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Method for controlling a wind turbine and corresponding wind turbine

The present invention relates to a method for controlling a wind turbine and the present invention also relates to a wind turbine.

Wind turbines are known and they are nowadays constructed from a tower with a nacelle arranged thereon and a large aerodynamic rotor. As a result of the rotating rotor, the wind turbine, in particular with regard to the tower, can be caused to vibrate. It may become problematic when a resonance frequency is excited as a result.

In order to overcome the problem, it is known to control a wind turbine in such a manner that as far as possible it omits such a speed range. With speed-variable wind turbines, on which the invention is also based, the speed increases during partial load operation with increasing wind speed. In order to omit a critical, resonance-exciting speed, the wind turbine can be controlled in such a manner that the corresponding critical speed range is passed through as quickly as possible. Such a concept may, however, in the field lead to an unfavourable degree of efficiency. This is because rapidly passing through such a critical speed range with increasing wind, that is to say, increasing speed, means that in the range initially only the speed is increased without increasing the power in order thereby to rapidly pass through this speed range. Accordingly, the result may be a loss of power.

It may be particularly problematic in this regard if the prevailing wind is, for instance, in a range in which the critical speed would occur. There is then the risk that the wind turbine would swing back and forth between a speed range below and a speed range above the critical speed.

The German Patent and Trademark Office has in the priority application relating to the present application examined the following prior art: DE 100 16 912 C1, US 2009/0292397 A1, US 2014/0327243A1, US 4,700,081A, WO 2012/139584 A1 and WO 2017/036481 A1. Additional prior art is disclosed in EP 3179097 A1.

An object of the invention is consequently to address at least one of the above-mentioned problems. In particular, a solution is intended to be provided in which an operation of the wind turbine at a resonance point is prevented with at the same time the highest possible level of efficiency. At least an alternative to previously known solutions is intended to be proposed.

According to the invention, a method according to claim 1 is proposed. Accordingly, a method for controlling a wind turbine is proposed and is based on a wind turbine having an aerodynamic rotor with rotor blades which can be adjusted in terms of the blade angle thereof. The wind turbine is speed-variable in this instance. As a result of the adjustment of the rotor blades in terms of their blade angle, the taking of power from the wind can be influenced.

The method relates to the part-load range which can also be referred to as part-load operation and in which the wind turbine does not yet reach nominal speed or nominal power since the wind also does not yet reach a nominal speed. The rotor speed is consequently in this range below a nominal speed and the power output of the wind turbine is below a nominal power. The power output is in this instance the power which is output by the generator of the wind turbine.

In order to control the wind turbine in this part-load range, in principle a speed/power characteristic line is used. This predetermines a relationship between a rotor speed which is adjusted in accordance with the prevailing wind and a power output which is adjusted relative thereto. In particular, the wind turbine is controlled in such a manner that a power output is associated with each rotor speed below the nominal speed. Depending on which rotor speed is currently applied, a corresponding power output is then adjusted. If this power output corresponds precisely to the mechanical power which can be taken from the wind at that time, a stable operating point at the rotor speed and the adjusted power output is produced. Otherwise, the speed changes and the power output is accordingly readjusted until such a stable operating point is produced. The operating point also thereby follows changes of the wind speed.

An important part of the operation of the wind turbine in part-load operation is consequently the constant adjustment of the power output according to the speed/power characteristic line. To this end, however, it is proposed that the speed/power characteristic line has a hysteresis range in the region of a problem speed to be avoided. In this hysteresis range, there is consequently no longer any clear speed/power characteristic line and the operating point in the hysteresis range is dependent on at least one additional condition, that is to say, where the operating point was directly beforehand.

The problem speed which is intended to be prevented may in particular be a rotor speed which excites the resonance frequency of the wind turbine. It is consequently in principle proposed that the operating characteristic line for the range of this problem speed be divided. This problem speed can thereby, as the speed increases, that is to say, as the wind increases, be counteracted differently from when the speed decreases, that is to say, as the wind decreases. It is now possible to avoid the problem speed in a different manner, wherein a path with a high degree of efficiency can thereby be selected.

It should also be taken into account that in principle instead of the use of the power output, a torque, that is to say, one which acts between the rotor and stator of the generator, can be used. The power P corresponds to the product of the torque M with the speed n ($P = M \times n$). At a constant speed n, which can be assumed at the latest in the steady state, the torque and the power differ consequently only by a factor. Consequently, as a basic alternative, it is proposed to use a speed/torque characteristic line instead of the speed/power characteristic line. According to one embodiment, it is proposed that in the hysteresis range the adjustment of the power output or the torque is carried out by means of a speed regulation by the rotor speed being regulated to a predetermined desired speed value by adjusting the power output. It is consequently proposed in the hysteresis range to implement the speed characteristic line, which can also be referred to as an operating characteristic line, differently from outside the hysteresis range. Outside the hysteresis range, in accordance with a fixed provision which is determined by the speed/power characteristic line, the power output is adjusted in accordance with the speed. Each rotor speed is in this instance associated with a power output.

In the hysteresis range, however, in particular in each case for a part-branch of the hysteresis a speed is predetermined as a desired speed value. In this hysteresis range, vertical branches may also occur, that is to say, characteristic line branches in which a plurality of power outputs are associated with a speed value via these vertical lines. There is then no adjustment of the power output, but instead a regulation of the rotor speed to the desired speed value. This is carried out in particular in such a manner that a speed increase above the current desired speed value in the hysteresis range is counteracted by an increase of the power output. The speed is thereby kept to the desired speed value predetermined at the time, whilst the power output can fluctuate in terms of its level in relative terms. In clear terms, the operating point is thereby kept to a vertical branch of the hysteresis range of the operating characteristic line, wherein the operating point can move up and down on this vertical characteristic line branch, depending on the wind speed.

Unlike in the remaining region of the operating characteristic line, in this hysteresis range it is consequently not accepted that the speed is adjusted to a new value in accordance with the wind speed, but instead this is counteracted by the adjustment of the power output.

Accordingly on such a hysteresis branch, as the wind speed increases, the power output increases, whilst the speed as a result of the regulation which has been carried out remains constant, in any case in the ideal case. This method can also in principle be carried out in an identical manner, at least having the same effect, by means of the adjustment of the torque in place of the power output. In principle, a hysteresis branch may also be synonymously referred to as a hysteresis portion and vice versa.

According to one embodiment, it is proposed that in the hysteresis range the blade angle be adjusted in accordance with the power output. Also in this instance, the adjusted torque can be used in place of the power output. It may thereby be possible for the working point which is adjusted on such a hysteresis branch to operate with the best-adapted blade angle possible. In this instance, it should be taken into account that the change of the power output at a constant speed also means that in spite of a constant speed there is a variation of the wind power since the power output in the stationary-adjusted state substantially corresponds to the power which is taken from the wind. This also means in turn that at the same speed on this hysteresis branch the wind speed varies and the tip speed ratio inevitably varies. To this end, it is proposed to adapt the blade angle to the changed tip speed ratio in order to operate as far as possible in an optimum aerodynamic manner. In this instance, it is also recognised that instead of measuring the wind speed which is regularly subjected to imprecisions, it is advantageous to use the adjusted power output; the same applies to a torque which has been adjusted instead.

The blade angle may in the hysteresis range also be adjusted in accordance with the speed in order to thereby improve the aerodynamic situation in the hysteresis range. In this instance, the adjustment of the blade angle may preferably also be carried out in accordance with the power output and the speed, or in accordance with an observed aerodynamic power.

According to one embodiment, it is proposed that the hysteresis range extends from a predetermined lower limit speed which is below the problem speed to an upper limit speed which is above the problem speed. In particular, it is proposed in this instance that these limit speeds are set in such a manner when the problem speed is a resonance speed. This resonance speed or quite generally the problem speed can thereby be omitted in a simple manner, at least substantially omitted.

Preferably, the hysteresis range is subdivided into a few, in particular four hysteresis portions, that is to say, a first to a fourth hysteresis portion.

The first hysteresis portion refers to one which for rotor speeds below the problem speed increases up to an upper limit power, alternatively up to an upper limit torque. The rotor speed is consequently for this first hysteresis portion below the problem speed and in particular it has in this instance a fixed value which can also be referred to as a lower limit speed. The hysteresis portion is consequently in particular a substantially vertical portion in front of the problem speed.

The second hysteresis portion adjoins the first hysteresis portion and extends up to a rotor speed above the problem speed. Since the second hysteresis portion adjoins the first one, the second hysteresis portion consequently has the upper limit power or the upper limit torque. It begins at a rotor speed below the problem speed. From here, this second hysteresis portion extends up to a rotor speed above the problem speed. In particular, this second hysteresis portion forms a substantially horizontal portion, that is to say, with a substantially constant power output.

It should be mentioned in this regard that such a horizontal hysteresis portion is not provided for stationary operating points to be located thereon. Instead, the operating state should ideally abruptly change from the end of the first hysteresis portion, at least as rapidly as possible at the end of the second hysteresis portion. An abrupt change is naturally non-physical since to this end the speed would have to jump to a higher value. The horizontal hysteresis portion is, however, provided for this change from the lower to the higher rotor speed to be carried out rapidly. Since this second hysteresis portion adjoins the first one, this means in particular that this second hysteresis portion is travelled, that is to say, is passed through as rapidly as possible, when more power is available than the upper limit power or a larger torque is present than the upper limit torque.

With this excess power or this excess torque, the rotor of the wind turbine can then be rapidly accelerated to the higher speed range at the end of the second hysteresis portion. The problem speed is then rapidly passed, wherein, however, as a result of the upstream first hysteresis portion, the wind turbine was first brought into an operating point of high power output, instead of being kept at low power and passing through the problem speed with such low power without a hysteresis range. As a result of this hysteresis range, it is therefore possible to achieve a high degree of efficiency, in spite of passing through the range of the problem speed.

The third hysteresis portion defines a branch which falls to a lower limit power or a lower limit torque for rotor speeds above the problem speed. This third hysteresis portion is consequently passed through particularly when the power output was already comparatively high and the rotor speed was already high, but, in particular as a result of decreasing wind, the power and speed become lower again in accordance with the operating characteristic line. The speed and power thus decline and this third hysteresis portion then results in the speed being maintained at a specific distance above the problem speed and at that location initially only the power output falls; the same applies to the torque as an alternative. In this instance, it is also in particular proposed that, by adjusting the power output or the torque, the speed is regulated to a desired value above the problem speed. Such a regulation leads to this speed in the event of decreasing wind initially maintaining this predetermined value of the third hysteresis portion, whilst the power output decreases further. As soon as the power output has reached the lower limit power or the torque has reached the lower limit torque, this still comparatively high rotor speed can no longer be maintained and the fourth hysteresis portion consequently adjoins.

On the fourth hysteresis portion, the rotor speed then falls below the problem speed. In this instance, the power output can initially stay the same. Consequently, in clear terms, the third hysteresis portion is substantially, at least preferably, vertical and the fourth hysteresis portion which adjoins is substantially or preferably horizontal. For the fourth hysteresis portion, as for the second hysteresis portion, there is also no provision for this to define stationary operating points but instead for the operating point to change as rapidly as possible along this fourth hysteresis portion.

In this instance, particularly when changing the operating point along the fourth hysteresis portion, a portion of the rotation energy is further discharged for braking the rotor.

In summary, for the first and third hysteresis portion a speed control using the power output or alternatively the torque is consequently preferably proposed in each case. As a result of this control, corresponding operating points which depending on the prevailing wind speed can also be assumed permanently are set on these portions.

The two preferably horizontal portions, that is to say, the second and fourth hysteresis portion, are provided for the respective operating point to change as rapidly as possible from a low rotor speed below the problem speed to a high speed above the problem speed or vice versa. If a wind speed, to which an operating point having a speed in the range of the problem speed actually belongs, is present with the operating characteristic line proposed with a hysteresis range a substantially stable operating point is nonetheless produced, that is to say, on the first hysteresis portion when the speed was already previously below the problem speed, or on the third hysteresis portion when the speed was already previously above the problem speed.

For the speed control and also for other control aspects, such as a switching between hysteresis portions which will be described below, a power or alternatively a torque can be used. In this instance, the following four variables which in principle have the same effect and taking into account their relationships may be interchangeable are in principle considered:

1. The power output which refers to the power which the generator produces or discharges, alternatively it may also refer to the power which the wind turbine discharges, is consequently an electrical variable and can also be referred to as electrical power P_{el}. The power output can in most cases be measured at least indirectly.

2. The mechanical torque T_{mech} which refers to the torque which acts on the rotor. It may be detected by a state monitor which will be described below.

3. The mechanical power P_{mech} which refers to the power which the rotor implements. It can be calculated from the mechanical torque T_{mech} and the speed n, in accordance with the formula $P_{mech} = T_{mech} x n$.

4. The electrical torque T_{el} which refers to a torque which is present in the generator, in particular between the stator and rotor, that is to say, electrodynamic rotor of the generator. It may be calculated from the electrical power P_{el} and the speed n, in accordance with the formula $T_{el}=P_{el}/n$.

Unless set out otherwise, when at least one of these four variables is described, each one of the remaining possibilities always comes into consideration. Only the mechanical torque and the mechanical power are preferably used as variables which are monitored by a state monitor. The two electrical variables, that is to say, the electrical torque and the electrical power output, can generally be detected with sufficient precision and sufficient speed without a state monitor.

These explanations relating to the meaning of the power also apply to the speed characteristic line and can accordingly also be transferred to a speed/torque characteristic line which could be used as an alternative to the speed/power characteristic line. This applies to any embodiments. As a torque which is intended to be adjusted, in principle an electrical generator torque is proposed, in particular for those embodiments which propose adjusting a torque. In so far as a torque, in particular an upper or lower limit torque, is taken into account as an input variable, this may also relate to the electrical generator torque, but it is preferably proposed for this purpose that the mechanical torque of the rotor of the generator be taken into account. In principle, the electrical generator torque and the mechanical torque of the rotor of the generator differ in terms of their dynamic behaviour, but in the stationary state are intended to be considered to be identical or substantially identical.

It should also be taken into account that those embodiments which take into account a speed/power characteristic line, particularly those which control the wind turbine based on the speed/power characteristic line, can nonetheless take into account a torque as an input variable. In particular, proposed switches between hysteresis ranges depending on a limit torque can also be considered with those embodiments which carry out a control based on a speed/power curve. Conversely, the same accordingly applies to controls which are carried out based on a speed/torque characteristic line.

These may also take into account power values as input variables.

According to one embodiment, it is proposed that the first hysteresis portion increase from the lower limit speed, therefore, when in particular an increasing rotor speed reaches the lower limit speed, to the upper limit power, or to the upper limit torque, in particular with a substantially constant rotor speed. This constant rotor speed is in this instance preferably predetermined as a desired speed value. In this first hysteresis portion, the rotor speed is then in particular readjusted and accordingly a vertical portion is substantially produced for the first hysteresis portion.

Furthermore, at least alternatively, it is proposed that the second hysteresis portion extends to an upper limit speed, in particular with the power being substantially constant or the torque being substantially constant. The second hysteresis portion consequently extends substantially horizontally from the lower to the upper limit speed. A stable operating point is not adjusted at that location. Instead, this second hysteresis portion is provided only for the speed to change as rapidly as possible from the lower limit speed to the upper limit speed. The problem speed is thereby passed quickly.

Furthermore, at least alternatively, there is provision for the third hysteresis portion to decrease from the upper limit speed, therefore, when in particular a decreasing rotor speed reaches the lower limit speed, to the lower limit power or to the lower limit torque, in particular with the rotor speed remaining substantially constant. In this instance, therefore, there is the underlying basis that the rotor speed originates from above the limit speed and falls on a characteristic line portion without hysteresis to the upper limit speed. Then in particular this upper limit speed is predetermined as a desired speed value and it is adjusted. With further decreasing wind, this means that the power output or the torque is reduced in order to keep the rotor speed at this upper limit speed as a desired value. This third hysteresis portion consequently extends substantially vertically, that is to say, at the upper limit speed.

Furthermore, or at least alternatively, the fourth hysteresis portion extends up to the lower limit speed, that is to say, from the upper limit speed to the lower limit speed. To this end, it is in particular proposed that the power output or the torque remains constant and accordingly this fourth hysteresis portion extends horizontally.

In the event that, in the first hysteresis portion, the wind speed falls again and the operating point moves again to the beginning of the first hysteresis portion, it is proposed that the speed control which is provided in the first hysteresis portion also be ended again and, if the wind falls again, the operating point is then guided on a portion of the operating characteristic line which is no longer part of the hysteresis range.

The third hysteresis portion also behaves in a quite similar manner and, as the wind speed increases, can also be left again at a characteristic line portion at which the rotor speed is above the upper limit speed. It is also proposed in this instance that the speed control be ended.

In this instance, it should also be taken into account that generally with increasing wind, when the operating point is on the first hysteresis portion and reaches its end, that is to say, reaches the upper limit power, the speed control is initially maintained, wherein the desired speed value is changed abruptly from the lower limit speed to the upper limit speed. If the wind speed does not decrease further precisely at this time, however, the speed control is also ended immediately afterwards if the power output or the torque increases further. Consequently, the hysteresis range is also left. The operating point is then located on the operating characteristic line above the hysteresis range, that is to say, for speeds above the upper limit speed and for power outputs above the upper limit power.

The procedure is quite similar when with decreasing wind the operating point moves on the third hysteresis portion and as a result of the speed control the speed is maintained at a value at the level of the upper limit speed, whilst the power output falls to a value at the level of the lower limit power. The speed control is then maintained in this instance, but the desired speed value then changes abruptly from the upper limit speed to the lower limit speed. The operating point thereby travels along the fourth hysteresis portion to the lower limit speed. Also in this instance, as the wind decreases further, the power output will decrease further, which leads to the end of the speed control. Consequently, the hysteresis range is then also left in a downward direction and the operating point is further guided on the operating characteristic line in a range below the hysteresis range.

According to the invention, it is proposed that the wind turbine be operated in such a manner that with increasing wind up to a or the lower limit speed a power output according to the speed/power characteristic line is adjusted. From the lower limit speed, as the wind increases further, the rotor speed is kept substantially constant and the power output is increased. This occurs in particular as a result of the mentioned speed regulation. The control then works until the power output has reached the upper limit power or the upper limit torque is reached. If this upper limit power or the upper limit torque is reached, the rotor speed is increased to the upper limit speed. According to the invention, it is proposed that this be carried out only after waiting for a predetermined switching delay. Within this switching delay, it can be verified whether the torque or the power output still actually remains so high, otherwise should the torque or the power output drop again, the increase of the speed can be omitted. If the speed is increased, however, this is carried out in particular in such a manner that the desired speed value jumps from the lower limit speed to the upper limit speed. The control then accordingly adjusts the rotor speed in accordance with this desired value increase. Depending on the control adjustment, the rotor speed increases accordingly quickly.

Based on this, the operating point is then located substantially above the hysteresis range. If the wind drops again, the rotor speed and the power output also decrease until the rotor speed has reached the upper limit speed in principle from above. The operating point is guided along this upper characteristic line branch from above to the upper point of the hysteresis range. To this end, it is monitored whether, coming from above, the upper limit speed is reached.

As soon as this is the case and the wind decreases again, the rotor speed is kept substantially constant, that is to say, above a speed control which has this upper limit speed value as a desired speed value. The power output is consequently the control variable again in this instance and it will decrease to reach this control target as the wind decreases further until it has reached the lower limit power. The same naturally also applies to reaching the lower limit torque if the torque is used for control. If this lower limit power or lower limit torque is reached, therefore, the rotor speed is reduced to the lower limit speed, in particular reduced as quickly as possible.

According to the invention, it is proposed that this be carried out only after waiting for a predetermined switching delay. Within this switching delay, it can be verified whether the torque or the power output actually continues to remain so low, otherwise should the torque or the power output increase further, the reduction of the speed can be omitted. As a switching delay, it is possible to use the same one as for the transition from the first to the second hysteresis portion, or a separate one, that is to say, another predetermined switching delay. The reduction of the speed is then also carried out again by means of the speed control in which the desired speed value is changed from the upper limit speed to the lower limit speed.

According to one embodiment, it is proposed that the wind turbine be operated in such a manner that, when the upper limit power or upper limit torque has been reached, that is to say, as a result of increasing wind speed, after waiting for the predetermined switching delay, the rotor speed is increased to the upper limit speed and the power output is reduced. This reduction of the power output results in additional energy being able to be converted into rotation energy of the rotor, which leads to a particularly rapid increase of the rotor speed, particularly when the wind speed also increases at the same time. The problem speed can thereby be passed as quickly as possible.

Additionally or alternatively, it is proposed that, when the lower limit power or the lower limit torque is reached, that is to say, as a result of decreasing wind speed, after waiting for the predetermined or another predetermined switching delay, the rotor speed be reduced to the lower limit speed and the power output is increased in order to pass the problem speed. As a result, even with decreasing wind speed, the problem speed can be passed rapidly since, as a result of the increase of the power output, power or energy is taken from the rotor and it is thereby braked.

According to one embodiment, it is proposed that, in order to operate the wind turbine in the hysteresis range of the speed characteristic line, a mechanical torque which is acting on the rotor be recorded. In particular, it is proposed that a state monitor be used to record the mechanical torque, in particular in order to detect that the upper and/or lower limit torque has been reached. In particular, it is proposed in this instance that a mechanical torque be monitored when operating the wind turbine in the first and/or in the third hysteresis portion of the hysteresis range. In the first and third hysteresis portion, reaching an upper or lower limit torque initially leads to a switching of the desired speed value. In order to initiate this in the most selective manner possible, it is proposed in this instance that the mechanical torque be monitored, that is to say, monitored in a system technical manner. At this point, the use of the mechanical torque, in particular the use of the monitored mechanical torque can bring about an improvement, in particular stabilisation, of the control in the hysteresis range. Particularly at the end of the first hysteresis range, the torque applied decides whether the speed can actually be increased to the upper limit speed with the prevailing wind. As a result of the use of the proposed monitoring of the mechanical torque, a stable value relating to this can be established. The transition from the first to the second hysteresis portion and consequently the increase of the rotor speed from the lower to the upper limit speed can thereby be started safely.

This applies similarly to the lower range of the third hysteresis portion, from which via the fourth hysteresis portion the speed is intended to be rapidly decreased.

At the same time, however, the state monitor can, in particular based on the monitored torque, establish a mechanical power. In particular, a power output from the generator can be established. This is also particularly closely related to the power which is taken at the time from the wind and which can be determined by taking into account an acceleration or braking power from the power output. It is thereby possible, by using such a monitor, to reliably implement the proposed control, in particular in the hysteresis range.

According to one embodiment, there is proposed a method which is characterised in that, in order to switch from the first to the second hysteresis portion, a first switching criterion which is dependent on a power or a torque is taken as a basis. Preferably in this instance, an electrical or mechanical power, in particular a monitored mechanical power or an electrical or mechanical torque, in particular a monitored mechanical torque is also used. The mechanical power can also be used as a replacement for a power output. The mechanical power may substantially correspond to the power output, but in particular the mechanical power (the same applies to the mechanical torque) says more about the state of the rotor.

Preferably, the first switching criterion is configured in such a manner that, in order to switch from the first to the second hysteresis portion, there is a wait for a predetermined switching delay and the switching is then carried out if during the entire switching delay an upper limit power or an upper limit torque is reached or exceeded. The switching is consequently not carried out immediately on reaching the relevant limit value, but instead it is first verified whether the high value is also maintained. If it is not maintained, the verification begins from the start as soon as the limit value has been exceeded again. However, if the value is maintained long enough at the high level, that is to say, for the duration of the switching delay, the switching is then initiated.

This switching delay and also in principle all other switching delays described are preferably in the range from a few seconds to minutes, preferably in a range from 5 seconds to 5 minutes, in particular in the range from 10 seconds to 2 minutes.

Additionally or alternatively, according to one embodiment, it is proposed that, in order to switch from the third to the fourth hysteresis portion, a second switching criterion which is dependent on a power or a torque be taken as a basis, and in particular it is proposed that the second switching criterion be configured in such a manner that, in order to switch from the third to the fourth hysteresis portion, there is a wait for a or the predetermined or additional predetermined switching delay and the switching is then carried out if, during the entire switching delay or additional switching delay, a value reaches or falls below a lower limit power or a lower limit torque. The switching from the third to the fourth hysteresis portion is consequently accordingly proposed in the same manner as the switching from the first to the second hysteresis portion, wherein the same or a different switching delay, that is to say, the additional switching delay, can be used. The extent of the switching delay is, however, in both variants preferably within the mentioned range.

The use of a switching criterion in which a switching delay as described is used also leads to the critical speed range being passed less often.

In particular on the basis of the power which is taken from the wind and which is determined by means of the monitor (the same applies to the torque), it is now also possible to use criteria according to which a switching from the first to the second hysteresis portion is carried out. According to one embodiment, a switching from the first to the second hysteresis portion can consequently be carried out only if for a switching time which can be referred to as time t_{min}, a power or a torque above the limit power or the limit torque can be taken from the wind or is brought about by the wind. The same can be carried out for the switching from the third to the fourth hysteresis portion. A switching from the third to the fourth hysteresis portion is initiated only when for the switching time, or another switching time, that is to say, in particular for the time t_{min} a power or a torque below the limit power or the limit torque is taken from the wind or is brought about by the wind.

Preferably, it is proposed that the state monitor used to establish the mechanical torque and where applicable the available power has the speed of the generator and the mechanical torque of the generator as state variables to be monitored.

As a result of the use of the speed of the generator and the mechanical torque of the generator as state variables to be monitored, it is in particular possible to make a good assessment of the current state of the generator. This is also particularly advantageous for a good and reliable control of the wind turbine in the hysteresis range.

Preferably, there is proposed a method which is characterised in that the state monitor used to establish the mechanical torque is defined by the following structure:

$$\begin{bmatrix} \dot{\hat{\omega}} \\ \dot{\hat{T}}_{mech} \end{bmatrix} = \begin{bmatrix} -k_\omega & \frac{1}{J} \\ -k_T & 0 \end{bmatrix} \begin{bmatrix} \hat{\omega} \\ \hat{T}_{mech} \end{bmatrix} + \begin{bmatrix} k_\omega & -\frac{1}{J} \\ k_T & 0 \end{bmatrix} \begin{bmatrix} \omega \\ T_{el} \end{bmatrix}$$

where

- J denotes the common moment of inertia of the rotor and generator,
- ω is the speed of the generator,
- k_ω and k_T are parameters for influencing the dynamic of the monitor,

- T_{el} is referred to as an electrical torque and is calculated as the quotient of the power P discharged from the generator and the speed ω, and
- T_{mech} denotes the mechanical torque of the rotor, wherein the monitored variables are identified with a ^ symbol and derivatives with respect to time are identified with a · symbol, wherein an available power is preferably calculated as the product from the monitored speed $\hat{\omega}$ and monitored mechanical torque $\hat{T}_{mech}$, wherein this available power can be used as a power output and consequently as a criterion in order to verify whether it has reached or exceeded or fallen below the upper or lower limit power. The power output may correspond to a power fed into an electrical intermediate store, in particular a power which is fed into a direct-current voltage intermediate circuit of an inverter. However, it may also correspond to a power fed into the power supply network, in particular a power supplied by means of an inverter into a power supply network.

As a result of this monitor structure, in a comparatively simple manner, that is to say, by using a model of the second order, an efficient and at the same time reliable monitoring of the wind turbine and in particular the generator thereof is possible.

According to one embodiment, it is proposed that the method be characterised in that in the first hysteresis portion for the rotor speed the lower limit speed is predetermined as the desired speed value and the rotor speed is regulated to the lower limit speed as a desired speed value by adjusting the power output,
- when the upper limit power or the upper limit torque is reached in the first hysteresis portion, a change is made to

the second hysteresis portion and for the rotor speed as a desired speed value the upper limit speed is predetermined so that the rotor speed is then regulated to the upper limit speed as a desired speed value by adjusting the power output, wherein in particular when the second hysteresis portion is reached from the first hysteresis portion the desired speed value is abruptly increased from the lower limit speed to the upper limit speed,

- in the third hysteresis portion for the rotor speed the upper limit speed is predetermined as a desired speed value and the rotor speed is regulated to the upper limit speed as a desired speed value by adjusting the power output, and/or
- when the lower limit power or the lower limit torque is reached in the third hysteresis portion, a change is made to the fourth hysteresis portion and for the rotor speed the lower limit speed is predetermined as the desired speed value and the rotor speed is regulated to the lower limit speed as the desired speed value by adjusting the power output, wherein in particular when the fourth hysteresis portion is reached from the third hysteresis portion the desired speed value is abruptly decreased from the upper limit speed to the lower limit speed.

Consequently, it is in particular possible as a result of the respective speed control for the operating point, whilst at the same time using a high degree of efficiency, to be able to be guided with a degree of distance from the problem speed. Furthermore, a situation is thereby provided which enables the rapid switching of the desired speed value so that a change can be quickly carried out from a speed below the problem speed to a speed above the problem speed or vice versa.

Preferably, it is proposed that the speed control of the hysteresis range be ended when the rotor speed drops by a predetermined threshold value below the lower limit speed, or the rotor speed rises by another or the same predetermined threshold value above the upper limit speed. In principle, the speed control should prevent the rotor speed from falling below the lower speed or rising above the upper speed. However, if this occurs to a significant extent, if, for example, a large spontaneous lull or a significant gust occurs, a criterion may then be to nonetheless leave the speed control. Preferably, it is proposed that the speed control of the hysteresis range be ended when the power output falls below the lower limit power or rises above the upper limit power. The torque can also be taken into account, whether it falls below the lower limit torque or exceeds the upper limit torque. This relates in particular to the torque of the rotor of the generator which can also be referred to synonymously as a generator torque. Preferably, to this end, the monitored mechanical torque is taken into account. A switching can be carried out either immediately when a value falls below or exceeds the lower or upper limit power, or in a time-delayed manner, in particular after a time t_{min}, during which a return to speed control operation is possible when a value exceeds or falls below the lower or upper limit power.

A clearly defined switching between the hysteresis range and another range of the operating characteristic line can thereby be carried out. In particular it should be emphasised in this instance and it is proposed according to one embodiment that a change to the hysteresis range be carried out depending on the rotor speed, but a change back from the hysteresis range be carried out depending on the power output or the torque.

According to one embodiment, it is proposed that the lower and the upper limit speed be selected depending on a predetermined desired frequency of passing through the hysteresis range. Additionally or alternatively, it is proposed that the lower and the upper limit speed be located by a predetermined speed difference below or above the problem speed. It has been recognised that the closer the lower and upper limit speed are to the problem speed, the more often the hysteresis range is passed, that is to say, with increasing wind over the first and second hysteresis portion and with decreasing wind again over the third and fourth hysteresis portion. The greater the distance between the lower and upper limit speed, on the one hand, and the problem speed, on the other hand, the longer an operating point in the hysteresis range would remain on the first or third hysteresis portion.

In this instance, it has been recognised, on the one hand, that the lower and upper limit speed should be located as close as possible to the problem speed in order to deviate as little as possible from an ideal operating characteristic line. On the other hand, it has also been recognised that not only the prevention of a resonance excitation makes a degree of spacing from the problem speed necessary, but also that an excessively frequent passing of the hysteresis range can be prevented. Preferably, the lower and upper limit speed are consequently selected taking into account these criteria, that is to say, in particular taking into account the extent to which the optimum operating characteristic line is maintained, that is to say, also the frequency of passing the hysteresis range.

By predetermining a speed difference, a uniform spacing with respect to the problem speed can be predetermined. The problem speed is then located symmetrically between the lower and the upper limit speed. According to one embodiment, a non-uniform spacing of the limit speed from the problem speed is proposed. It has been recognised that it can thereby be taken into account that a typical normal operating characteristic line of a wind turbine has a different power gradient of the operating characteristic line for different speeds. At higher speeds, the power gradient of the operating characteristic line is generally steeper. It is consequently preferably proposed that a smaller spacing of the upper limit speed from the problem speed be selected than the spacing between the lower limit speed from the problem speed.

According to the invention, a wind turbine according to claim 15 is also proposed.

The wind turbine is provided to carry out a method according to at least one of the embodiments described above. Preferably, the corresponding method steps or method features of at least one embodiment described above are implemented to this end in the control device. For the wind turbine, as a basic alternative it is also proposed that a speed/torque characteristic line be used in place of the speed/power characteristic line.

The invention is explained in greater detail below by way of example with reference to embodiments and the appended Figures. In the drawings:

Figure 1 is a perspective illustration of a wind turbine,

Figure 2 shows a proposed operating characteristic line with a hysteresis range,
Figure 3 is a schematic illustration of a control structure for controlling the wind turbine.

Figure 1 shows a wind turbine 100 having a tower 102 and a nacelle 104. A rotor 106 having three rotor blades 108 and a spinner 110 is arranged on the nacelle 104. The rotor 106 is moved with a rotational movement during operation by the wind and thereby drives a generator in the nacelle 104.

Figure 2 shows an operating characteristic line 200 having a plurality of portions and variation possibilities. The operating characteristic line 200 indicates in principle a power P which is intended to be adjusted depending on a detected speed n and can thus also be referred to as a speed/power characteristic line. This operating characteristic line 200 indicates the part-load operation or part-load range of a wind turbine which extends from the speed 0 or from a switching-on speed n_A which can also be synonymously referred to as a starting speed, to a nominal speed n_N. The range with speeds greater than the nominal speed n_N is referred to as full-load range or full-load operation and consideration thereof is not of particular relevance for the present invention.

The operating characteristic line 200 extends substantially from the switching-on speed n_A which in the example has the value 4 rpm in a substantially continuously and monotonously increasing curve to the nominal speed n_N at which it reaches substantially nominal power P_N.

In the graph, there is also indicated a problem speed n_P, which, for example, may be a speed which excites a resonance of the wind turbine. Consequently, it can also be referred to as a resonance speed. Where possible, the wind turbine should be prevented from operating at this problem speed n_P.

A control based on the unmodified operating characteristic line 200 would in the entire range thereof, and consequently also in the range of the problem speed n_P, adjust operating points.

In order to prevent this, the prior art proposes a bypass portion 202 which is illustrated with dots in Figure 2. This where applicable also slightly exaggerated bypass portion 202 leaves the operating characteristic line 200 as the speed increases in a range prior to the problem speed n_P, in particular prior to a lower limit speed n_u. This bypass portion is then very flat in this region and even partially has a negative inclination. This has the effect that with increasing wind speed the operating characteristic line 200 is first left, as a result of the negative inclination of the bypass portion 202, then the power, that is to say, in particular the power output is decreased, although the power which is taken or can be taken from the wind increases. This power portion which is consequently not used then leads to the acceleration of the rotor of the wind turbine so that the speed rapidly increases. Only when the problem speed n_P has been exceeded, in particular in the direction of the region of the upper limit speed n_o, does the power then increase, which consequently only then counteracts the increase of the speed.

The problem speed n_P can consequently be passed quickly. However, it can also be seen that this bypass portion produces less power or the wind turbine is operated in this instance in such a manner that it produces less power.

In order to improve this bypass portion 202, the hysteresis range 204 is proposed. The hysteresis range 204 has four hysteresis portions, that is to say, the first to fourth hysteresis portion 211 to 214.

If the wind speed now increases and the operating point of the wind turbine moves along the operating characteristic line 200, beginning from the starting speed n_A, it can reach the lower limit speed n_u. If this is reached, the conventional control according to the operating characteristic line 200 switches to a speed control. The lower limit speed n_u of this control is now predetermined as the desired speed value. If the wind speed now increases further, the control attempts to keep this desired speed value, that is to say, the lower limit speed n_u, in which the power output is increased. The operating point thereby then moves on the first hysteresis portion 211. With increasing wind speed, this operating point consequently moves on the first hysteresis portion 211 in an upward direction, the power thereof thus increases. If the operating point on the first hysteresis portion 211 now reaches the upper limit power P_o, wherein an upper limit torque can also be used instead in this instance, a switch is made to the second hysteresis portion 212. This can be carried out in a time-delayed manner, after, for a switching delay, in particular a time t_{min}, a power above the upper limit power has been output or monitored.

This means that the control initially remains unchanged but keeps the value of the upper limit speed n_o as a desired speed value. The power output is consequently initially not increased, where applicable as a result of the control even reduced, which is not illustrated on the left in the characteristic line of Figure 2. The additional power can thereby be converted by the increasing wind into a speed increase and the operating point then rapidly reaches the upper limit speed n_o on the second hysteresis portion 212. The hysteresis range 204 is then in principle left since it can be assumed in this instance that the wind speed will at least slightly increase further. The operating point on the unchanged operating characteristic line 200 is then guided further in the direction towards the nominal speed n_N or nominal power P_N, depending on the wind speed.

However, if the wind speed decreases again from there, the speed can fall to the upper limit speed n_o. If this is the case, a switch is made again here from a normal characteristic line operation to a speed control. The upper limit speed n_o is used as a desired speed value. The power is then reduced in order to prevent a further reduction of the speed in order therefore to maintain this desired speed value of the upper limit speed n_o.

With further decreasing wind, this is carried out until the power output reaches the lower limit power. This occurs on the third hysteresis portion 213. However, if this lower limit power, starting from above, is reached, the desired speed value is switched from the upper limit speed n_o to the lower limit speed n_u. Instead of the lower limit power, a lower limit torque can also be used as a trigger. The switching can also be carried out in a time-delayed manner after a switching delay, in particular a time t_{min}. To this end, the current mechanical torque from a state monitor for monitoring the mechanical torque can be used. The same also applies during the transition from the first to the second hysteresis portion when the reaching of the upper limit torque is monitored.

In any case, at the end of the third hysteresis portion, as a result of the switching of the desired speed value, the fourth hysteresis portion 214 is passed. In this instance, however, the speed rapidly decreases from the upper limit speed n_o to the lower limit speed n_u. If the end of the fourth hysteresis portion 214 is reached, there is thus an operating point with the lower limit speed n_u and the lower limit power P_u, the starting point of the hysteresis range 204 would be reached again. If the wind speed continues to decrease, the hysteresis range 204 is left and the system control then moves again to a conventional characteristic line control.

It should be noted in particular, at least according to one embodiment, that the first hysteresis portion 211 is actuated by reaching the lower limit speed n_u. Reaching the lower limit speed n_u, starting from even lower speeds, thus actuates this first hysteresis portion 211. However, this first hysteresis portion is ended by reaching the upper limit power or the upper limit torque thereof. The second hysteresis portion and consequently the hysteresis range 204 is also then left when the power output or the torque increases again. Accordingly, the third hysteresis portion is also actuated by reaching a speed and left by reaching a torque or a power output.

Figure 3 schematically illustrates a control structure. With this control structure 300, the wind turbine 302 which is indicated only schematically therein and which may correspond to the wind turbine 100 of Figure 1 is intended to be controlled. An important block for the present invention is the switching block 304 which, with respect to the characteristic line illustration of Figure 2, controls entry into the hysteresis range 204 or leaving the hysteresis range 204. In this instance, it should be taken into account that this switching block 304 is intended to be understood schematically and in place of the illustrated switching in this switching block 304 other embodiments, in particular using corresponding software solutions, are also considered. Hard switching also does not necessarily have to be carried out, but instead in the switching block 304, or in another manner, and also a transition region must be produced.

In any case, this switching block 304 illustrates that in any case, in order to control the wind turbine, a power P is predetermined. This power P is accordingly provided for control at the wind turbine 302 as a desired power value. This desired power P is implemented there, which inter alia can be carried out by adjusting an exciter current when a remotely excited synchronous generator is used. In another manner, however, a power output of the generator can be controlled, such as, for example, by controlling the stator current, when the generator is a synchronous generator. This power can also be implemented differently in other generator types and the implementation of such a power using a generator is in principle known to the person skilled in the art.

The controller structure 300 now shows both variants in order to predetermine such a power P. The conventional variant involves adjusting the power in accordance with a speed over an operating characteristic line. This is carried out by means of a characteristic line block 306. This block operates in principle in the manner explained with reference to the operating characteristic line 200 in Figure 2, that is to say, without the hysteresis range 204 or outside the hysteresis range 204.

If the current operating point is not outside the hysteresis range 204, however, the control which is guided in accordance with the hysteresis explained in connection with Figure 2 is used. The starting of the control in the hysteresis range is then carried out when the speed in the event of a speed increase reaches the lower limit speed n_u, or, with a speed decrease coming from above, reaches the upper limit speed n_o. Consequently, the switching block 304 receives the speed n as an input variable. Therefore, the switching block 304 can then switch to the hysteresis range.

If the hysteresis range 204 is intended to be left again, this is identified in that, with increasing wind, an upper limit torque is exceeded, that is to say, in particular at the end of the second hysteresis portion 212, or, with decreasing wind, a value falls below a lower limit torque, that is to say, at the end of the fourth hysteresis portion 214. In order to recognise this, the switching block 304 further receives the relevant mechanical torque T_{mech} for this. A torque T can alternatively be referred to as a torque M.

This mechanical torque T_{mech} is estimated by a state monitor 308. The state monitor 308 receives for this as input variables the electrical torque T_{el} and the speed n. The electrical torque T_{el} is generally known from the detected currents of the generator used. As a speed n, it is possible to use the speed which is also otherwise used for the control. Instead of the speed n, the circular frequency ω can also be used. These two variables differ only in their constitution or in the selected unit or therefore differ only by a constant factor.

The control in the hysteresis range 204 is then carried out in such a manner that a desired speed value n_s is supplied to the summation element 301 in which the actual speed n is subtracted from the desired speed n_s. The result of this desired/actual comparison is the control error e. This control error is supplied to the second control block 312 which determines therefrom the power P, that is to say, in a technical control context determines it as the control variable. The power P determined in this manner is then supplied to the switching block 304. If the switching block 304, as a result of the criteria explained above, has switched to the control over the hysteresis range, this power P, which the second control block 312 outputs, is ultimately passed to the wind turbine 302.

This is also intended to be understood schematically since the control structure 300 is ultimately naturally also part of the wind turbine 302.

The second control block 312 may, for example, be in the form of a P controller with a significant amplification. In principle, other controller types may also be considered, such as, for example, a P-I controller, but, with the object which is intended to be achieved in this instance, a small control deviation which the use of a P controller can produce, can be accepted. If, in the case of a simple P controller, in the second controller block 312 only a sufficiently large amplification, that is to say, a sufficiently large P proportion is selected, it is thus nonetheless possible with the first and third hysteresis portion 211 or 213 to assume a substantially perpendicular path.

The desired speed n_s is in this instance determined by the first controller block 311. To this end, the first controller block 311 receives as an input variable the monitored mechanical torque. If this is so large that it reaches an upper limit torque, an upper limit speed n_o is output as the desired speed n_s. However, if the torque falls below or to a lower limit torque, the lower limit speed n_u is output as the desired speed n_s.

This first controller block 311 is consequently a non-linear controller which also takes into account the last adjusted values. If the mechanical torque T_{mech} is in a range between a lower or upper limit torque, the desired speed n_s may according to other conditions be the lower limit speed n_u or the upper limit speed n_o. In this instance, different types of implementation are considered. One is that the first controller block 311 initially selects in each case the last output value for the desired speed n_s and changes the desired speed value n_s only when the value falls below or exceeds the relevant limit torque value. Additionally or alternatively, however, it is also considered that the current speed n is taken into account and accordingly, at a speed which substantially corresponds to the lower limit speed n_u, this is also output as a desired speed value as long as the torque has not yet exceeded the upper limit torque. The same applies when the speed substantially corresponds to the upper limit speed n_o. This is because it is then also output as a desired value as long as the torque has not yet fallen below the lower limit torque. In order to illustrate this, the first controller block 311 receives the speed n as an additional input variable.

By way of precaution, it should again be noted that the switching block 304 is intended to be understood only symbolically since the selection between control via the operating characteristic line using the characteristic line block 306, on the one hand, and via the speed control via the first controller block 311, the summation element 310 and the second controller block 312, on the other hand, may naturally also make other internal adaptations necessary.

If, for example, in the second controller block 312, a PI controller were to be implemented, naturally upon deactivation, that is to say, during control using the characteristic line block 306, a control error e should be prevented from being constantly calculated and the integrator thereby prevented from being continuously integrated upwards. However, this is only one example and it is known to the person skilled in the art that, depending on the selection of the control, that is to say, depending on the selection of whether control is carried out inside or outside the hysteresis range, other internal variables may also be affected.

In some wind turbine types, specific speed ranges have to be avoided or rapidly passed through within the normal operating range. This was achieved according to the prior art with modified speed/power characteristic lines which in the range of the problem speed have “troughs”, the characteristic line consequently extends horizontally, or even falls in terms of its power as the speed increases so that the wind turbine passed the problem range in an accelerated manner or did not operate permanently there. However, particularly as a result of gradient limitations in the speed/power characteristic line, this is linked with losses of output.

The proposed solution makes provision, in particular via a torque monitor, to estimate the aerodynamic torque applied. A hysteresis can consequently then be defined at which the wind turbine accelerates only from a specific threshold torque to a speed above the problem speed and when operating above the problem speed, when the speeds falls only brakes to below the problem speed again from a smaller threshold torque. The width of the hysteresis range, that is to say, the distance of the lower limit speed from the upper limit speed, then defines, depending on the wind dynamics, the frequency of the problem range being passed. The width can accordingly be predetermined.

Based on the torque monitor, a closed speed circuit is possible in the part-load range and is proposed according to one embodiment.

Efficiency losses can thereby be reduced compared with the previously known solution.

Patentkrav

1. Fremgangsmåde til styring af et vindenergianlæg (100, 302) med en aerodynamisk rotor (106) med rotorvinger (108), der er indstillelige i deres vingevinkel, omfattende trinnene

- drift af vindenergianlægget (100, 302) i et delbelastningsområde,
- med et rotoromdrejningstal under et nominelt omdrejningstal (n_N) og
- med en afgivelseseffekt under en nominel effekt,
- anvendelse af
- en omdrejningstal-effektkarakteristik, som angiver en sammenhæng mellem et rotoromdrejningstal, der indstilles afhængigt af den fremherskende vind, og en afgivelseseffekt, der skal indstilles i forhold dertil, eller
- en omdrejningstal-omdrejningsmoment-karakteristik, som angiver en sammenhæng mellem et rotoromdrejningstal, der indstilles afhængigt af den fremherskende vind, og et omdrejningsmoment, der skal indstilles i forhold dertil,
- indstilling af
- en afgivelseseffekt i overensstemmelse med omdrejningstal-effektkarakteristikken eller
- et omdrejningsmoment i overensstemmelse med omdrejningstal-karakteristikken, hvor
- omdrejningstal-effektkarakteristikken eller omdrejningstal-omdrejningsmomentkarakteristikken i området af et problemomdrejningstal (np), som skal undgås, har et hysterese-område (204), og hvor vindenergianlægget (100, 302) drives på en sådan måde, at
- at der ved tiltagende vind op til et nedre grænseomdrejningstal (n_u) indstilles en afgivelseseffekt i overensstemmelse med omdrejningstal-effektkarakteristikken, eller der indstilles et omdrejningsmoment i overensstemmelse med omdrejningstal-omdrejningsmomentkarakteristikken,
- rotoromdrejningstallet fra det nedre grænseomdrejningstal (n_u) ved yderligere tiltagende vind holdes i det væsentlige konstant, og afgivelseseffekten eller omdrejningsmomentet øges, indtil afgivelseseffekten har nået en øvre grænseeffekt (P_o), eller der nås et øvre grænsemoment, og

- når den øvre grænseeffekt (P_o) eller det øvre grænsemoment nås efter afventning af en på forhånd angivet omskiftningsforsinkelse, rotoromdrejningstallet øges til et øvre grænseomdrejningstal (n_o), især øges hurtigst muligt, for at styre problemomdrejningstallet (np), og
- når vinden igen aftager, når rotoromdrejningstallet først ligger over det øvre grænseomdrejningstal (n_o), der indstilles en afgivelseseffekt op til det øvre grænseomdrejningstal (n_o) i overensstemmelse med omdrejningstal-effektkarakteristikken, eller der indstilles et omdrejningsmoment i overensstemmelse med omdrejningstal-omdrejningsmomentkarakteristikken, og
- rotoromdrejningstallet fra det øvre grænseomdrejningstal (n_o) ved yderligere aftagende vind holdes i det væsentlige konstant, og afgivelseseffekten reduceres, indtil afgivelseseffekten har nået en nedre grænseeffekt (P_o), eller omdrejningsmomentet reduceres, indtil der nås et nedre grænsemoment, og
- når den nedre grænseeffekt (P_u) eller det nedre grænsemoment nås efter afventning af den på forhånd angivne eller en yderligere på forhånd angivet omskiftningsforsinkelse, rotoromdrejningstallet reduceres til det nedre grænseomdrejningstal (n_u), især reduceres hurtigst muligt, for at styre problemomdrejningstallet (n_P).

2. Fremgangsmåde ifølge krav 1,
kendetegnet ved, at
indstillingen af afgivelseseffekten eller omdrejningsmomentet sker via en omdrejningstalregulering i hysterese-området, ved at rotoromdrejningstallet ved indstilling af afgivelseseffekten eller omdrejningsmomentet reguleres til en forudbestemt omdrejningstalindstillingsværdi.

3. Fremgangsmåde ifølge krav 1 eller 2,
kendetegnet ved, at
vingevinklen indstilles i hysterese-området afhængigt af afgivelseseffekten eller omdrejningsmomentet og/eller omdrejningstallet.

4. Fremgangsmåde ifølge et af de foregående krav,
kendetegnet ved, at

- hysterese-området rækker fra et forudbestemt nedre grænseomdrejningstal (n_u) under problemomdrejningstallet (n_P) indtil et øvre grænseomdrejningstal (n_o) over problemomdrejningstallet (n_P), og/eller
- problemomdrejningstallet (n_P) er et resonansrotoromdrejningstal.

5. Fremgangsmåde ifølge et af de foregående krav,
kendetegnet ved, at
hysterese-området har følgende afsnit:
- et første hysterese-afsnit (211), som stiger op til den øvre grænseeffekt (P_o) eller det øvre grænsemoment for rotoromdrejningstal under problemomdrejningstallet (np),
- et andet hysterese-afsnit (212), som er tilsluttet det første hysterese-afsnit (211), og som forløber op til et rotoromdrejningstal over problemomdrejningstallet (n_P),
- et tredje hysterese-afsnit (213), som falder til den nedre grænseeffekt eller det nedre grænsemoment for rotoromdrejningstal over problemomdrejningstallet (np), og
- et fjerde hysterese-afsnit (213), som er tilsluttet det tredje hysterese-afsnit (214), og som forløber op til et rotoromdrejningstal over problemomdrejningstallet (n_P).

6. Fremgangsmåde ifølge krav 5,
kendetegnet ved, at
- det første hysterese-afsnit (211) stiger fra det nedre grænseomdrejningstal (n_u) indtil den øvre grænseeffekt (P_o) eller indtil det øvre grænsemoment, især ved et i det væsentlige vedvarende rotoromdrejningstal, og desuden eller alternativt
- det andet hysterese-afsnit (212) forløber op til det øvre grænseomdrejningstal (n_o), især ved en i det væsentlige vedvarende afgivelseseffekt eller vedvarende omdrejningsmoment, og desuden eller alternativt
- det tredje hysterese-afsnit (213) falder fra det nedre grænseomdrejningstal (n_o) indtil den nedre grænseeffekt (P_o) eller indtil det nedre grænsemoment,

især ved et i det væsentlige vedvarende rotoromdrejningstal, og desuden eller alternativt

- det fjerde hysterese-afsnit (214) forløber op til det nedre grænseomdrejningstal (n_u), især ved en i det væsentlige vedvarende afgivelseseffekt eller vedvarende omdrejningsmoment.

7. Fremgangsmåde ifølge et af kravene 1 til 5,

kendetegnet ved, at,

når den øvre grænseeffekt (P_o) eller det øvre grænsemoment nås efter afventning af den på forhånd angivne omskiftningsforsinkelse, rotoromdrejningstallet øges indtil det øvre grænseomdrejningstal (n_o), og afgivelseseffekten reduceres for at styre problemomdrejningstallet (n_P), og/eller

- når den nedre grænseeffekt (P_u) eller det nedre grænsemoment nås efter afventning af den på forhånd angivne eller den yderligere på forhånd angivne omskiftningsforsinkelse, rotoromdrejningstallet reduceres indtil det nedre grænseomdrejningstal (n_u), og afgivelseseffekten øges for at styre problemomdrejningstallet (n_P).

8. Fremgangsmåde ifølge krav 5 eller 6 eller ifølge krav 7, når afhængigt af krav 5,

kendetegnet ved, at

- der til drift af vindenergianlægget (100, 302) i hysterese-området (204) af omdrejningstal-effektkarakteristikken eller omdrejningstal-omdrejningsmomentkarakteristikken optages et omdrejningsmoment (T_{mech}), der indvirker på rotoren (106), især at

- en tilstandsobservatør anvendes til optagelse af det mekaniske omdrejningsmoment (T_{mech}), især for at registrere opnåelsen af det øvre og/eller nedre grænseomdrejningsmoment, hvor

- der især observeres et mekanisk omdrejningsmoment (T_{mech}) ved drift af vindenergianlægget (100, 302) i det første og/eller tredje hysterese-afsnit af hysterese-området (204).

9. Fremgangsmåde ifølge krav 5 eller 6 eller ifølge et af kravene 7-8, når afhængigt af krav 5,

kendetegnet ved, at

- der lægges et første omskiftningskriterium til grund, som afhænger af en effekt eller et omdrejningsmoment, for at omskifte fra det første til det andet hysterese-afsnit, og især
- det første omskiftningskriterium er udformet således, at den på forhånd angivne omskiftningsforsinkelse afventes for at skifte fra det første til det andet hysterese-afsnit, og omskiftningen så sker, når den øvre grænseeffekt (P_o) eller det øvre grænsemoment er nået eller overskredet under hele omskiftningsforsinkelsen, og/eller
- der lægges et andet omskiftningskriterium til grund, som afhænger af en effekt eller et omdrejningsmoment, for at omskifte fra det tredje til det fjerde hysterese-afsnit, og især
- det andet omskiftningskriterium er udformet således, at den på forhånd angivne eller yderligere på forhånd angivne omskiftningsforsinkelse afventes for at omskifte fra det tredje til det fjerde hysterese-afsnit, og omskiftningen så sker, når den nedre grænseeffekt (P_u) eller det nedre grænsemoment er nået eller underskredet under hele omskiftningsforsinkelsen eller yderligere omskiftningsforsinkelse.

10. Fremgangsmåde ifølge et af de foregående krav,

kendetegnet ved, at

tilstandsobservatøren eller en tilstandsobservatør, der anvendes til registrering af det mekaniske omdrejningsmoment (T_{mech}) og eventuelt den til rådighed stående effekt, har omdrejningstallet for generatoren og det mekaniske omdrejningsmoment (T_{mech}) for generatoren som tilstandsstørrelser, der skal observeres.

11. Fremgangsmåde ifølge et af de foregående krav,

kendetegnet ved, at

tilstandsobservatøren eller en tilstandsobservatør, der anvendes til registrering af det mekaniske omdrejningsmoment (T_{mech}), er defineret af strukturen:

$$\begin{bmatrix} \dot{\hat{\omega}} \\ \dot{\hat{T}}_{mech} \end{bmatrix} = \begin{bmatrix} -k_\omega & \frac{1}{J} \\ -k_T & 0 \end{bmatrix} \begin{bmatrix} \hat{\omega} \\ \hat{T}_{mech} \end{bmatrix} + \begin{bmatrix} k_\omega & -\frac{1}{J} \\ k_T & 0 \end{bmatrix} \begin{bmatrix} \omega \\ T_{el} \end{bmatrix}$$

hvor

- J betegner rotorens (106) og generatorens fælles træghedsmoment,
- ω er omdrejningstallet for generatoren,
- kω og kT er parametre til påvirkning af observatørens dynamik,
- T_{el} betegnes som elektrisk omdrejningsmoment (T_{el}) og beregnes som kvotient af en effekt P, der afgives af generatoren, og omdrejningstallet ω, og
- T_{mech} betegner det mekaniske omdrejningsmoment (T_{mech}) af rotoren (106), hvor

de observerede størrelser er identificeret med et ^-tegn og afledningerne med hensyn til tid er identificeret med et hævet punkt, hvor fortrinsvis en til rådighed stående effekt beregnes som et produkt ud fra det observerede omdrejningstal $\hat{\omega}$ og observeret mekanisk omdrejningsmoment $\hat{T}_{mech}$, hvor denne til rådighed stående effekt kan anvendes som mekanisk effekt (P_{mech}) og især kan anvendes som afgivelseseffekt for at kontrollere, om denne når eller overskrider eller underskrider den øvre eller nedre grænseeffekt.

12. Fremgangsmåde ifølge krav 5 eller 6 eller ifølge et af kravene 7-11, når afhængigt af krav 5,

kendetegnet ved, at

- det nedre grænseomdrejningstal (n_u) angives på forhånd for rotoromdrejningstallet som omdrejningstalindstillingsværdi i det første hysterese-afsnit (211), og rotoromdrejningstallet reguleres til det nedre grænseomdrejningstal (n_u) som omdrejningstalindstillingsværdi ved indstilling af afgivelseseffekten,
- når den øvre grænseeffekt (P_o) eller det øvre grænseomdrejningsmoment nås i det første hysterese-afsnit (211), omskiftes der til det andet hystereseafsnit (212), og det øvre grænseomdrejningstal (n_o) angives på forhånd for rotoromdrejningstallet som omdrejningstalindstillingsværdi, således at rotoromdrejningstallet reguleres til det øvre grænseomdrejningstal (n_o) som omdrejningstalindstillingsværdi ved indstilling af afgivelseseffekten eller indstilling af omdrejningsmomentet, hvor der især, når det andet hysterese-afsnit (212) nås

fra det første hysterese-afsnit (211), pludselig øges fra det nedre grænseomdrejningstal (n_u) til det øvre grænseomdrejningstal (n_o) ud fra omdrejningstal-indstillingsværdien,
- det øvre grænseomdrejningstal (n_o) angives på forhånd i det tredje hysterese-afsnit (213) for rotoromdrejningstallet som omdrejningstalindstillingsværdi, og rotoromdrejningstallet reguleres til det øvre grænseomdrejningstal (n_u) som omdrejningstalindstillingsværdi ved indstilling af afgivelseseffekten, og/eller der
- når den nedre grænseeffekt (P_u) eller det nedre grænseomdrejningsmoment nås i det tredje hysterese-afsnit (213), omskiftes til det fjerde hysterese-afsnit (214), og det nedre grænseomdrejningstal (n_u) angives på forhånd for rotoromdrejningstallet som omdrejningstalindstillingsværdi, og rotoromdrejningstallet reguleres til det nedre grænseomdrejningstal (n_u) som omdrejningstalindstillingsværdi ved indstilling af afgivelseseffekten eller indstilling af omdrejningsmomentet, hvor der især, når det fjerde hysterese-afsnit (214) nås fra det tredje hysterese-afsnit (213), pludselig reduceres fra det øvre grænseomdrejningstal (n_o) til det nedre grænseomdrejningstal (n_u) ud fra omdrejningstalindstillingsværdien.

13. Fremgangsmåde ifølge et af de foregående krav,
kendetegnet ved, at
- en omdrejningstalregulering eller omdrejningstalreguleringen af hystereseområdet (204) afsluttes, når
- rotoromdrejningstallet falder med en forudbestemt tærskelværdi under det nedre grænseomdrejningstal (n_u), eller
- rotoromdrejningstallet stiger med en yderligere eller den samme forudbestemte tærskelværdi over det øvre grænseomdrejningstal (n_o), eller
- afgivelseseffekten underskrider den nedre grænseeffekt (P_u) eller
- overskrider den øvre grænseeffekt (P_o), eller når
- et omdrejningsmoment, især det mekaniske omdrejningsmoment (T_{mech}) af generatorens rotor (106) underskrider det nedre grænsemoment eller
- overskrider det øvre grænsemoment.

14. Fremgangsmåde ifølge et af de foregående krav,
kendetegnet ved, at
- det nedre og det øvre grænseomdrejningstal (n_u, n_o) vælges afhængigt af en på forhånd angivet ønsket hyppighed af en gennemkørsel af et hysterese-område (204), og/eller at
- det nedre og det øvre grænseomdrejningstal (n_u, n_o) ligger med en på forhånd angivet omdrejningstaldifference under eller over problemomdrejningstallet (np).

15. Vindenergianlæg (100, 302) med en aerodynamisk rotor (106) med rotorvinger (108), som er indstillelige i deres vingevinkel, omfattende en styreindretning, **kendetegnet ved, at** vindenergianlægget (100, 302) er forberedt til at udføre mindst en fremgangsmåde ifølge et af kravene 1 til 14, især at mindst en fremgangsmåde ifølge et af kravene 1 til 14 er implementeret i styreindretningen, hvor styreindretningen er forberedt til at gennemføre trinnene
- drift af vindenergianlægget (100, 302) i et delbelastningsområde,
- med et rotoromdrejningstal under et nominelt omdrejningstal (n_N) og
- med en afgivelseseffekt under en nominel effekt,
- anvendelse af
- en omdrejningstal-effektkarakteristik, som angiver en sammenhæng mellem et rotoromdrejningstal, der indstilles afhængigt af den fremherskende vind, og en afgivelseseffekt, der skal indstilles i forhold dertil, eller
- en omdrejningstal-omdrejningsmoment-karakteristik, som angiver en sammenhæng mellem et rotoromdrejningstal, der indstilles afhængigt af den fremherskende vind, og et omdrejningsmoment, der skal indstilles i forhold dertil,
- indstilling af
- en afgivelseseffekt i overensstemmelse med omdrejningstal-effektkarakteristikken eller
- et omdrejningsmoment i overensstemmelse med omdrejningstal-karakteristikken, hvor
- omdrejningstal-effektkarakteristikken eller omdrejningstal-omdrejningsmomentkarakteristikken i området af et problemomdrejningstal (np), som skal undgås, har et hysterese-område (204)

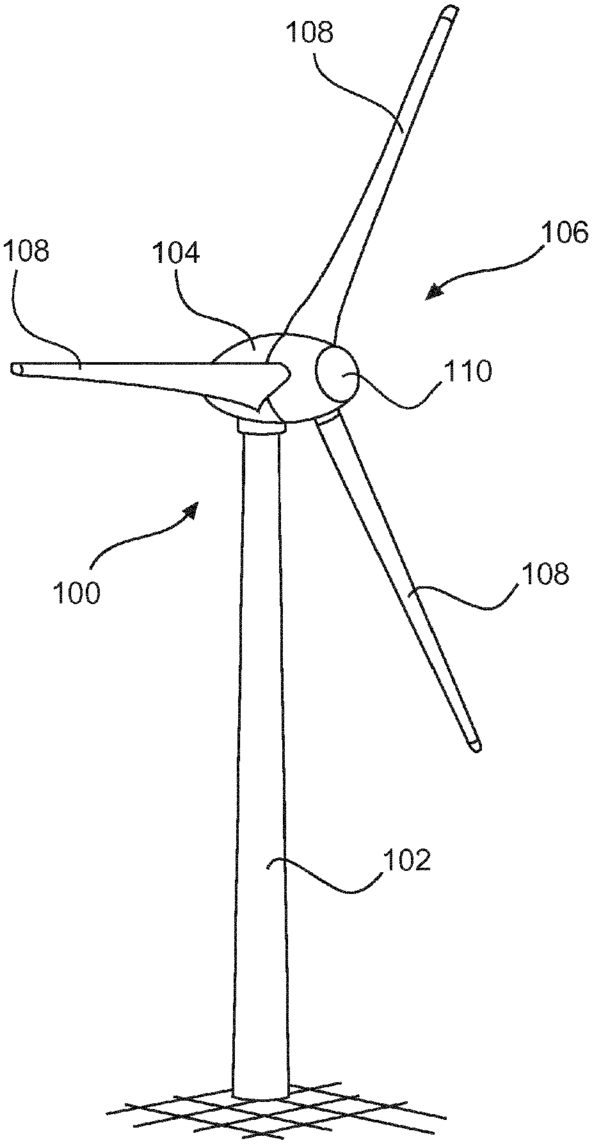

Fig. 1

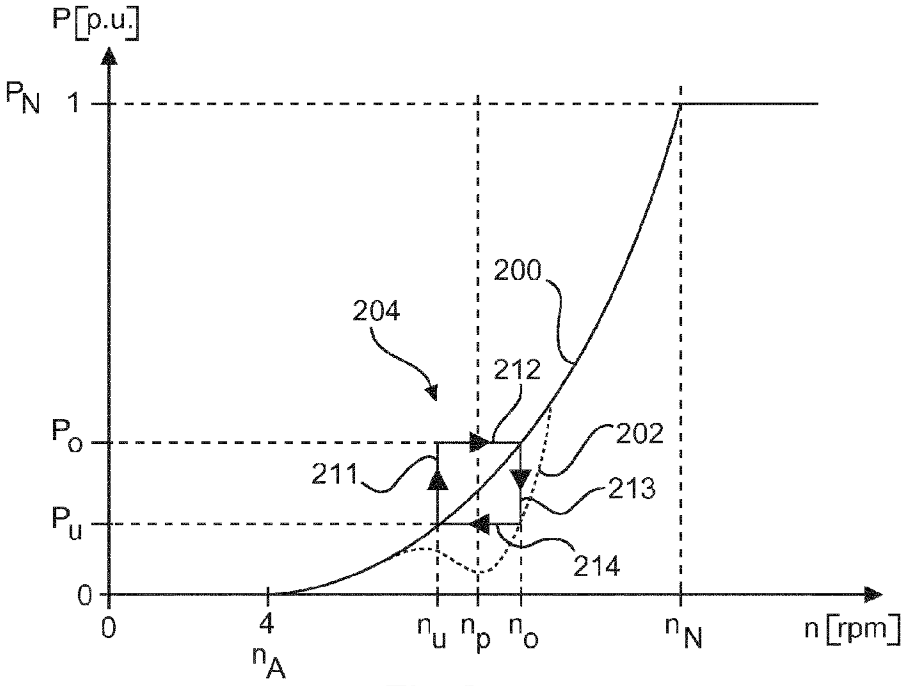
P [p.u.]
P_N
1
200
204
212
202
P_o
211
213
P_u
214
0
0
4
n_A
n_u
n_p
n_o
n_N
n [rpm]

Fig. 2

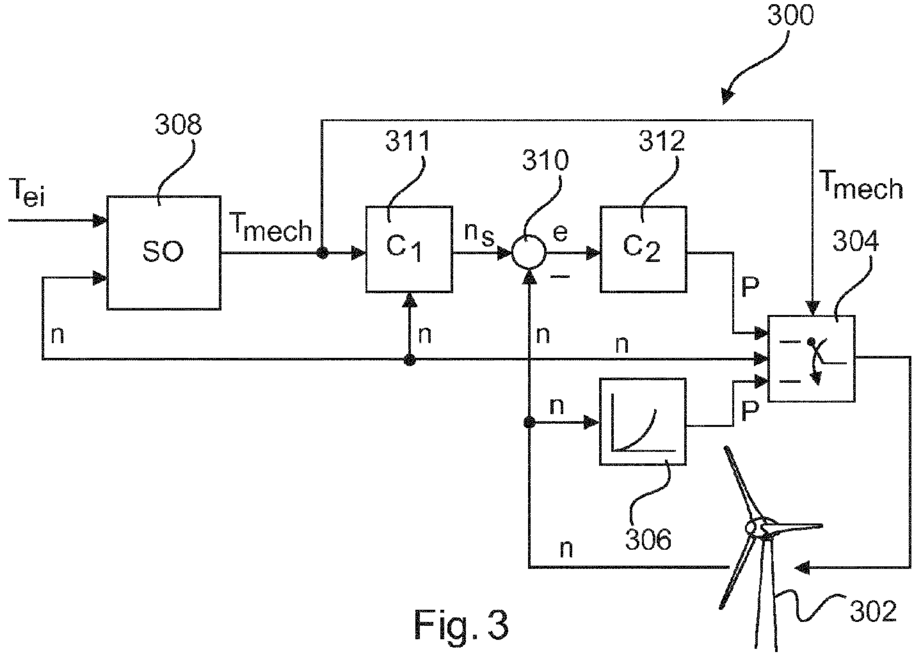
300
308
311
310
312
T_{ei}
SO
T_{mech}
C_1
n_s
e
–
C_2
T_{mech}
304
P
n
n
n
n
n
P
P
306
n
302

Fig. 3