage.

AC measuring instruments usually show the effective middle voltage value and not the maximum voltage.

A lamp connected to an alternating electrical current will blink, as the voltage constantly varies. The frequency of the voltage variation or cycles in Denmark, and most other countries is 50 Hz (50 cycles per second). Such rapid cycles make the blinking of the lamp of no real importance. The glowing wire in



AC-system

a normal electric bulb does not have time to become cold in the short period between cycles, and therefore does not in practice blink. In comparison light emitting from a neon tube is completely shut off each time the voltage is at zero. The eye however cannot distinguish variations in light intensity that occur faster than 15 times a second, so therefore we see light from a neon tube also as constant.

The main advantage of alternating current over direct current is that the voltage can be altered using transformers. This is not the place to describe in detail the functioning of a transformer, but in principal it is possible to alter from one voltage to another voltage almost without loss of energy.

Most know the small transformers used as power supply to radios, mobile telephones, etc. A small box is plugged into a 220 volt outlet connected to the grid and 9 volts comes out at the other end (normally also rectified to direct current, but that is another story). For the grid as a whole, it is the transformation to a higher voltage that is of importance.

The advantage of high voltage is that energy losses in power transmission lines, are greatly reduced by using increased voltages. In order to understand this, one must know a couple of the fundamental formulas in electrical engineering. As an example consider the case of a typical 220 volt electrical tool, a 2.200 Watt (W) grinder.

The current one obtains at specific power and voltage ratings may be calculated with the formula:

$$I = P / U$$

Where ”I” is the current, ”P” is the power and ”U” is the voltage. In the example of the grinder, with power P = 2.200 W and voltage U = 220 V We obtain the current of 2.200 / 220 = 10 A.

The power loss from the wires may be calculated with the formula:

$$T = R \times I^2$$

Where ”T” is the power loss and ”R” is the resistance of the wire. A normal household electric wire with a cross section of 1.5 mm^2 has a resistance of 0.02 Ohm per meter. A 10 meter long wire will have a resistance of 0.2 Ohm and the power loss in the wire will therefore be $T = 0.2 \times 10^2 = 20$ W. This is not so much, only about 1% of the grinder’s usable power.

The power loss is however quite significant, when one considers the distance from the user to the power station. With a typical distance of about 20 km , the resistance in a 1.5 mm^2 wire will be about 400 Ohm, and the power loss will therefore be $T = 400 \times 10^2 = 40{,}000$ W or almost 20 times the power of the grinder! Of course small 1.5 mm^2 wires are not used as power supply cables from the power station out to the consumer, but even with large 50 mm^2 cables, the power loss is still larger than the rated power of the grinder.

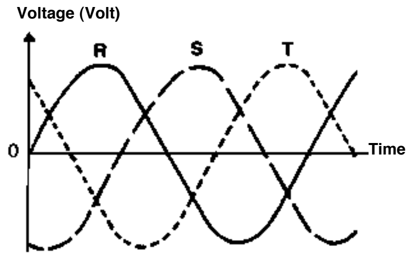
It is in this situation that high voltage transmission wires have their use. If instead of 220 V the power station sends an electrical current of 10.000 V out in the electrical grid to the consumer, the first formula for current will give I = 2.200 /10.000 = 0.22 A, and the other formula for power loss will give $T = 400 \times 0.22^2 = 20$ W still using the same (unrealistic) wire dimension of 1.5 mm^2. The use of high voltage power lines has therefore reduced power loss from an unacceptable level to that which is more acceptable.

In practice current is transmitted from power stations with a voltage of up to 400,000 V . This is then transformed to a lower voltage in large centralized transformer stations, for example down to 10,000 V. Near the consumer the final transformation down to 220 V is made.

For safety reasons high voltage is not used near the consumer, as electrical current becomes more dangerous, the higher the voltage is increased. Likewise the demands on the safety insulation of electrical material also increases.

Voltage at any one given place on the grid is therefore a compromise between a desire on the one side for a minor power loss (requiring high voltage), and on the other hand the necessity of a low or moderate risk of danger and at the same time reasonably cheap electrical installations (requiring lower voltage).

THREE PHASE ALTERNATING CURRENT



Three phase AC (three super-imposed sinus curves)

Even though the cycles in the alternating current are of no great importance for lamps and other such things, it is impractical for certain other machines that the current is always alternating around zero. Therefore, years ago, it was discovered that AC could be supplied with three phases.

The principle of 3 phase electrical power is that the generator at the power station supplies 3 separate alternating currents, whose only difference is that they peak at three different times. The knack with these three separate alternating currents, or phases, is that it is thereby possible to ensure that the sum of the delivered power is always constant, which is not possible with two or four phases.

It is perhaps a little impractical with three phase current, because it is necessary to run four different wires out to the consumer, three different phase wires and a neutral wire (zero). However for electric motor use, the advantages of three phase alternating current are many. The voltage difference between two of the phases is greater than that between any one single phase and zero. Where the voltage difference is 220 V between one phase and zero, it is 380 V between two phases.

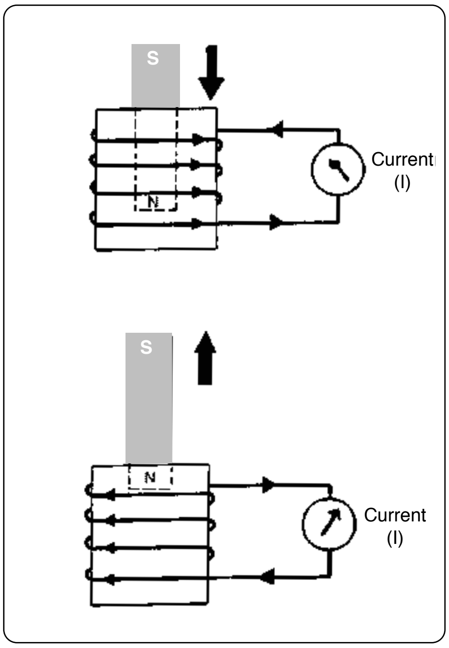
This is often used in high energy consumption equipment such as kitchen ovens etc., which normally always are connected to two phase power. In a household installation usually only one of the phases plus the neutral wire is led to an ordinary socket. Normally the installation has several groups, and one phase will typically cover one part of the house, and another phase will run to the other rooms. Three phase sockets are rather large and are often known as power sockets, mainly because of their use in electrical motor operation. For ease in distinguishing between the different phases, in Denmark the three phases have been named R, S, and T.

On the older Danish transmission lines supported by wooden masts, phases were placed in a certain specific order, reading from the bottom up, according to the Danish words for root (R), trunk (S) and top (T).

INDUCTION AND ELECTROMAGNETISM

Before finally describing the generator itself, we must briefly explain a couple of the basic principles of electromagnetism.

Many perhaps remember our school days, when the physics teacher placed a magnetic bar inside a coil of copper wire connected to a measuring instrument. If the magnet is stuck inside the coil, an electric current is registered in the coil circuit. If the magnet is withdrawn, a current of the same strength is registered, but in the opposite direction. The faster the changes of the magnetic field in the coil, the greater the current. The same occurs if instead of the magnet being stuck into the open coil it is merely moved past one of the ends of the coil. The effect is especially powerful if the coil has a iron core.



The principles of induction

One can say that alterations in the magnetic field, induce a current in the coil, and the phenomena is known as induction.

In just the same way that a magnetic field can bring about an electric current, so can an electric current likewise cause a magnetic field to be created. Electromagnetism was first demonstrated by the Danish scientist H.C Ørsted in his famous experiment, where an electrical current was able to turn a compass needle. He had therefore demonstrated the first electromagnet.

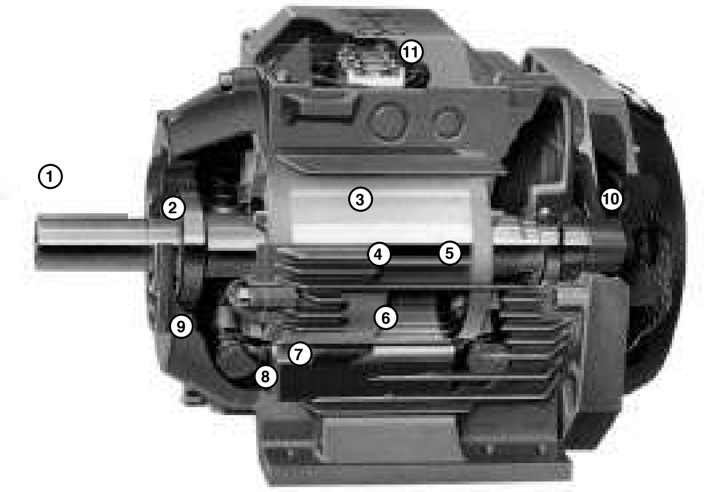
In practice a good electromagnet is best made as a coil with an iron core, in just the same way as the previously mentioned form of coil that produces an electric current when a magnet is moved past at a close distance. Like a permanent magnet an electromagnet has two poles, a north pole and a south pole. The position of these two poles depends on the direction of the flow of electrical current.

THE WIND TURBINE GENERATOR AS A MOTOR

The asynchronous generator we will describe here is the most common type of generator used in Danish wind turbines. It is often referred to as the induction generator, too. As far as we know the asynchronous generator was first used in Denmark by Johannes Juul, known for the 200 kW Gedser wind turbine from 1957. Already some years prior to this construction he erected a 13 kW experimental wind turbine with an asynchronous generator at Vester Egesborg in the south of the large Danish island of Zeeland.

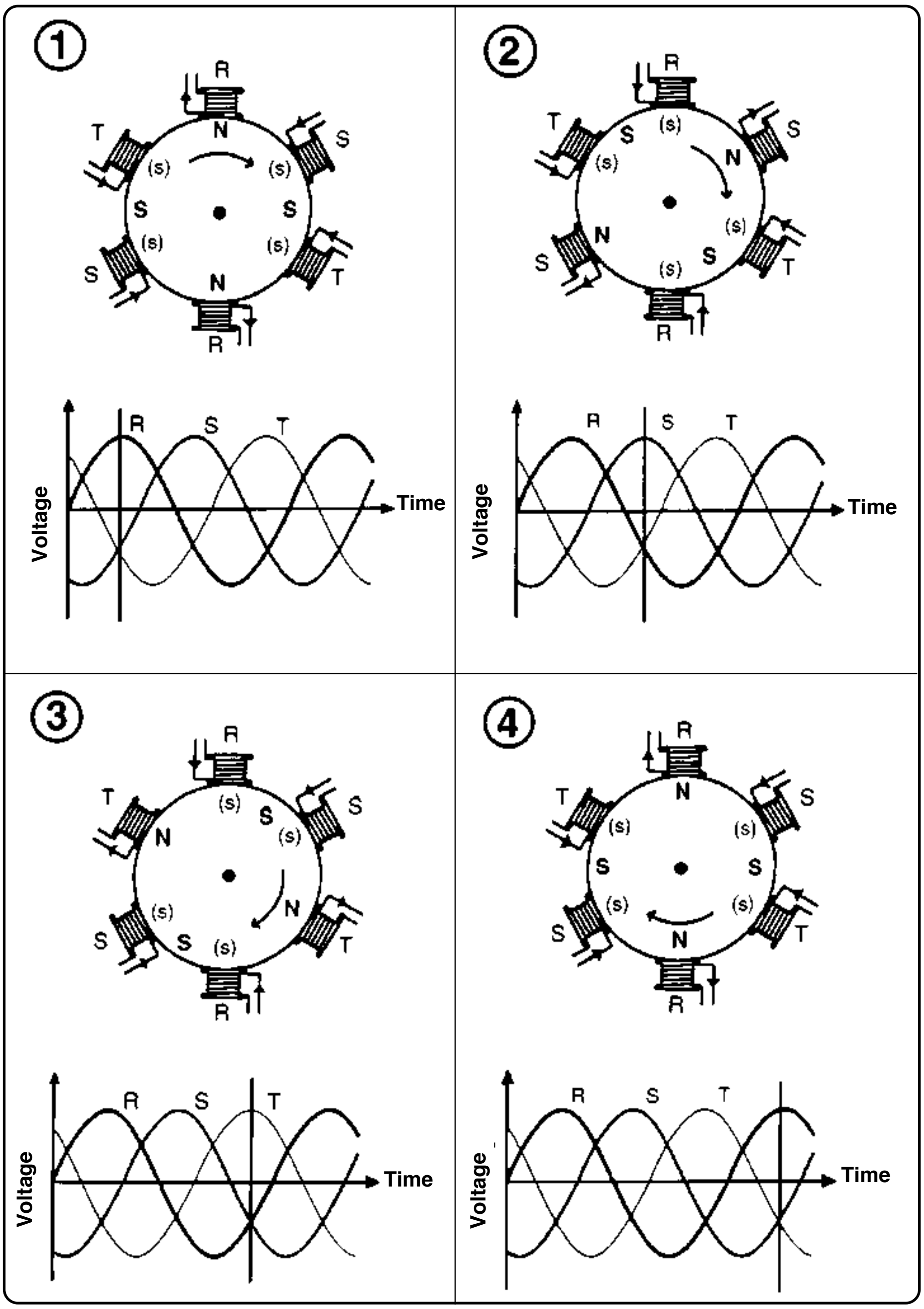
The asynchronous generator is in reality a type of motor that can also operate as a generator, and we will first consider this type as a motor. This is the most common electric motor, sitting in almost every washing machine, and widely used as a motor unit in industry.

The motor consists of two main parts, the stator and the rotor. The stator contains a series of coils, the number of which must be divisible by three. The motor illustrated on this page has six coils, placed in slots on the inside of the stator, a cylinder assembled of thin iron plates. The rotor sits on an axle placed inside this stator. The rotor is also assembled of thin iron plates. A row of thick aluminum bars joined at each end with an aluminum ring, fit in key ways on the outer surface of the rotor. This rotor construction looks a bit like a squirrel cage, and accordingly the asynchronous motor is also called a squirrel cage motor.



1. Generator shaft
2. Rolling bearings
3. Rotor
4. Rotor aluminium bar
5. Rotor aluminium ring
6. Stator
7. Coil
8. Stator plates
9. Coil heads
10. Ventilator
11. Connection box

Components of an asynchronous motor



4 situations of the rotation magnetic field

The six coils in the stator are connected together, two by two to the three different phases of the electrical grid. This arrangement insures that there is a rotating magnetic field inside the stator itself. This is best illustrated by the above diagram.

At a specific time "1" the current in phase R is at its maximum, and this produces a magnetic field with a strong north pole at both the opposite coils connected to the phase R. At phase S and phase T the current is somewhat under zero, and the two pairs of coils produce a medium strength south pole, producing a powerful south pole halfway between the two coils.

At time "2" the current at phase S is at a maximum, and the north pole is now at the two opposing coils connected to this phase. The current at phases R and T is likewise reduced to under zero, and the south pole is now between these two coils.

At time "3" the current at phase T now is at a maximum, and the north pole is at the two coils connected to phase T. The south pole has also turned, and is now halfway between the coils connected to phases R and S.

At time "4" the situation has now returned to as it was at the start of the electrical current rotation, with the north poles at the end of the coils connected to phase R.

In one complete cycle, from the current peak to the next following peak, the magnetic field has rotated through half a circle. There are 50 cycles per second, so the field turns at 25 times per second, or 60 x 25 = 1.500 rpm (revolutions per minute).

To understand how a generator works, it is easiest to first consider two different situations where a generator operates as a motor, at 0 rpm. and at 1.500 rpm.

In the first case the rotor is stationary, while the stator turns at 1.500 rpm. The coils in the rotor experience rapid variations of a powerful magnetic field. A powerful current is thereby induced in the short circuited rotor wire windings. This induced current produces an intense magnetic field around the rotor. The north pole in this magnetic field is attracted by the south pole in the stator's turning magnetic field (and of course, the other way round) and this will give the rotor a torque in the same direction as the moving magnetic field. Therefore the rotor will start turning.

In the second situation, the rotor is turning at the same speed as the stator magnetic field of 1.500 rpm. This rotational figure is called the synchronous rotational speed. When the stator magnetic field and the rotor are synchronized, the rotor coils will not experience variations in the magnetic field, and therefore current will not be induced in the short circuited rotor windings. Without induced current in the rotor, there will be no magnetic field in the rotor windings and the torque will be zero.

On account of bearing friction the motor must produce a little torque to keep rotating, and therefore cannot run at exactly the same speed as the rotating magnetic field. As soon as the speed slows down, there will be a difference between the speed of the rotating magnetic field and the rotor. The rotor thus again experiences a variation in the magnetic field that induces a current in the rotor windings. This current then produces a magnetic field in the rotor, and the rotor can produce a torque.

During motor operation, the stator experiences a constantly changing magnetic field, being dragged round by its rotating magnetic field. During this process, electrical current is induced in the stator, which results in a power consumption. In fact, the slower the rotor turns in relation to the rotating magnetic field of the stator, the stronger the induction in the stator, and therefore the greater the power consumption.

The fact that the rotor has no torque at the precise synchronous rotational speed and therefore will always run slightly slower has given this motor type its name, the asynchronous motor.

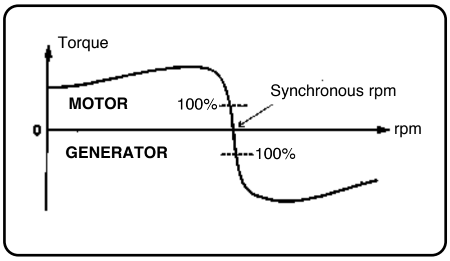
GENERATOR OPERATION

As we have previously mentioned, the asynchronous motor can also run as a generator. This simply happens when you, instead of forcing the rotor to turn at a rotational speed lower than the synchronous speed, exceed this synchronous speed by applying an outside energy source, such as a diesel motor or a set of wind turbine rotor blades.

Once again, the greater the difference between the rotating magnetic field of the stator (which is always 1.500 rpm) and the speed of the rotor, the greater the torque produced by the rotor. When a working as a generator, the rotating field however acts as a brake in slowing the rotor. The stator experiences a variable magnetic field from the rotor that "drags" its rotating magnetic field and thereby induces an electrical current in the stator. In comparison to motor operation the induced currents in the rotor and stator will flow in the opposite direction, which means that power will be sent to the grid. The faster the rotor turns in relation to the rotating magnetic field of the stator, the greater the induction in the stator and the greater the production of power.

In practice the difference between the speed of rotational magnetic field of the stator and the rotational speed of the rotor is very little. A rotor will typically turn about 1% faster at full power production. If the synchronous rotational speed is 1.500 rpm then the rotor rotational speed at full power will be 1.515 rpm.

The interesting torque curve of the asynchronous electric motor, also operating as a generator, is shown below. At speeds below the synchronous rotational speed, the motor yields a positive torque.



Torque curve

Typically a maximum torque of about 2.5 times the torque of the nominal power. If the rotational speed exceeds the synchronous level, the torque becomes negative, and the generator acts as a brake.

At the Bonus factory, we have a rather interesting apparatus, that demonstrates this shift between a motor and generator. A small asynchronous motor is connected to an electric meter. The motor has a gearbox giving a shaft speed of 60 rpm.

A small crank handle is fixed to the shaft. The motor starts when it is plugged into a normal mains socket coming from the electrical grid and consumes a small amount of electrical energy due to friction loss in the motor and gearbox.

If one attempts to resist the rotation of the shaft by holding back the crank, the consumption of energy will increase. If the crank however is used to increase the speed of the motor, then the electric meter will start to run backwards, showing that current is flowing the other way. In this way one can, by using human muscle power, feed electrical power to the grid, in just the same way that a wind turbine feeds power to the grid. It is difficult to achieve more than 1/20 kW so a work force of twelve thousand employees is needed to compete with one single 600 kW wind turbine operating in a good wind. Visitors to Bonus may try their hand at our generator demonstration model.

CUT- IN

If a wind turbine is connected to the grid during a period of no wind, the asynchronous generator will operate as a motor and drag the rotor blades round like a large electric fan. The wind turbine therefore is disconnected from the grid during periods of calm.

The wind turbine is likewise disconnected during periods of low wind speeds, allowing the blades to slowly rotate. The control system of the wind turbine however constantly monitors the rotational speed, and after the blades reach a certain pre-set level, the system permits a gradual cut-in to the grid.

The cut-in to the grid is carried out by the use of a kind of electronic contacts called thyristors, allowing continuously variable up and down regulation of the electrical current. Such thyristors allow smoother and gentler generator cut-in, thus preventing sudden surges of current causing possible grid damage. Likewise this gentler switching procedure prevents stress forces in the gearbox and in other mechanical components. A direct cut-in, using a much larger electrical switching unit result in violent shock-effects, not only to the grid but also to the whole transmission system of the wind turbine itself.

Unfortunately, thyristors have the disadvantage of an power loss of about 1-2%, so after the finish of the cut-in phase, current is led past the thyristors direct to the grid by the means of a so-called " by-pass switch ".

CLOSING REMARKS

It has been necessary to make many simplifications in the above description. We have considered such important terms, as self-induction, reactive current and phase compensation to be too complicated in a more general description such as this. During the induction process, in reality it is not an electric current that is created, but an electromotive force giving rise to a certain current dependent upon the resistance.

We have used the rotational speed for a 4-pole and 6 coil generator (3 x 2). In the diagram showing the rotating field, one can observe that there are 2 north poles and 2 south poles, 4 in all. Other generators may have 9 coils, which would mean 3 north poles and 3 south poles. Such a 6 pole generator has a synchronous rota-tional speed of 1.000 rpm.

Bonus wind turbines up to and including the 150 kW models have 6 pole generators, while the larger models have 4 pole generators.

CONTROL AND SAFETY SYSTEMS

Control and safety systems comprise many different components. Common for all of these is that combined together they are part of a more comprehensive system, insuring that the wind turbine is operated satisfactory and preventing possible dangerous situations from arising.

Details in control and safety systems are somewhat different according to different types of wind turbines. We have in previous articles described components and their functions that roughly cover most Bonus wind turbine models, regardless of their age. However it is necessary in this article to be much more specific, so we choose to concentrate on the Bonus 600 kW Mk IV.

PROBLEM DESCRIPTION

In constructing wind turbine control and safety systems one is soon aware of a couple of rather important problems. These problems pose special demands on the systems, because they have to function in the complex environment of a wind turbine.

The first problem is common to all control and safety systems: A wind turbine is without constant supervision, apart from the supervision of the control system itself. The periods between normal qualified maintenance schedules is about every 6 months, and in the intervening 4,000 hours or so the control system must function trouble-free, whether the wind turbine is in an operational condition or not.

In almost every other branch of industry there is a much higher degree of supervision by trained and qualified staff. On factory production lines, operatives are normally always present during production. For example, in power stations the system is constantly supervised from a central control room. Should a fault or breakdown occur, rapid intervention is possible and, as a rule, one has always some sort of good impression of what has actually happened in any unforeseen occurrence. However a wind turbine must be able to look after itself and in addition have the ability to register faults and retrieve this stored information concerning any special occurrence, should things possibly not go exactly quite as expected.

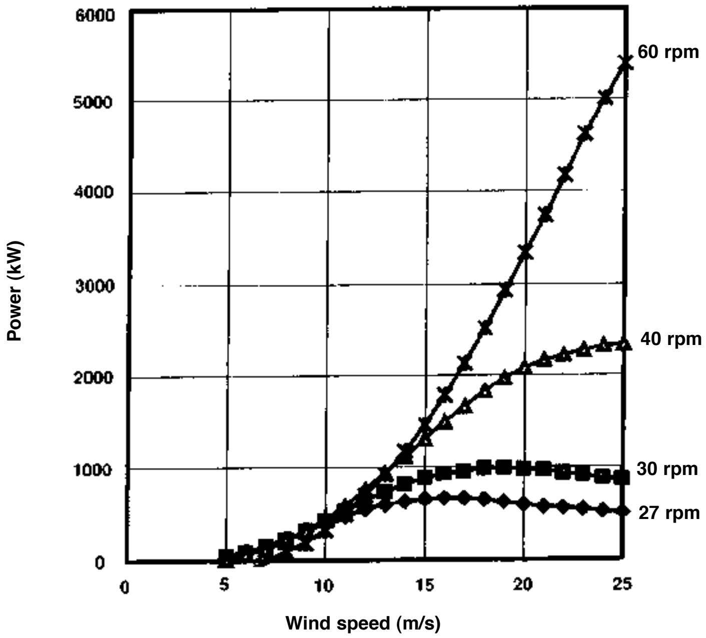
The high demands on reliability require systems that are simple enough to be robust, but at the same time give the possibility for necessary supervision. The number of sensors and other active components need to be limited as far as possible, however the necessary components must be of the highest possible quality. The control system has to be constructed so that there is a high degree of internal control, and to a certain degree the system must be able to carry out its own fault finding.

The other problem most of all relates to the safety systems. A wind turbine, if not controlled, will spontaneously overspeed during high wind periods. Without prior control it can then be almost impossible to bring to a stop.

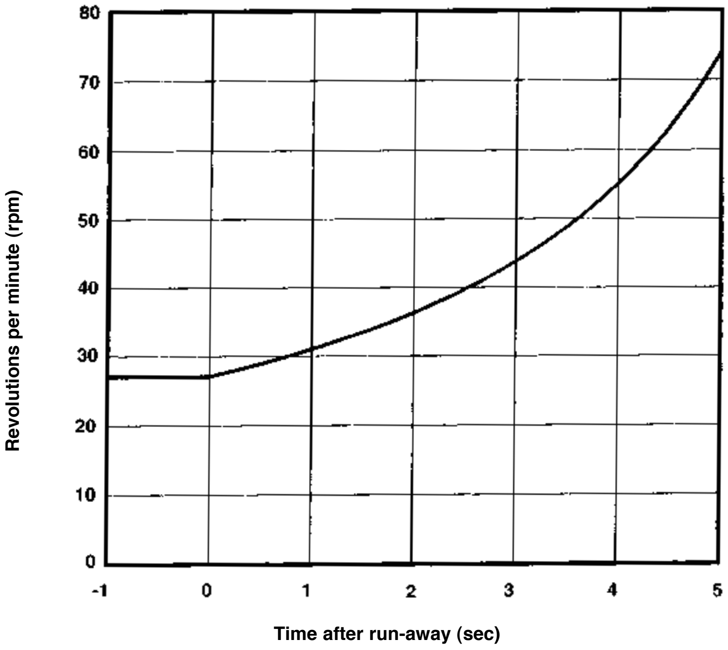
During high wind, a wind turbine can produce a much higher yield than its rated power. The wind turbine blade rotational speed is therefore restricted, and the wind turbine maintained at the rated power, by the grid-connected generator.

If the grid connection is lost, by reason of a power line failure or if the generator for some other reason is disconnected, while the wind turbine is in operation, the wind turbine would immediately start to rapidly accelerate. The faster the speed, the more power it is able to produce. The wind turbine is in a run-away condition.

The following diagrams dramatically illustrates run-away in high wind. The first graph shows the power curve for the 600 kW wind turbine as a function of the blade rotational speed. The bottom curve illustrates the normal power curve controlled by the generator, at a blade rotational speed of 27 rpm. The three other curves show power production at 30 rpm, 40 rpm and 60 rpm.



Power curves at different rotational speeds (rpm)



Rotational acceleration during run-away

At a wind speed of 20 m/s, a wind turbine will normally produce slightly under 600 kW. Allowed to accelerate a mere 10% to a blade rotational speed of 30 rpm, it is then able to increase power production to 1.000 kW. At a blade rotational speed of 40 rpm the power increases to 2.000 kW and 3.300 kW at 60 rpm. At a wind speed of 25 m/s, if the blades were permitted to rotate at a speed of 60 rpm, the power production would be as high as 5.400 kW.

The second graph illustrates just how rapidly the blade rotational speed accelerates in a run-away situation. After a mere 0.6 seconds the rotor speed accelerates to 30 rpm, and after 2.5 seconds the blades achieve 40 rpm. As noted above the power output at 40 rpm is 2.000 kW, an output far above the ability of the braking system to restrain.

So it is vital that the safety systems must possess very rapid reactive response in order to prevent such runaway.

95% of all deliberations behind design of wind turbine safety systems have to do with this one task of safely regaining control of the wind turbine, should the generator speed control suddenly become non-operative during high wind conditions, and thereafter securely bring the wind turbine to a halt.

Basically there are two main methods by which one prevents a run-away:

1. Either one can prevent that the blades are actually able to achieve this increased power production under this condition of rapidly accelerating blade rotational speed.

2. Or by some other means one can prevent the rotational speed from rising to an unacceptably dangerous level.

Here we have the principles for the use of aerodynamic braking (1) and the mechanical brake (2).

THE CONTROLLER

In one way or another the controller is involved in almost all decision-making processes in the safety systems in a wind turbine. At the same time it must oversee the normal operation of the wind turbine and carry out measurements for statistical use etc.

The controller is based on the use of a micro computer, specially designed for industrial use and therefore not directly comparable with a normal PC. It has a capacity roughly equivalent to that of a 80286 PC system processor. The control program itself is not stored in a hard disk, but is stored in a microchip called an EPROM. The processor that does the actual calculations is likewise a microchip.

Most wind turbine owners are familiar with the normal keyboard and display unit used in wind turbine control. The computer is placed in the control cabinet together with a lot of other types of electro-technical equipment, contactors, switches, fuses, etc.

The many and varied demands of the controller result in a complicated construction with a large number of different components. Naturally, the more complicated a construction and the larger the number of individual components that are used in making a unit, the greater the possibilities for errors. This problem must be solved, when developing a control system that should be as fail-safe as possible.

To increase security measures against the occurrence of internal errors, one can attempt to construct a system with as few components as possible. It is also possible to build-in an internal automatic “self-supervision“, allowing the controller to check and control its own systems. Finally, an alternative parallel back-up system can be installed, having more or less the same functions, but assembled with different types of components. On the 600 kW Mk. IV wind turbine, all three principles are used in the control and safety systems. These will be further discussed one at a time in the following.

A series of sensors measure the conditions in the wind turbine. These sensors are limited to those that are strictly necessary. This is the first example of the targeted approach towards fail-safe systems. One would otherwise perhaps think, as we now have access to computers and other electronic devices with almost unlimited memory capacity, that it would merely be a matter of measuring and registering as much as possible. However this is not the case, as every single recorded measurement introduces a possibility for error, no matter how high a quality of the installed sensors, cables and computer. The choice of the necessary sensors is therefore to a high degree a study in the art of limitation.

The controller measures the following parameters as analogue signals (where measurements give readings of varying values) :

- Voltage on all three phases
- Current on all three phases
- Frequency on one phase
- Temperature inside the nacelle
- Generator temperature
- Gear oil temperature
- Gear bearing temperature
- Wind speed
- The direction of yawing
- Low-speed shaft rotational speed
- High-speed shaft rotational speed

Other parameters that are obviously interesting are not measured, electrical power for example. The reason being that these parameters can be calculated from those that are in fact measured. Power can thus be calculated from the measured voltage and current

The controller also measures the following parameters as digital signals (where the measurements do not give readings of varying values, but a mere an on/off signal) :

- Wind direction
- Over-heating of the generator
- Hydraulic pressure level
- Correct valve function
- Vibration level
- Twisting of the power cable
- Emergency brake circuit
- Overheating of small electric motors for the yawing, hydraulic pumps, etc.
- Brake-caliper adjustment
- Centrifugal-release activation

Even though it is necessary to limit the number of measurements, certain of these are duplicated, for example at the gearbox, the generator and the rotational speed. In these cases we consider that the increased safety provided, is more important than the risk of possible sensory failure.

Internal supervision is applied on several levels. First of all the computer is equipped with certain control functions, known as “watchdogs“. These supervise that the computer does not make obvious calculation errors. In addition the wind turbine software itself has extra control functions. For example in the case of wind speed parameters. A wind turbine is designed to operate at wind speeds up to 25 m/s, and the signal from the anemometer (wind speed indicator) is used in taking the decision to stop the wind turbine, as soon as the wind speed exceeds 25 m/s.

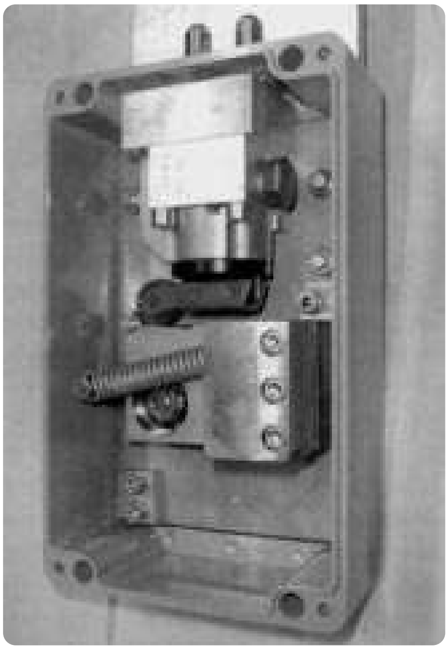

Cup anemometer for wind speed indication (left) • Lightning conductor (middle) • Wind direction indicator (right)

As a control function of the anemometer the controller supervises wind speed in relation to power. The controller will stop the wind turbine and indicate a possible wind measurement error, if too much power is produced during a period of low wind, or too little power during a period of high wind.

A wind measurement error could be caused by a fault in the electrical wiring, or a defect bearing in the anemometer. A constant functional check of the relationship between wind speed and power production ensures that it is almost impossible for the wind turbine to continue operation with a wind measurement error, and the possibility of a wind turbine being subject to stronger winds than its designed wind speed rating, is therefore more or less eliminated.

The third safety principle for the controller lies in duplication of systems. A good example is the mechanical centrifugal release units. These supervise the blade rotational speed and activate the braking systems, even if the speed measurement system of the controller should fail.

A 600 kW Mk IV wind turbine has two centrifugal release units. One of these is hydraulic and placed on the wind turbine hub. It is normally called a CU (Centrifugal release Unit). Should the wind turbine operate at too high a rotational speed, a weight will be thrown out and thereby open a hydraulic valve.


Interior view of the CU

Once the valve is open, hydraulic oil will spill out from the hydraulic cylinders that hold the blade tips in place, thereby activating the blade tip air brakes. No matter what actions the controller or the hydraulic system thereafter attempts to carry out, pressure cannot be maintained in the cylinders and the air brakes will continue to remain activated, until a serviceman resets the centrifugal release manually.

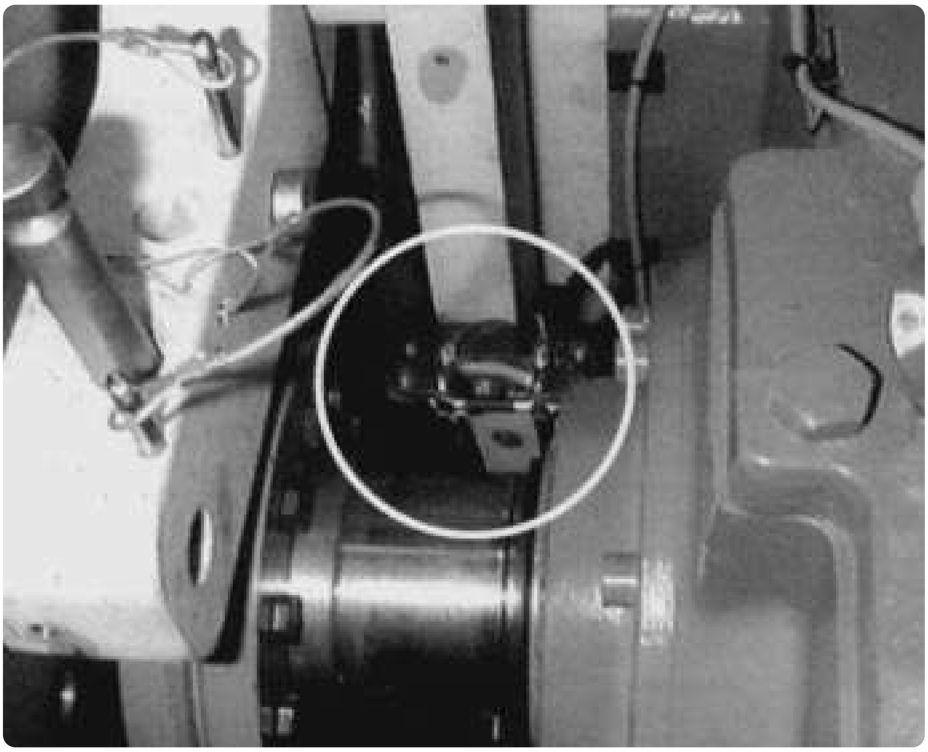
The advantages of the hydraulic centrifugal release units is that it is completely independent the controller and the hydraulic system. This ensures that a possible fatal software design error, not discovered during design review, will not result in a possible run-away of the wind turbine.

The second centrifugal release unit is an electro-mechanical unit, fixed to the high speed shaft of the gearbox. This is normally called an HCU, where H is short for "high-speed". Should the wind turbine over-speed, two small arms are thrown out mechanically cutting off the electrical current to the magnetic valves of the air brakes and the mechanical braking system.

This is a so-called fail-safe system, where the electrical circuit must remain switched on in order to maintain the valves for the air brakes and for the mechanical brake in a closed position. Should the electrical circuit be broken because of a disconnection from the grid or as a result of a shut down from the controller itself, the valves will open and activate the brakes causing the wind turbine to slow down and stop.

The HCU is able to mechanically cut the braking circuit, and thereby activate both braking systems. The hub-mounted CU only cuts the blade hydraulic system. The HCU therefore is superior, however its successful operation is based in turn upon satisfactory operation of the normal valve systems, while the CU has its own extra valve system. Both systems thus have their own advantages and disadvantages considered from the point of view of safety.

Both centrifugal release units are adjusted to be activated at very near the normal operational rotational speed, therefore, on rare occasions, release can occur prematurely. This is not normally the case in Denmark, but following from unexpected power cuts at certain foreign projects, causing the turbines shortly to operate in stand-alone mode, we have experienced release activation. Otherwise centrifugal release systems are only intended to be activated during maintenance testing.



HCU placed on the high speed shaft of the gearbox

HYDRAULICS

The controller decides which operations are to be carried out in the safety system, while the hydraulic system operates the braking systems.

In a hydraulic system a liquid under pressure is used to move certain components. This liquid is called hydraulic oil, having a resemblance to lubricating oil. The operating pressure is about 1.000 Bar (one Bar is equivalent to one atmosphere). The moving components are pistons in hydraulic cylinders. With a pressure of 100 Bar a piston in a 50 mm hydraulic cylinder (similar to the units used in pulling the blade tips into position) produces a force of 2 tons.

The hydraulic systems of both the tip-brakes and the mechanical brake are also fail-safe systems, i.e. hydraulic pressure is necessary for the wind turbine to operate. The hydraulic system ensures that pressure is established when the wind turbine starts. It also releases the pressure when the turbine must stop.

Pressure is built up with a pump controlled by a pressure sensitive switch. Following attainment of the required pressure level, occasional operation of the pump maintains the level. A reserve pressure tank is also included in the system. This small steel tank contains a rubber membrane separating the hydraulic oil from an enclosed body of air. When the oil is under pressure, this will press against this body of air, which in turn will act as a kind of cushion giving a counter pressure, thereby enabling the pressure in the whole system to be maintained.

The release of pressure from the tip-brakes and the mechanical brake is carried out by the means of magnetic valves. These are held in a closed position by the use of an electromagnet and will automatically open with a lack of electrical current. They are therefore operated by being simply switched off.

In order to avoid operational failure problems that any one specific make of valve could possibly produce, two different makes of valves from two different manufacturers are placed in parallel in each of the two different systems for both air brakes and the mechanical brake. Secure and safe operation is ensured even with only one single operational valve, and their functioning is checked at every routine maintenance schedule.

In addition the mechanical hydraulic CU is fixed at the hub of the rotor blade itself. This unit is completely independent of the functioning of the magnetic valves in releasing the pressure in the air brake hydraulic cylinders.

TIP BRAKES

The moveable blade tips on the outer 2.8 meters of the blades function as air brakes, usually called tip brakes.

The blade tip is fixed on a carbon fiber shaft, mounted on a bearing inside the main body of the blade. On the end of the shaft inside the main blade, a construction is fixed, which rotates the blade tip if subject to an outward movement. The shaft also has a fixture for a steel wire, running the length of the blade from the shaft to the hub, enclosed inside a hollow tube.

During operation the tip is held fast against the main blade by a hydraulic cylinder inside the hub, pulling with a force of about 1 ton on the steel wire running from the hub to the blade tip shaft.

When it is becomes necessary to stop the wind turbine, the restraining power is cut-off by the release of oil from the hydraulic cylinder, thereby permitting centrifugal force to pull the blade tip outwards. The mechanism on the tip shaft then rotates the blade tip through 90 degrees, into the braking position. The hydraulic oil outflow from the hydraulic cylinder escapes through a rather small hole, thus allowing the blade tip to turn slowly for a couple of seconds before it is fully in position. This thereby avoids excessive shock loads during braking.

As previously described in the section on the hydraulic system, the construction set-up is fail-safe requiring an active component (oil pressure) in order to keep the turbine in an operational mode, while a missing active component (no oil pressure) activates the system.

The tip brakes effectively stop the driving force of the blades. They therefor have the function as described under point 1 in the section dealing with problems - to prevent the blades having a greatly increased power production with increased rotational speed. They cannot however normally completely stop blade rotation, and therefore for every wind speed there is a corresponding free-wheeling rotational speed. However even for the highest wind speeds experienced in Denmark, the free-wheeling rotational speed is much lower than the normal operational rotational speed, so the wind turbine is in a secure condition, even if the mechanical brake should possibly fail.

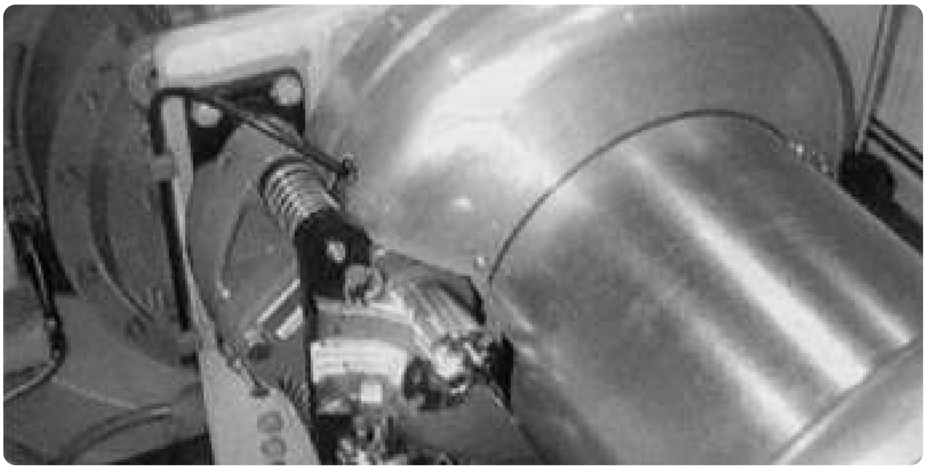
Tip brake in function

THE MECHANICAL BRAKE

The Mechanical brake is a disc brake placed on the gearbox high-speed shaft. The brake disc, made of steel, is fixed to the shaft. The component that does the actual braking is called the brake caliper. Likewise this is also a fail-safe system, hydraulic oil pressure is necessary to prevent the brake unit from braking. Should oil pressure be lacking, a powerful spring presses the brake blocks in against the brake disc.

Braking is a result of friction between the brake block and the disc. Wind turbine brakes experience large stress forces, therefore it is necessary to use special materials for brake blocks on large wind turbines. These are made of a special metal alloy, able to function under high temperatures of up to 700 degrees Centigrade. By comparison, the temperature of the brakes on a car rarely exceed 300 degrees.

The mechanical brake function is as described under point 2 of the section dealing with the possible problem situations - to prevent the rotational speed of the blades from increasing above the rated rotational speed.



The Mechanical Brake

BONUS®
Energy A/S

A/S reg. nr. 67.911
Fabriksvej 4 • box 170
7330 Brande
Tlf: 97 18 11 22
Fax: 97 18 30 86
E-mail: bonus@bonus.dk
Web: www.bonus.dk