SYSTEM AND METHOD FOR COMPENSATING ROTOR IMBALANCE IN A WIND TURBINE

Abstract: Method for compensating rotor imbalance in a wind turbine. The wind turbine comprises a rotor and a mast, wherein said rotor comprises a rotor shaft that is provided with an n number of rotor blades. A blade pitch angle of each rotor blade can be individually adjusted by a respective actuator. The method comprises closed-loop repetition of the following steps: - determining and monitoring loads of the wind turbine with the use of a sensor circuit; monitoring a set blade pitch angle for each of the rotor blades by means of a blade pitch sensor of the wind turbine; - determining a quantity indicative of rotor imbalance, based upon the recorded loads; - determining at least one correction value for influencing the aerodynamic conversion of at least n-1 rotor blades so that the contribution of loads on all of the rotor blades collectively on the quantity indicative of rotor imbalance is minimized; effectuating at least one specific corrective value for influencing the aerodynamic conversion of the at least n-1 rotor blades.

Fig 1

The figure shows a schematic representation of a wind turbine with labeled parts for the rotor, blade, actuator, and sensor circuit. The rotor comprises multiple blades, and the blade pitch angles are adjustable by actuators. The sensor circuit monitors the loads and affects the pitch angles to minimize imbalance.
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System and method for compensating rotor imbalance in a wind turbine

The present invention relates to a method for compensating rotor imbalance in a wind turbine. The invention also relates to a system for compensating rotor imbalance in a wind turbine. In addition, the invention relates to computer software for implementing said method.

A wind turbine comprises a rotor provided with a number of rotor blades. The rotor is coupled by means of a shaft to an electric generator, possibly via some form of transmission. The electric generator is provided with an output for the output of electrical energy, for example through a power converter to an electricity network. The assembly of rotor, transmission, generator and power conversion unit are arranged in a nacelle on a mast.

Wind turbines always show some rotor imbalance due to deviations in the profile and mass properties of the rotor blades, as well as differences in the blade pitch when the rotor is assembled. The differences in profile characteristics and differences in blade pitch when assembled, result in an aerodynamic imbalance. The differences in mass properties lead to a mass imbalance. The forces and moments resulting from imbalance turn along with the rotation of the rotor.

Among other things, the rotor imbalance results in alternating loads being exerted on the static components. These varying loads are exerted periodically in the azimuth angle of the rotor and are designated as Ip variations that have a period of once every rotation, i.e. they have the same frequency (Ip) as the rotation of the rotor. This therefore leads to variations in the tilting and yaw moments and in the vertical and horizontal forces exerted on the nacelle. In order for the wind turbine to resist these loads, the wind turbine needs to be designed 'heavier'.

In addition, variations in tilting Ip and yaw moments often interfere with control circuits, the aim of which is to reduce the blade moments generated by excitations from the flow, for example caused by tower sweeping and by windshear and turbulence, to frequencies in the range of Ip. These control circuits reduce blade loads at about Ip by making adjustments to blade pitch variations almost periodically to the usual course of the blade pitch; in a 3-bladed wind turbine these variations are each offset by 120 degrees. In fact, these blade pitch variations are achieved by Ip modulation of the arithmetically processed tilting and yaw moment. This operation, called a feedback or control law, comprises low-pass filtering, time integration and scaling. It now appears that Ip variations in the tilting and yaw moment can lead to amplified 2p variations (with the double frequency of Ip variations) in the ultimate blade moments. This is then associated with increased 3p variations (with the triple frequency of the Ip-variation) in the tilting and yaw moment.
It is known that the mass imbalance of the rotor can be decreased by static balancing. This is difficult and never fully effective in the dynamic situation during operation, for example due to the occurrence of blade distortions under the effects of the forces of air flow. Also, there is no method available for effectively compensating varying loads in real-time conditions that are caused by aerodynamic imbalance due to the combined effects of variable rotations and fluctuating wind speeds.

It is an objective of the invention to provide a system that mitigates or eliminates one or more of the drawbacks related to the compensation of the rotor imbalance, as known from the prior art.

This object is achieved by applying a method for compensating rotor imbalance in a wind turbine, wherein the wind turbine comprises a rotor and a mast, wherein the rotor comprises a rotor shaft that is provided with an n number of blades, wherein the rotor shaft is connected to a top section of the mast and wherein a pitch of each rotor blade is individually adjustable by means of a respective actuator; wherein the method comprises the execution in real-time of the following steps repeatedly when in use:
- determining and monitoring loads of the wind turbine with the use of a sensor circuit for sensing bending moments in the rotor shaft;
- monitoring a set blade pitch for each of the rotor blades by means of a blade pitch sensor of the wind turbine.

- determining the (progressive) average bending moments on the rotor shaft as a quantity indicative of rotor imbalance based upon the monitored loads;
- determining at least one correction value for influencing the aerodynamic conversion of at least n-1 rotor blades by minimizing the (progressive) average of the bending moment values so that the contribution of loads on all of the rotor blades collectively on the quantity indicative of rotor imbalance is kept to a minimum, wherein the determination of at least one correction value for influencing the aerodynamic conversion of at least n-1 blade comprises feedback of the quantity indicative of rotor imbalance as an adjustment of said at least one correction value of at least n-1 rotor blades via an inverse of trigonometric relationships between deflection moments in the rotor blades and bending moments in the rotor shaft, wherein the feedback from the quantity indicative of rotor imbalance comprises low-pass filtering, time integration and scaling;
- effectuating the at least one specific corrective value for influencing the aerodynamic conversion of the at least n-1 rotor blades.

In an advantageous manner, the forces exerted on each of the rotor blades can be equalized as much as possible, so that a reduction of the rotor imbalance can be achieved under dynamic operating conditions. The invention also enables the exclusion of static balancing or even for it to be performed in a simplified manner, as a result of which the installation of the wind turbine can be carried out with less effort.
In one embodiment the method according to the invention comprises measuring the bending moments as averages without an absolute offset.

In one embodiment the method according to the invention comprises the feedback of the quantity indicative of rotor imbalance, comprising the execution of mathematical operations in accordance with a control law according to a method applied in modern control theory, selected from a group comprising Robust Control, Linear Quadratic Regulation (LQR), Linear Quadratic Gaussian control (LQG), H-infinite control ($H_{\infty}$) and $\mu$-synthesis.

In one embodiment, the method according to the invention comprises at least one correction value for influencing the aerodynamic conversion that relates to a control signal for adjusting a blade pitch value, and effectuating the at least one specific correction value for the transmission of the control signal to the actuator of the respective rotor blade.

In one embodiment the method according to the invention comprises determining and monitoring loads, when said wind turbine is in use, comprising measuring bending moment values in a cross-section of the rotor shaft along two non-parallel vectors.

In one embodiment the method according to the invention includes the wind turbine, further comprising a yaw bearing for pivotally connecting at least the rotor and the mast, wherein the determination of imbalance forces, when said wind turbine is in use, comprises determining a tilt moment and a yaw moment at the yaw bearing.

In one embodiment the method according to the invention comprises the wind turbine, further comprising a yaw bearing for pivotally connecting at least the rotor and the mast, wherein the determination of imbalance forces, when said wind turbine is in use, comprises determining a tilt moment at the yaw bearing.

In one embodiment the method according to the invention comprises measuring a vertical and laterally exerted force in the top of the mast.

In one embodiment the method according to the invention comprises the measurement of at least a rotational acceleration along a direction vector in a plane defined by a vertical and lateral direction vector.

In one embodiment the method according to the invention comprises the measurement of at least a translational acceleration along a direction vector in a plane defined by a vertical and lateral direction vector at some distance from the centre of the top of the mast.

In one embodiment, the method according to the invention includes the wind turbine comprising a nacelle, and the nacelle comprises the rotor shaft and is coupled to the mast via the yaw bearing and wherein the determination of the tilt moment and the
yaw moment at die yaw bearing comprises measuring accelerations at the nacelle in the vertical and horizontal plane at some distance from the centre of the top of the mast.

In one embodiment, the method according to the invention includes the wind turbine comprising a nacelle, and the nacelle comprises the rotor shaft which is coupled to the mast via the yaw bearing and wherein the determination of the tilt moment at the yaw bearing comprises measuring accelerations at the nacelle in the vertical and horizontal plane at some distance from the centre of the top of the mast.

In one embodiment the method according to the invention includes the wind turbine comprising a nacelle, and the nacelle comprises the rotor shaft and is coupled to the mast via the yaw bearing and wherein the bending moments are determined as averages without absolute offset, based upon a measured nacelle acceleration perpendicular to the rotor plane and upon measured blade deflection moments that are not necessarily offset-free.

In one embodiment the method according to the invention comprises that a sensor circuit is selected from a group of at least one sensor and a combination of sensors.

Furthermore, the invention relates to a computer system for compensating rotor imbalance in a wind turbine, wherein the wind turbine comprises a rotor and a mast, wherein the rotor comprises a rotor shaft that is provided with an n number of rotor blades, wherein the rotor shaft is coupled to a top section of the mast and wherein a blade pitch of each rotor blade is individually adjustable; wherein the wind turbine is provided with at least one sensor for monitoring forces and blade pitch sensors for monitoring a set blade pitch for each of the rotor blades;

wherein the computer is provided with a central processing unit and memory, wherein the memory is linked to the processing unit and wherein the processing unit is linked to the sensors, wherein the computer is arranged, when the wind turbine is in use, to repeat the following operations:
- determining and monitoring loads of the wind turbine with the use of a sensor circuit for sensing bending moments in the rotor shaft;
- monitoring a set blade pitch for each of the rotor blades by means of a blade pitch sensor of the wind turbine.
- determining the (progressive) average bending moments on the rotor shaft as a quantity indicative of rotor imbalance based upon the monitored loads;
- determining at least one correction value for influencing the aerodynamic conversion of at least n-1 rotor blades by minimizing the (progressive) average of the bending moment values so that die contribution of loads on all of the rotor blades collectively on the quantity indicative of rotor imbalance is kept to a minimum, wherein the determination of at least one correction value for influencing the aerodynamic conversion of at least n-1 blade comprises feedback of the quantity indicative of rotor imbalance as an adjustment
of said at least one correction value of at least n-1 rotor blades via an inverse of trigonometric relationships between deflection moments in the rotor blades and bending moments in the rotor shaft, wherein said feedback from the quantity indicative of rotor imbalance comprises low-pass filtering, time integration and scaling;

- effectuating the at least one specific corrective value for influencing the aerodynamic conversion of the at least n-1 rotor blades.

The invention further relates to computer software stored on a computer-readable medium for compensating rotor imbalance in a wind turbine, wherein the wind turbine comprises a rotor and a mast, wherein the rotor comprises a rotor shaft that is provided with an number of rotor blades, wherein the rotor shaft is coupled to a top section of the mast and wherein a blade pitch of each rotor blade is individually adjustable; wherein the wind turbine is provided with at least one sensor for monitoring forces and blade pitch sensors for monitoring a set blade pitch for each of the rotor blades; wherein the computer is provided with a central processing unit and memory, wherein the memory is linked to the processing unit and wherein the central processing unit is linked to the sensors, wherein the computer software comprises executable code which, when loaded on the computer, enables the computer to repeatedly execute in real-time the following operations when the wind turbine is in use:

- determining and monitoring loads of the wind turbine with the use of a sensor circuit for sensing bending moments in the rotor shaft;
- monitoring a set blade pitch for each of the rotor blades by means of a blade pitch sensor of the wind turbine;
- determining the (progressive) average bending moments on the rotor shaft as a quantity indicative of rotor imbalance, based upon the monitored loads;
- determining at least one correction value for influencing the aerodynamic conversion of at least n-1 rotor blades by minimizing the (progressive) average of the bending moment values so that the contribution of loads on all of the rotor blades collectively on the quantity indicative of rotor imbalance is kept to a minimum, wherein the determination of at least one correction value for the aerodynamic effect of conversion of at least n-1 blade comprises feedback of the quantity indicative of rotor imbalance as an adjustment of said at least one correction value of at least n-1 rotor blades via an inverse of trigonometric relationships between deflection moments in the rotor blades and bending moments in the rotor shaft, wherein said feedback from the quantity indicative of rotor imbalance comprises low-pass filtering, time integration and scaling;

- effectuating the at least one specific corrective value for influencing the aerodynamic conversion of the at least n-1 rotor blades.

In one embodiment, the computer software according to the invention comprises determining at least one correction value for influencing the aerodynamic conversion of at
least n-1 rotor blades comprising the use of either a method of approximation or method of reconstruction.

The invention further relates to a computer-readable medium that comprises computer executable code which, when loaded on the computer system, enables the computer, as described above, to execute the method as described above.

Further embodiments according to the present invention are described in the subsequent claims.

The invention will now be described in further detail with reference to several drawings illustrating exemplary embodiments thereof. The drawings are intended exclusively to illustrate the objectives of the invention and not to restrict the scope of the invention, which is defined by the appended claims.

In the drawings:
figure 1 shows a schematic view of a wind turbine provided with a system in a first embodiment;
figure 2 shows a schematic view of a wind turbine provided with a system in a second embodiment;
figure 3 shows a schematic view of a wind turbine provided with a system in a third embodiment;
figure 4 shows schematic orientations of loads possibly occurring in the wind turbine;
figure 5 shows a flow diagram for a method according to one embodiment, and
figure 6 shows a schematic view of a computer for executing computer software in accordance with the method according to one embodiment.

In the following figures, the same reference numerals refer to corresponding components in each of the figures.

Figure 1 shows a schematic view of a wind turbine 1a. Wind turbine 1a comprises a rotor R with a rotor shaft provided with a number of rotor blades B. The rotor R is coupled to a transmission T for attaching the rotor shaft to an electric generator G by means of the rotor shaft. The electric generator G is provided with an output for the output of electrical energy, for example through a power converter (not shown) to an electricity network. The assembly of rotor R, transmission T and generator G is located in a nacelle L on a mast M. The assembly of rotor R, transmission T and generator G is pivotally connected to the mast M by means of a yaw bearing KS that constitutes part of a yaw system KS. It will be understood that the transmission T may be excluded when the rotor shaft is coupled directly to the generator, i.e. in the case of a low-speed generator.

The wind turbine 1 is adjustable by means of a number of parameters in order to achieve an optimal efficiency under certain arbitrary conditions, wherein the parameters are related to the parts R, B, K, G shown and mentioned here in figure 1. Other
parameters could possibly also be of importance, such as would be known to a person skilled in the field.

The present invention provides the insight that Ip variations in the static components of the wind turbine as a result of rotor imbalance can be eliminated by influencing the aerodynamic conversion (the conversion at the rotor blades of energy from the area of sweep to rotational energy of the rotor) of each individual rotor blade. A condition is that the aerodynamic conversion of each rotor blade can be influenced separately. The aerodynamic conversion can be influenced by rotating the rotor blade along a longitudinal axis and by controlling the blade pitch. The blade pitch of each rotor blade B is adjustable so that a power absorbed from the flow of air by the wind turbine can be controlled. The adjustment of blade pitch by means of an adjustment control system, for example by means of actuators (shown schematically for the upper rotor blade by arrow A1) can be implemented in the blade root of each rotor blade, but also halfway along the longitudinal axis. In essence, any method for influencing the aerodynamic conversion is suitable, as long as the deflection moment in the blade root can be significantly adjusted. The deflection moment is defined as the moment of force in a rotor blade, the vector of which is directed perpendicular to the plane in which the rotor shaft and the longitudinal axis of the rotor blade lie. A sensor SO on each rotor blade is linked to the blade pitch adjustment system for monitoring a set blade pitch value.

The yaw system K is arranged pivotally around a yaw bearing KS in order to adjust the position of the rotor R relative to the horizontal direction of the flow of air.

The power converter is provided with an electrical control system that is arranged to control the electric power and rotational speed characteristic of the generator G.

In the first embodiment of the system, each rotor blade is provided with a sensor S1 attached to the blade root in close proximity to the rotor shaft for monitoring a value of the deflection moment in the respective rotor blade. Additionally, in a further embodiment the radial and tangential force in the root of the respective rotor blade can also be measured.

An anemometer W is positioned next to the wind turbine Ia.

Figure 2 shows a schematic view of a wind turbine Ib provided with a system in a second embodiment.

In the second embodiment of the system, the rotor shaft of the wind turbine Ib is provided with a sensor S2 for detecting bending moments in the rotor shaft.

Figure 3 shows a schematic view of a wind turbine Ic provided with a system in a third embodiment.

In the third embodiment of the system, the yaw bearing KS of the wind turbine Ic is equipped with a sensor S3 for monitoring the tilting and yaw moment, wherein the tilt
moment vector lies on the horizontal plane and is perpendicular to the shaft and the yaw moment vector in the vertical plane parallel to the mast.

In addition, or alternatively, the system can be provided with one or more acceleration sensors S4 for conducting acceleration measurements from which tilting and yaw moments can be deduced. An acceleration measurement, for example, can be performed by measuring the vertical and lateral nacelle acceleration at a certain distance, in the direction of the rotor R, from the centre of the top of the mast. Both here and in the following description, 'lateral' is designated as a direction in the horizontal plane, perpendicular to the rotor shaft.

Additionally, in a further embodiment, the vertical and lateral force on or close to the yaw bearing can be measured (for example, by sensor S3), or the vertical and lateral acceleration in a second position on the nacelle (for example, by sensor S4).

A condition in the first embodiment is that the signals recorded from the rotor blades are measured without any individual offset. An offset in the measurement results in the minimization of the sum of the actual imbalance and offset. This means that this offset, when compensation is activated, ultimately becomes effective as rotor imbalance.

For the measured values recorded on the rotor shaft in the second embodiment, the bending moments are measured as averages without applying any absolute offset. For the measured values recorded at the yaw bearing in the third embodiment, the amplitudes of the Ip variations are both measured offset-free.

If the measuring signals in the second and third embodiment do not meet the above-mentioned respective conditions, then an effect will occur in both embodiments, during active compensation, similar to that described in the first embodiment.

Figure 4 shows, schematically, orientations in a wind turbine of any loads that may occur.

The mast M has a vertical orientation O1. The KRM vector of the yaw moment is given in the top of the mast, which is directed along the vertical orientation O1. The vector for the tilt moment TM is directed in the lateral direction (designated by O2, which is perpendicular to the vertical orientation O1 and the rotor shaft RA). The rotation vector RV is directed along the rotor shaft RA. In addition, one rotor blade B is shown. In rotor blade B, the radial force FR (exerted on the rotor centre RC) is directed along the longitudinal axis LA of the rotor blade B. The tangential force FT (exerted on the rotor centre RC) is directed perpendicular to the radial force FR in the plane of the rotor. The vector KL of the deflection moment in the blade root of the rotor blade B is directed perpendicular to the longitudinal axis LA of the rotor blade B.
Figure 5 shows a flow diagram for a method 100 according to one embodiment. When the turbine is started, or after receiving an initialization signal, a cyclic algorithm is activated with an indicative cycle time or period time of 0.1s. This then initiates a first step 105 for initializing, among other things, the adjustments to the control signals for the blade pitches.

Subsequently, in step 110, a measurement is conducted of the deflection moments and possibly the radial and tangential forces in the blade roots (first embodiment Ia; use of sensor S1), or the bending moments in the rotor shaft (second embodiment Ib; use of sensor (S2), or the tilting and yaw moment and the rotor pitch and possibly the vertical and lateral force exerted on the yaw bearing (third embodiment Ic; use of a combination of sensors (S3, S5) or (S4, S5)).

Then, in step 120, the bending moment values are determined along two vectors perpendicular to each other in the cross-section of the rotor shaft; one of these vectors is parallel to the longitudinal axis of the rotor blade selected for the rotor pitch. These bending moments in embodiment Ia are derived from the measured loads and the rotor geometry, as well as the distance from the rotor centre to the center of the cross-section where the radial and tangential forces also be measured. In embodiment Ib the desired bending moments then result from the measurements and the orientation of the vectors along which measurements are conducted in relation to the vectors of the desired bending moments.

In the third embodiment Ic, the bending moments are deduced from the tilting and yaw moment and the value of the rotor pitch, as well as the distance from the yaw bearing to the cross-section if the vertical and lateral force exerted on the yaw bearing is also measured.

In step 130 the bending moment values thus obtained are converted to desired adjustments to the blade pitches from the geometry of the two direction vectors for the bending moments in relation to those of the rotor. This is done with the aim of adjusting the aerodynamic load of the individual rotor blades in such a manner that the (progressive) mean of the bending moments is minimized whilst retaining the quantity of energy generated by the wind. In this respect, the invention is based upon the principle that a relatively small change to a blade pitch of a rotor blade results in a substantially proportional change of the load exerted on the rotor blade by the wind. The conversion of bending moments to adjustments to the blade pitches (feedback) comprises the inverse of the trigonometric relationships for deducing shaft bending moments from blade deflection moments, as incorporated in the later presented example of an algorithm. In addition, the feedback comprises low-pass filtering, time integration and scaling for minimizing the (progressive) mean value of the bending moments via low-frequency adjustment of the blade pitches. Minimum mean bending moments in the shaft automatically imply
minimum rotor imbalance. The blade pitches are adjusted to a time-scale that is greater than approx. three times the cycle time of the rotor.

In step 140, the desired adjustments to the blade pitches derived from step 130 are converted to control signals for the appropriate adjustment of the blade pitches. If a desired adjustment is not possible in connection with the range of a blade pitch, all adjustments are amended with the same, smallest possible offset that does not lie beyond this range. As a result of this offset, the imbalance compensation will have some slight effect on the energy extracted from the wind. It is also possible not to adjust the pitch of one of the blades. Here, the imbalance compensation will generally have a greater effect on the energy extracted from the wind.

In step 150, one first waits till the cycle time has lapsed, after which step 110 is repeated. This is not done after a re-initialization signal 152, after which step 105 is executed, and after a stop signal 154, after which the method is completed by step 160. Below is an explanation of the method applied to compensate rotor imbalance of the wind turbine, before an example of an algorithm is given.

The objective of the imbalance compensation, for example, is to minimize the Ip variations in the tilting and yaw moment at the position of the yaw bearing. The rotor centre is located at some distance from the yaw bearing KS. The rotor centre is understood to be the point of the rotor R where the rotor blades B meet and are coupled to each other. In one embodiment, the method provides for feedback control for compensation by adjusting the blade pitches based on measurements of load signals in the root of each rotor blade. Based on the measurements of the deflection moments and radial and tangential forces, the bending moment values are determined along two vectors in the (fictive) cross-section of the rotor shaft at the position of the yaw bearing. The rotor imbalance results in mean values of the bending moments that are unequal to zero due to the deflection moments via the trigonometric relationships arising from the rotor geometry and the momentum that arises from the radial and tangential forces as a result of not coinciding with rotor centre and yaw bearing. (Moment is the exerted force multiplied by the arm. The arm is defined as the distance between rotor centre and yaw bearing).

In the method described, these bending moments are averaged to zero, as described in step 130. As a result, the Ip variations in the tilt and yaw moment are eliminated at the yaw bearing. The deflection moments and the radial and tangential forces on the three blades will not generally be precisely equal; this will not lead to any Ip variations in the tilt and yaw moment.

It will be clear that an embodiment in which measurements of the tilt and yaw moment are translated into bending moment values through the rotor pitch will result in virtually the same compensation of rotor imbalance.
When measurements of deflection moments are applied for reducing lp-blade variations in the blade load, it is then preferable that the compensation control makes the deflection moments on average equal to each other. By now considering the bending moment values along two vectors in the cross section of the rotor shaft at the position of the rotor centre, the compensation is no longer 'distributed' over the deflection moments and radial and tangential forces, but instead the deflection moments are made purely equal to each other whilst the radial and tangential forces are an (uncontrolled) effect of this 'imbalance of deflection moments'; this is due to the fact that blade forces have no effect on the bending moments in the rotor shaft in the rotor centre. This method of compensating imbalance is achieved in an embodiment wherein the bending moments are only deduced from the deflection moments via the trigonometric relationships that result from the rotor geometry.

An embodiment is also conceivable, wherein the bending moments in the rotor centre are measured directly on the shaft.

A third embodiment is also conceivable, wherein the bending moments at the rotor centre are composed from measurements of the tilt and yaw moment and the lateral and vertical force at the yaw bearing via the rotor pitch and the distance between the yaw bearing and rotor centre.

An example will now be discussed of an algorithm for compensating rotor imbalance that corresponds to the method according to the present invention. In the example of an algorithm that now follows, a wind turbine is considered with three rotor blades all of which are arranged in a single rotor plane. The rotor blades are each offset at 120 degrees within the rotor plane. Furthermore, a choice was made to influence the aerodynamic conversion by rotating each of the three rotor blades along the respective longitudinal axis of the rotor blade and to regulate the blade pitch. The blade pitches are designated as $\theta_1$, $\theta_2$ and $\theta_3$ for the first, second and third rotor blades respectively.

In this particular embodiment the bending moment values on the rotor shaft are calculated on the basis of measurements of the deflection moment in the root of each of the rotor blades with the aid of the measuring sensor S1 for measuring the deflection moment of the respective rotor blade.

A wind load exerted on a rotor blade that is directed perpendicular to the rotor plane causes a deflection moment in the rotor blade. The deflection moment is designated as $Mk_1$, $Mk_2$ and $Mk_3$ for the first, second and third rotor blade respectively.

The following trigonometric relationships apply to the bending moment values $Mb_1$ and $Mb_2$ with the deflection moments $Mk_1$, $Mk_2$, $Mk_3$ ($^\circ$ stands for degrees):
\[ M_{bi} = M_{k1} \cos(0^\circ) + M_{k2} \cos(120^\circ) + M_{k3} \cos(240^\circ) \quad [Ia] \]
\[ M_{b2} = M_{k1} \sin(0^\circ) + M_{k2} \sin(120^\circ) + M_{k3} \sin(240^\circ) \quad [Ib], \]

wherein \( M_{bi} \) is the bending moment along a direction vector that coincides with the rotation of the rotor that points in the direction of the longitudinal axis of the first rotor blade, and wherein \( M_{b2} \) is the bending moment along a direction vector perpendicular to the above-mentioned direction vector of bending moment \( M_{bI} \).

Variations in the blade pitches result in variations in the deflection moments, which are approximately proportional hereto. The following then applies to variations the deflection moment \( \Delta M_{ki} \) and variations in the blade pitch \( \Delta \theta_i \) (\( i=1,2,3 \)):

\[ \Delta M_{ki} = C x \Delta \theta_i \quad [2], \]

wherein \( C \) is a proportional constant, also designated as a process gain factor.

The blade pitch variations \( \Delta \theta_1, \Delta \theta_2 \) and \( \Delta \theta_3 \) are composed of 'virtual' variations \( \Delta \theta_{b1} \) and \( \Delta \theta_{b2} \):

\[ \Delta \theta_1 = \Delta \theta_{b1} \cos(0^\circ) + \Delta \theta_{b2} \sin(0^\circ) \quad [3a] \]
\[ \Delta \theta_2 = \Delta \theta_{b1} \cos(120^\circ) + \Delta \theta_{b2} \sin(120^\circ) \quad [3b] \]
\[ \Delta \theta_3 = \Delta \theta_{b1} \cos(240^\circ) + \Delta \theta_{b2} \sin(240^\circ) \quad [3c] \]

Via equations [2], [3a], [3b], [3c] the variations \( \Delta M_{b1}, \Delta M_{b2} \) in the bending moments \( M_{b1}, M_{b2} \) then follow:

\[ \Delta M_{b1} = 3/2 \times C \times \Delta \theta_{b1} \quad [4a] \]
\[ \Delta M_{b2} = 3/2 \times C \times \Delta \theta_{b2} \quad [4b] \]

In this embodiment the algorithm for the method comprises:
- determining the bending moments \( M_{b1}, M_{b2} \) derived from deflection moments \( M_{k1}, M_{k2}, M_{k3} \) with the aid of the equation [Ia], [Ib];
- mapping of \( M_{b1}, M_{b2} \) to virtual blade pitch variations \( \Delta \theta_{b1}, \Delta \theta_{b2} \) via a control law;
- applying blade pitch variations \( \Delta \theta_1, \Delta \theta_2, \Delta \theta_3 \) based upon \( \Delta \theta_{b1}, \Delta \theta_{b2} \) on the blade pitch \( \theta_1, \theta_2, \theta_3 \) of the respective rotor blade ([3a], [3b], [3c])

In one embodiment the control law for the mapping (feedback) of \( M_{b1}, M_{b2} \) to \( \Delta \theta_{b1}, \Delta \theta_{b2} \) basically comprises an algorithm based on a time integer:

\[ \Delta \theta_{b1}(t) = \Delta \theta_{b1}(t - \Delta t) + K \times M_{b1}(t) \times \Delta t \quad [5a] \]
\[ \Delta \theta b_2(t) = \Delta \theta b_2(t - \Delta t) + K \times M b_2(t) \times \Delta t \]  
[5b],

where \( K \) is a 'controller gain factor' and \( \Delta t \) is a cycle time for the algorithm.

Over time, this average value is essentially equal to zero due to the feedback of the time integer from the measurement signal. This is a result familiar to experts in the field. It will be clear that the 'controller gain factor \( K \)' will need to be adjusted to the process gain factor \( C \) in equation 4.

The control applied has a low frequency: a frequency for adjusting the set blade pitch of each rotor blade according to the specific blade pitch adjustment is lower than the frequency of the component varying in time. The choice of the controller gain \( K \) in relation to the process gain \( C \), in conjunction with low-pass filtering ensures that the control according to the invention is active on a time scale much larger than the rotation time of the rotor.

It should be noted that the algorithm comprises at least: (i) a control law for mapping the bending moment values to virtual blade pitch variations and (ii) a trigonometric translation of these virtual blade pitch variations into true variations on the three blade pitches (i.e. the respective blade pitch of each of the rotor blades).

Alternatively, instead of adjusting the three blade pitches, similar options can be applied to influence the aerodynamic conversion of the three rotor blades, such as synthetic jets, micro-tabs, flaps.

In the algorithm, the feedback of bending moments to virtual blade pitch variations, such as those according to [5a], [5b], can basically be subjected to any arithmetic operation (in the form of a control law).

In these cases, preference is given to certain classes of arithmetic operations. A proper function is achieved, for example, by allowing the time integer to be preceded by low-pass filtering. In addition, control laws that follow the modern control theory are applied, such as regulator design techniques based upon minimizing a quadratic criterion such as LQR (Linear Quadratic Regulator) and LQG (Linear Quadratic Gaussian), and further to this, the Robust Control technique and techniques based on minimizing the so-called Hoc-standard and refinements thereof, such as \( \mu \)-synthesis.

The control law of the algorithm can be implemented in a processing computer or similar digital technology, but it is not restricted thereto; it is sometimes possible to implement the control law using analogue electronics via capacitors, coils, resistors etc. An embodiment of a processing computer will be described below with reference to figure 6.

The bending moment values are reconstructed from measurements of deflection moments, possibly in conjunction with measurements of radial and tangential forces on
the blade root of each rotor blade using a respective measuring sensor Sl. Alternatively, the bending moment values can be measured directly on the rotor shaft by using one or more measuring sensors S2.

In one embodiment the bending moment values can be deduced by measurements of the tilting and yaw moment in the top of the mast by applying one or more sensors S3; no measurement values of the vertical and lateral force on the yaw bearing are used. The tilt moment is designated as $M_{til}$ and the yaw moment as $M_{yaw}$ whereas the vertical and lateral force is designated by $F_{vert}$ and $F_{lat}$. The horizontal distance from the top of the mast to the cross section of the shaft in which the bending moments are determined, is designated as $d$.

As a result of rotor imbalance $M_{til}, M_{yaw}, F_{vert}$ and $F_{lat}$ show Ip variations. Determination of the bending moment values of the rotor shaft from $M_{til}$ and $M_{yaw}, F_{vert}$ and $F_{lat}$ requires a trigonometric operation to be applied to the rotor pitch $\psi$ in relation to the horizontal plane, i.e. the time integer of the speed of rotation. The following then applies:

$$M_{b1} = \cos(\psi) \cdot (M_{til} + d \cdot F_{vert}) - \sin(\psi) \cdot (M_{yaw} - d \cdot F_{lat})$$

[6a]

$$M_{b2} = \sin(\psi) \cdot (M_{til} + d \cdot F_{vert}) + \cos(\psi) \cdot (M_{yaw} - d \cdot F_{lat})$$

[6b]

Because the Ip variations are of significance to $M_{til}$ and $M_{yaw}, F_{vert}$ and $F_{lat}$ as regards compensation of the rotor imbalance by the inertia of the rotor and the nacelle, or by directly deducing the loads from these; this is explained in more detail below.

Measured values of the tilt and yaw moment can also be derived from the measurement of at least one moment along an axis which lies in a plane defined by the direction vectors of the tilting and yaw moment, but which do not coincide with any of these direction vectors. The desired measurement values are then derived from the projections from the shaft along which measurements are conducted on shafts parallel to the direction vectors of the tilting and yaw moment.

Values of the vertical and laterally directed force can also be deduced from the measurement of at least one force along an axis which lies in the plane defined by the vertical and lateral direction vector but which does not coincide with any of these direction vectors.

It is clear that measurements of the vertical and laterally directed (translational) acceleration and the rotational acceleration in the tilting and yaw direction can be determined in a similar manner from acceleration measurements along one axis in such a vertical plane which does not coincide with the vertical or lateral direction vector.
By combining the moment and force measurements in the top of the mast (M) or the yaw bearing KS with acceleration measurements, a more relatively precise approximation can be made of the imbalance forces in the rotor. For example, the inclined tilting movement of the rotor and the nacelle, the ‘tilting’, consumes part of the imbalance forces through the moment of inertia \(J_{\text{tilt}}\) and the rotational acceleration \(\alpha_{\text{tilt}}\). The causal tilt moment \(M_{\text{tilt-ex}}\) is then deduced as follows from the measured tilt moment \(M_{\text{tilt}}\):

\[
M_{\text{tilt-ex}} = M_{\text{tilt}} + J_{\text{tilt}} \times \alpha_{\text{tilt}}
\]  

[7]

This causal tilt moment \(M_{\text{tilt-ex}}\) is then directly related to the imbalance forces. It will be clear that the causal tilt moment can be determined in a similar manner when measuring a vertical translational acceleration \(a_{\text{tran, vertical}}\) at a horizontal distance \(r\) from the yaw bearing:

\[
M_{\text{tilt-ex}} = M_{\text{a},i} + J_{\text{tilt}} \times a_{\text{vert}} / r
\]  

[8]

The vertical causal force \(F_{\text{vm-ex}}\) is then determined by measuring the vertical force \(F_{\text{inertial}}\) and the mass \(M_{\text{W}}\) of the nacelle and rotor in conjunction with the translational acceleration of the centre of gravity of the assembly of nacelle and rotor, wherein the nacelle also comprises the rotor shaft and generator. Assuming that this lies at a horizontal distance \(X_{\text{c}}\) from the yaw bearing and that \(a_{\text{veq}}\) is measured again at a distance \(r\), then the following methods of determination apply to \(F_{\text{vm-ex}}\):

\[
F_{\text{vert-ex}} = F_{\text{vert}} + M_{\text{W}} \times X_{\text{c}} \times a_{\text{vert}} / r
\]  

[9]

or

\[
F_{\text{vert-ex}} = F_{\text{vert}} + M_{\text{W}} \times X_{\text{c}} \times \alpha_{\text{tilt}}
\]  

[10]

This causal vertical force \(F_{\text{vert-ex}}\) is again directly related to the imbalance forces. Similar methods of determination apply to the values of the causal yaw moment \(M_{\text{yaw-ex}}\) and the causal lateral force \(F_{\text{lat-ex}}\), albeit that the lateral acceleration of the top of the mast now also comes into play. Let’s assume that this is also measured. Designate this lateral mast acceleration as \(a_{\text{lat}}\) \(\alpha_{\text{lat}}\), and a second measured value of the translational acceleration as \(a_{\text{lat}}\) (at distance \(r\)). A measurement of the rotational acceleration in the yaw direction is designated as \(\alpha_{\text{yaw}}\). The following methods of determination can then be applied:
The loads exerted in the yaw bearing can be determined by using methods of approximation based only on acceleration measurements. Three examples v1-v3 are given below:

v1. In the case of a freely yawing wind turbine, no yaw moment can be measured in the yaw bearing; this is always 0. The following then applies:

\[ M_{yaw,exc} = Myaw + Jyaw \times (a_{lat} - a_{lat, top}) / t \]  

[12];

\[ Flat_{exc} = Fiat + M W \times (a_{lat} - a_{lat, top}) / r \]

[13]

\[ Flat_{exc} = Flat + M W \times (a_{lat} - a_{lat, top}) / r \]

[14]

v2. There is no free yawing behaviour but the torsional rigidity of the mast is known; set this equal to \( s_{yaw} \). In good approximation the yaw moment in the top of the mast is equal to the product of \( s_{yaw} \) and a cumulative torsional rotation across the length of the mast. The latter can be approximated by the double time integer of the rotor acceleration in the direction of yaw. The following then applies:

\[ M_{yaw,exc} = Jyaw \times a_{yaw} \]

[15]

\[ M_{yaw,exc} = Jyaw \times (3|_t - a_{lat, top}) / r \]

[16]

v3. The rigidity of the tower for lateral displacement is known; set this equal to \( s_{lat} \). By approximation, the lateral force in the top of the tower is then equal to the product of \( s_{lat} \) and a cumulative lateral distortion across the length of the mast. The latter can be approximated by the double time interval of the lateral translational acceleration of the top of the tower. The following then applies:

\[ Myaw_{exc} = Syaw \times \int Oyaw X dt^2 d\tau + Jyaw X Oyaw \]

[17]

\[ Myaw_{exc} = Syaw X \int (a_{lat} - a_{lat, u,p}) / r X dt^2 d\tau + Jyaw X (a_{lat} - a_{lat, top}) / r \]

[18]
\[ F_{\text{lat,exc}} = s_{i_t} \times U_{\text{lat}} \times x \text{dt2xdtl} + M W \times x_{\text{lat-top}} + Xc \times (x_{\text{lat}} - x_{\text{lat,ref}})/r \] \[ \text{or} \]
\[ \text{Flat}_{\text{exc}} = \text{Slat} \times \int \alpha \times x \text{dt2xdtl} + M W \times X_{\text{lat-top}} + Xc \times x_{\text{yaw}} \]

In an embodiment, an estimator can also be based upon a fully dynamical turbine model that is included in a Kalman filter.

In one embodiment rotor imbalance is compensated on the basis of a determination method that is insensitive to measurement offset for two bending moment coordinates in the rotor shaft and a decoding method for determining the adjustments to the blade pitches derived from the geometry of the direction vectors of the two bending moments in relation to those of the rotor.

The intermediate feedback includes filtering, time integration and a scaling for minimizing the (progressive) mean value of the bending moments through low-frequency adjustment of the blade pitches.

The decoding operation comprises the inverse of the trigonometric relationships for determining shaft bending moments derived from blade deflection moments, as is later presented in an example of an algorithm. As included in this algorithm, the determination of 2 shaft bending moment coordinates consecutively comprises (i) an approximation of the axial force from the scaled sum of the deflection moments in the blade roots, (ii) an approximation of the tilt moment deduced from the collective effect on the measured forward-reverse movement of the tower of the previously determined axial force and the tilt moment itself, (iii) low-pass filtering of the tilt moment and (iv) determining two shaft bending moment coordinates along two direction vectors perpendicular to each other on the rotor shaft from the filtered tilt moment via the measured rotor position.

The bending moment coordinates thus determined are then subjected to at least low-pass filtering, time integration and scaling, after which adjustments of the blade pitches are determined according to the above-described decoding method.

Instead of performing an approximation of the axial force from deflection bending moments, an axial force measurement can be applied directly. However, bending moments are easier to measure and the rotor blades are generally already equipped with measuring sensors to do this, in view of the condition monitoring and reduction of \( I_p \) load variations on the rotor blades.

The measurement of the blade deflection moments are only used to abstract turbulence effects via axial force from the measured forward-reverse tower movement from which the tilt moment is derived. The axial force affects this tower movement, especially at frequencies well below \( I_p \), around the natural frequency of the first bending form, and at frequencies around multiples of the number of rotor blades. The arithmetic
origin of the Ip component in the approximated tilt moment now only lies in the measured forward-reverse movement of the tower. Acceleration sensors that can be used to conduct these measurements show no offset in the Ip component.

Furthermore, an offset in a measurement of a deflection moment is therefore not included in the blade pitch adjustments. This therefore prevents under-compensation or over-compensation.

The Ip-component contributes in both the tilting and the yaw moment to the average values of the shaft bending moments, which are a measure of rotor imbalance. The approximation of shaft bending moments from the Ip component of only the tilt moment results in average values which amount to half of the values obtained from both rotor moments. Moreover, disregarding the yaw moment results in a 2p component in the shaft bending moments. Both effects on the approximated shaft bending moments do not undermine the application of the method described for imbalance compensation if this is taken into account in the aforementioned scaling and filtering in the feedback.

An example will now be discussed of an algorithm for reconstructing or approximating the loads that cause rotor imbalance that corresponds to the method according to the present invention.

The following example of an algorithm a wind turbine is considered with three rotor blades in one rotor plane. The rotor blades are individually offset at 120 degrees in the rotor plane. Furthermore, a choice was made to influence the aerodynamic conversion by rotating each of the three rotor blades along the respective longitudinal axis of the rotor blade and to regulate the blade pitch. The blade pitches are designated as Th1, Th2 and Th3 for the first, second and third rotor blades respectively.

The bending moment values on the rotor shaft are calculated on the basis of the approximated tilting and bending moment on the rotor with the aid of measuring sensor S4 for the forward-reverse acceleration of the nacelle, measuring sensor S5 for monitoring the blade pitch and measuring sensor S1 for measuring the deflection moment of the respective rotor blade.

The tilt moment is approximated from the collective effect on the forward-reverse tower displacement of the approximated axial force and of the tilt moment itself. This is done on the basis of the displacement equation corresponding to the forward-reverse nacelle movement in the first bending form of the tower.

The deflection moment is designated as Mk1, Mk2 and Mk3 for the first, second and third rotor blade respectively; the forward-reverse acceleration of the nacelle is designated as afa; the rotor position as Psi. A variation in the approximated axial force, designated as ΔFax, is proportional to the sum of variations of the three deflection moments according to
\[ \Delta \text{Fax} = k \ast (\Delta \text{M}1 + \Delta \text{M}2 + \Delta \text{M}3) \] \[21\]

Here, \( \Delta \text{M}ki \) is the difference between the momentary measured value for \( \text{M}ki \) and a progressive average of a third of the sum of \( \text{M}k1 \), \( \text{M}k2 \) and \( \text{M}k3 \), for \( i = 1,2,3 \). \( k \) is a scaling factor.

The scaling factor \( k \) can be determined by a person skilled in the field of aerodynamic conversion using software customary in the wind turbine industry and depends on the progressive average values of wind speed, blade pitches of the rotor blades and the rotational speed of the rotor.

A customary displacement equation for the forward-reverse nacelle movement in the first bending form of the tower is as follows:

\[ m \ast afa + d \ast vfa + s \ast xfa = \Delta \text{Fax} - 3/2 \ast \text{MtiMT} \] \[22\]

Here, \( H \) is the tower height and \( m, d, s \) are the so-called tower top equivalent mass, damper constant and elasticity constant respectively.

For a skilled person in the field of constructional dynamics, these tower top equivalent parameters \( m, d, s \) can be determined by using software customary in the wind turbine industry. Only the damper constant \( d \) depends on the progressive average values of the wind speed, blade pitches of the rotor blades and rotational speed of the rotor. The remaining parameters may be assumed as being constant.

The variation \( \Delta \text{Mtilt} \) in the rotor tilt moment is approximated on the basis of the measured nacelle acceleration \( afa \) and the approximated axial force variation \( \Delta \text{Fax} \) based upon the aforementioned displacement equation according to

\[ \Delta \text{Mtilt} = \frac{2H}{3} \left[ \Delta \text{Fax} - m \ast afa - d \ast \int_{t-T}^{t} afa \, dt1 - s \ast \left( \int_{t-T}^{t} afa \, dt2 \, dt1 - ~ \text{xfa} \right) \right] \] \[23\]

Here, \(~ \text{xfa} \) is the progressive average forward-reverse nacelle position with time window \( T \). Therefore, no progressive average value is obtained for the tilt moment. However, this is not a drawback because only the \( \text{lp} \)-component of the rotor tilt moment is important for the compensation of imbalance.

The following trigonometric relationships apply to the bending moment values \( \text{Mb}1 \) and \( \text{Mb}2 \) with the approximated tilt moment variation \( \Delta \text{Mtilt} \) via the rotor pitch \( \Psi \):

\[ \text{Mb}1 = \Delta \text{Mtilt} \times \cos(\Psi) \] \[24a\]
Mb2 = -ΔM_{tilt} \times \sin(Psi) \quad [24b],

Here, MbI is the bending moment in the horizontal plane and Mb2 is the bending moment in the vertical plane for the rotor pitch of 0 or 180 degrees. It is evident that Ip component in ΔM_{tilt} results in the same mean value in MbI and Mb2, which will be half of the actual mean bending moment values. In addition, a 2p component in MbI and Mb2 will manifest as a 90 degree shift.

In order to understand this, the trigonometric relationships for the correlation between the shaft bending moments MbI and Mb2 and the deflection moments MkI, Mk2, Mk3 are also given:

\[
\begin{align*}
MbI &= \cos(0^\circ) \cdot MkI + \cos(120^\circ) \cdot Mk2 + \cos(240^\circ) \cdot Mk3 \quad [24c] \\
Mb2 &= \sin(0^\circ) \cdot MkI + \sin(120^\circ) \cdot Mk2 + \sin(240^\circ) \cdot Mk3 \\
\end{align*}
\]

Variations in the blade pitches lead to variations in the deflection moments which are proportional hereto. The following then applies to the variations of the deflection moment ΔM_{k_i} and variations of the blade pitch ΔT_{h_i} (i=1,2,3):

\[
\Delta M_{k_i} = C \times \Delta T_{h_i} \quad [25],
\]

where C is a proportional constant, also designated as a process gain factor.

The decoding method in the compounded blade pitch variations ΔT_{h_1}, ΔT_{h_2} and ΔT_{h_3} consists of 'virtual' variations ΔT_{hbl} and ΔT_{hbl2} according to the inverse of the trigonometric relationships for determining MbI, Mb2 from MkI, Mk2, Mk3:

\[
\begin{align*}
\Delta T_{h_1} &= \Delta T_{hbl} \times \cos(0^\circ) + \Delta T_{hbl2} \times \sin(0^\circ) \quad [26a] \\
\Delta T_{h_2} &= \Delta T_{hbl} \times \cos(120^\circ) + \Delta T_{hbl2} \times \sin(120^\circ) \quad [26b] \\
\Delta T_{h_3} &= \Delta T_{hbl} \times \cos(240^\circ) + \Delta T_{hbl2} \times \sin(240^\circ) \quad [26c] \\
\end{align*}
\]

Via equations [25], [26a], [26b], [26c] the variations ΔM_{bl}, ΔM_{b2} in the bending moments MbI, Mb2 then follow:

\[
\begin{align*}
\Delta M_{bl} &= 3/2 \times C \times \Delta T_{hbl} \quad [27a] \\
\Delta M_{b2} &= 3/2 \times C \times \Delta T_{hbl2} \quad [27b] \\
\end{align*}
\]
In this embodiment the algorithm for the method comprises:

- approximation of the axial variation \( \Delta \text{Fax} \) derived from deflection moment measurements \( \text{Mk1}, \text{Mk2}, \text{Mk3} \) with the aid of equation [21];
- approximation of the tilt moment variation \( \Delta \text{Mt\_tilt} \) derived from acceleration measurement \( f_a \) and axial force approximation \( \Delta \text{Fax} \) with the aid of equation [23];
- determining the bending moments \( \text{Mb1}, \text{Mb2} \) derived from the approximated tilt moment variation with the aid of the equation [24a], [24b];
- mapping of \( \text{Mb1}, \text{Mb2} \) to virtual blade pitch variations \( \Delta \text{Thbl}, \Delta \text{Thb2} \) via a control law
- applying blade pitch variations \( \Delta \text{Th\_1}, \Delta \text{Th\_2}, \Delta \text{Th\_3} \) based upon \( \Delta \text{Thbl}, \Delta \text{Thb2} \) on blade pitch \( \text{Th1}, \text{Th2}, \text{Th3} \) of the respective rotor blade ([26a], [26b], [26c]);

\[
\Delta \text{Thbl}(t) = \Delta \text{Thbl}(t - \Delta t) + K \times \text{Mb1\_f2p}(t) \times \Delta t \quad [28a]
\]
\[
\Delta \text{Thb2}(t) = \Delta \text{Thb2}(t - \Delta t) + K \times \text{Mb2\_f2p}(t) \times \Delta t \quad [28b],
\]

where \( K \) is a 'controller gain factor' and \( \Delta t \) is a cycle time for the algorithm and \( \text{Mb1\_f2p}, \text{Mb2\_f2p} \) are the proposed approximated shaft bending moment values after filtering the 2p component.

Over time, this average value is essentially equal to zero due to the feedback of the measurement signal.

It will be clear that the 'controller gain factor' \( K \) should be adjusted to the process gain factor \( C \) in equation [25] and the under-approximation of the average shaft bending moments, as indicated in equations [24a] and [24b].

The controller has a low frequency: The choice of the controller gain factor \( K \) in relation to the process gain factor \( C \), in conjunction with low-pass filtering and amplified filtering at about a 2p-frequency ensures that the system according to the invention operates on a time scale much larger than the rotation time of the rotor.

It should be noted that the algorithm comprises at least: (i) a method for the robust determination of the 1p component in the tilt moment on the rotor, (ii) a control law for mapping bending moment values to virtual blade pitch variations and (iii) a trigonometric translation of the virtual blade pitch variations into real-time variations on the three blade pitches (i.e. the respective blade pitch of each of the rotor blades).

The above described embodiment the bending moments are determined by average without absolute offset, based on a measured nacelle acceleration perpendicular to the rotor plane and measured blade deflection moments that are not necessarily offset-free.
Figure 6 shows schematic view of a computer for executing computer software in accordance with the method according to the invention.

The computer 8 comprises a central processing unit 21 with peripheral equipment. The central processing unit 21 is connected to memory means 18, 19, 22, 23, 24 which store instructions and data. Furthermore, the computer may have one or more reading units 30 (for example, to read floppy disks, CDROMs, DVDs, portable non-volatile memories, etc.), a keyboard 26, and a mouse 27 as input devices and output devices, a display 28 and a printer 29. Other input units, such as a trackball, a scanner and a touch screen, as well as other output devices, can be provided.

Furthermore, the central processing unit 21 can be provided with a network adapter 32 for data communications with a network 33. The network adaptor 32 is connected to the network 33. The network can be any network suitable for data communications. For example, the network can be a Local Area Network (LAN) or a Wide Area Network (WAN). Other computer systems can be linked to the network 33, which can communicate with the computer 8 via that network connection 32.

The memory means shown in Figure 6 comprise one or more means selected from RAM 22 (E) EPROM 23, ROM 24, tape unit 19, and hard disk 18. However, there may be more and/or other storage units provided, as will be clear to an expert in the field. Moreover, if necessary, one or more of the memory resources may be placed at a distance from the central processing unit 21.

The central processing unit 21 is shown as a single unit, but may also comprise various secondary processing units that operate in parallel or are controlled by a single central processing unit. These secondary processing units can be arranged at some distance from each other, as will be known to those skilled in this field.

The computer 8 comprises an interface 34 for receiving signals from one or more measuring sensors S1, S2, S3, S4, S5, which are arranged for measuring signals of the deflection moment and possibly the radial and tangential force in the root of each rotor blade (S1), two bending moments in a cross-section of rotor shaft (S2), the tilt and yaw moment and possibly any vertical and lateral force in the yaw bearing (S3) or the vertical and lateral acceleration in one or more locations at some distance from the yaw bearing (S4) and/or rotational acceleration in the tilting and yaw direction (S4), the rotation angle of the rotor (S5). The interface 34 is connected to the central processing unit 21.

The computer 8 also comprises an interface 35 for receiving a measuring signal of the selected blade pitch of each rotor blade from measuring sensor S0 and for transmitting control signals to each of the rotor blades for defining the blade pitches, as visualized in Figure 1 via actuator A1, or for controlling other devices for influencing the aerodynamic conversion, such as micro-tabs, flaps and synthetic jets. A choice can be made not to influence for just one of the rotor blades the aerodynamic conversion for compensating
imbalance, as is explained above. The interface 35 is connected to the central processing unit 21.

The computer 8 comprises functionality in hardware and/or software in order to execute the above method. The computer is equipped, or is operable in the way of computer software, to perform calculations in accordance with one or more of the aforementioned methods. Such computer software stored in or on a computer-readable medium, enables the computer, after being loaded from the computer-readable storage into the memory of the computer, to determine the first variable(s) and the second variable(s) according to the present invention.

In one embodiment the computer is a SCADA system (SCADA: supervisory command and data acquisition) that is suitable for data processing and analysis. And one embodiment the computer is arranged to execute the following method for compensating the rotor imbalance in a wind turbine when in use.

The processing unit of the computer is designed to receive signals with the aid of a measuring sensor (s) in order to translate rotor imbalance into controllable quantities, namely the (progressive) average bending moment values on the rotor shaft, as explained above. In doing so, the measuring sensor(s) record loads in the rotor blades and/or the yaw bearing.

Also, the processing unit is arranged to record measuring signals of a set blade pitch for each of the rotor blades by means of a respective blade pitch sensor SO of the wind turbine.

Subsequently, the processing unit is arranged to convert the bending moment values in the rotor shaft to desired adjustments to the blade pitches so that the aerodynamic conversion can be influences so that, essentially, rotor imbalance no longer occurs. This is achieved by minimizing the (progressive) average of the bending moment values.

Finally, die processing unit is designed to accommodate the actuators of each rotor blade to transmit a control signal for adjusting the pitch of each rotor blade according to the specified blade pitch adjustment.

It will be evident that the method and system according to the present invention can also be applied to wind turbines which have two or more than three rotor blades. To this end, only the trigonometric relationships need to be adjusted.

Alternative and equivalent embodiments of the present invention are conceivable within the scope of the invention, as will be apparent to those skilled in the art. The aim and scope of the invention is restricted only by the appended claims.
Claims

1. Method of rotor imbalance compensation in a wind turbine, wherein the wind turbine comprises a rotor (R) and a mast (M), wherein the rotor comprises rotor shaft that is provided with an \( n \) number of blades (B), wherein the rotor shaft is connected to a top section of the mast (M) and wherein a pitch of each rotor blade is individually adjustable by means of a respective actuator (AI), and wherein the method comprises the execution repeated in time of the following steps when said wind turbine is in use:

- determining and monitoring loads of the wind turbine (Ia; Ib; Ic) with the use of the sensor circuit (S1; S2; S3, S5; S4, S5) for sensing bending moments in the rotor shaft;
- monitoring a blade pitch for each of the rotor blades by means of a blade pitch sensor (SO) of the wind turbine (Ia; Ib; Ic);
- determining the (progressive) average bending moments on the rotor shaft as a quantity indicative of rotor imbalance, based upon the monitored loads;
- determining at least one correction value for influencing the aerodynamic conversion of at least \( n-1 \) rotor blades by minimizing the (progressive) average of the bending moment values so that the contribution of loads on all of the rotor blades collectively on the quantity indicative of rotor imbalance is kept to a minimum, wherein the determination of at least one correction value for influencing the aerodynamic conversion of at least \( n-1 \) blade comprises feedback of the quantity indicative of rotor imbalance as an adjustment of said at least one correction value of at least \( n-1 \) rotor blades via an inverse of trigonometric relationships between deflection moments in the rotor blades and bending moments in the rotor shaft, wherein said feedback from the quantity indicative of rotor imbalance comprises low-pass filtering, time integration and scaling;
- effectuating the at least one specific corrective value for influencing the aerodynamic conversion of the at least \( n-1 \) rotor blades.
2. Method according to claim 1, wherein the bending moments are measured as averages without absolute offset,

3. Method according to claim 1, wherein the feedback of the quantity indicative of rotor imbalance comprises the execution of mathematical operations in accordance with a control law according to a method applied in modern control theory, selected from a group comprising Robust Control, Linear Quadratic Regulation (LQR), Linear Quadratic Gaussian control (LQG), H-infinite control ($H_\infty$) and $\mu$-synthesis.

4. Method according to any of the claims 1-3, wherein the at least one correction value for influencing the aerodynamic conversion relates to a control signal for adjusting a blade pitch value, and effectuating the at least one specific correction value comprises the transmission of the control signal to the actuator of the respective rotor blade.

5. Method according to claim 1, wherein determining and monitoring loads, when said wind turbine is in use, comprises measuring bending moment values in a cross-section of the rotor shaft along two non-parallel vectors.

6. Method according to claim 1, wherein the wind turbine further comprises a yaw bearing for pivotally connecting at least the rotor and the mast, wherein the determination of imbalance forces, when said wind turbine is in use, comprises determining a tilt moment and a yaw moment at the yaw bearing.

7. Method according to claim 1, wherein the wind turbine further comprises a yaw bearing for pivotally connecting at least the rotor and the mast, wherein the determination of imbalance forces, when said wind turbine is in use, comprises determining a tilt moment at the yaw bearing.
8. Method according to claim 6 or 7, further comprising the measuring of a vertical and laterally exerted force in the top of the mast.

9. Method according to claim 6 or 7 or 8, further comprising the measuring of at least a rotational acceleration along a direction vector in a plane defined by a vertical and lateral direction vector.

10. Method according to any of the claims 6-9, further comprising the measurement of at least a translational acceleration along a direction vector in a plane defined by a vertical and lateral direction vector at some distance from the centre of the top of the mast.

11. Method according to claim 1, wherein the wind turbine comprises a nacelle (L), and the nacelle comprises the rotor shaft and is coupled to the mast via the yaw bearing and wherein the determination of the tilt moment and the yaw moment at the yaw bearing comprises measuring accelerations at the nacelle in the vertical and horizontal plane at some distance from the centre of the top of the mast.

12. Method according to claim 1, wherein the wind turbine comprises a nacelle (L), and the nacelle comprises the rotor shaft and is coupled to the mast via the yaw bearing and wherein the determination of the tilt moment at the yaw bearing comprises measuring accelerations at the nacelle in the vertical and horizontal plane at some distance from the centre of the top of the mast.

13. Method according to claim 1, wherein the wind turbine comprises a nacelle (L), and the nacelle comprises the rotor shaft and is coupled to the mast via the yaw bearing and wherein the bending moments are determined by average without absolute offset, based on a measured nacelle acceleration perpendicular to the rotor plane and measured blade deflection moments that do not need to be offset-free.
14. Method according to claim 1, wherein said sensor circuit is selected from a group of at least one sensor (S₁; S₂) and a combination of sensors (S₃, S₅; S₄, S₅).

15. Computer system for compensating rotor imbalance in a wind turbine, wherein the wind turbine comprises a rotor (R) and a mast (M), wherein the rotor comprises a rotor shaft that is provided with a number of rotor blades (B), wherein the rotor shaft is coupled to a top section of the mast (M) and wherein a blade pitch of each rotor blade is individually adjustable (AI); wherein the wind turbine is provided with at least one sensor (S₁; S₂; S₃, S₅; S₄, S₅) for monitoring forces and blade pitch sensors (SO) for monitoring a set blade pitch for each of the rotor blades; wherein the computer is provided with a central processing unit (21) and memory (18, 19, 22, 23, 24), wherein the memory is connected to the central processing unit, and wherein the central processing unit is linked to the sensors (SO, S₁; SO, S₂; SO, S₃, S₅; SO, S₄, S₅), wherein the computer is arranged, when the wind turbine is in use, to repeat in time the following actions:

- determining and monitoring loads of the wind turbine (Iₐ; I₉; I₃) with the use of the sensor circuit (S₁; S₂; S₃, S₅; S₄, S₅) for sensing bending moments in the rotor shaft;

- monitoring a blade pitch for each of the rotor blades by means of a blade pitch sensor (SO) of the wind turbine (Iₐ; I₉; I₃);

- determining the (progressive) average bending moments on the rotor shaft as a quantity indicative of rotor imbalance, based upon the monitored loads;

- determining at least one correction value for influencing the aerodynamic conversion of at least n-1 rotor blades by minimizing the (progressive) average of the bending moment values so that the contribution of loads on all of the rotor blades collectively on the quantity indicative of rotor imbalance is kept to a minimum, wherein the determination of at least one correction value for influencing the aerodynamic conversion of at least n-1 blade comprises feedback of the quantity indicative of rotor imbalance as an adjustment of said at least one correction value of at least n-1 rotor blades via an inverse of trigonometric relationships between deflection moments in the rotor blades and bending.
moments in the rotor shaft, wherein said feedback from the quantity indicative of rotor imbalance comprises low-pass filtering, time integration and scaling; - effectuating the at least one specific corrective value for influencing the aerodynamic conversion of the at least n-1 rotor blades.

16. Computer software stored on a computer-readable medium for compensating rotor imbalance in a wind turbine, wherein the wind turbine comprises a rotor (R) and a mast (M), wherein the rotor comprises a rotor shaft that is provided with an n number of rotor blades (B), wherein the rotor shaft is coupled to a top section of the mast (M) and wherein a blade pitch of each rotor blade is individually adjustable (Al); wherein the wind turbine is provided with at least one sensor (Sl; S2; S3, S5; S4, S5) for monitoring forces and blade pitch sensors (SO) for monitoring a set blade pitch for each of the rotor blades; wherein the computer is provided with a central processing unit (21) and memory (18, 19, 22, 23, 24), wherein the memory is connected to the central processing unit, and wherein the central processing unit is linked to the sensors (SO, Sl; SO, S2; SO, S3, S5; SO, S4, S5), wherein the computer software comprises executable code which, when loaded on the computer, enables the computer, to repeatedly in time execute the following operations when the wind turbine is in use:
- determining and monitoring loads of the wind turbine (Ia; Ib; Ic) with the use of the sensor circuit (Sl; S2; S3, S5; S4, S5) for sensing bending moments in the rotor shaft;
- monitoring a blade pitch for each of the rotor blades by means of a blade pitch sensor (SO) of the wind turbine (Ia; Ib; Ic);
- determining the (progressive) average bending moments on the rotor shaft as a quantity indicative of rotor imbalance, based upon the monitored loads;
- determining at least one correction value for influencing the aerodynamic conversion of at least n-1 rotor blades by minimizing the (progressive) average of the bending moment values so that the contribution of loads on all of the rotor blades collectively on the quantity indicative of rotor imbalance is kept to a minimum, wherein the determination of at least one correction value for
influencing the aerodynamic conversion of at least n-1 blade comprises feedback of the quantity indicative of rotor imbalance as an adjustment of said at least one correction value of at least n-1 rotor blades via an inverse of trigonometric relationships between deflection moments in the rotor blades and bending moments in the rotor shaft, wherein said feedback from the quantity indicative of rotor imbalance comprises low-pass filtering, time integration and scaling; - effectuating the at least one specific corrective value for influencing the aerodynamic conversion of the at least n-1 rotor blades.

17. Computer software according to claim 16, wherein determining at least one correction value for influencing the aerodynamic conversion of at least n-1 rotor blades comprises the use of either a method of approximation or method of reconstruction.

18. A computer-readable medium that comprises computer executable code which, when loaded on the computer system according to claim 15, enables the computer to execute the method according to any of the claims 1-14.
Fig 4
Fig 5

Start, initialisations

measurement:
1a: deflection moments (and forces) in blade roots
1b: bending moments in rotor axis
1c: tilting and yaw moment in top of mast and rotor pitch

Determining bending moments:
1a: from deflection moments;
1b: from bending moments by projection on axes
1c: from tilting and yaw moment through rotor pitch

Calculating adjustments to individual blade pitches from bending moment values, feedback to minimize average values of bending moments, setting blade pitches through the inverse trigonometric relationship between blade deflection load and bending of rotor axis.

Verify settings of blade pitch values, test settings against allowed range of blade pitch, execute adjustment of blade pitches through control signals.

Schedule new control cycle, wait until the cycle time has lapsed (from determining bending moments)

\[ N \quad \text{Again initialize ?} \quad Y \]

\[ N \quad \text{stop signal ?} \quad Y \]

Stop, keep last adjustments to blade pitches
### INTERNATIONAL SEARCH REPORT

**International application No**

PCT/NL2009/050482

#### A. CLASSIFICATION^ SUBJECT MATTER

INV. F03D7/04

**According to International Patent Classification (IPC) or to both national classification and IPC**

#### B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

F03D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical search terms used)

EPO-Internal

#### C. DOCUMENTS CONSIDERED TO BE RELEVANT

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Date of the actual completion of the international search 6 January 2010

Date of mailing of the international search report 18/01/2010

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Beran, Jiří

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