(19) DANMARK

(10) **DK/EP 3884153 T3**

Patent- og
Varemærkestyrelsen

(12) Oversættelse af
europæisk patentskrift

(51) Int.Cl.: ***F 03 D 7/04 (2006.01)***

(45) Oversættelsen bekendtgjort den: **2025-03-31**

(80) Dato for Den Europæiske Patentmyndigheds
bekendtgørelse om meddelelse af patentet: **2025-02-12**

(86) Europæisk ansøgning nr.: **19809428.6**

(86) Europæisk indleveringsdag: **2019-11-22**

(87) Den europæiske ansøgnings publiceringsdag: **2021-09-29**

(86) International ansøgning nr.: **EP2019082244**

(87) Internationalt publikationsnr.: **WO2020104664**

(30) Prioritet: **2018-11-23 DE 102018129622**

(84) Designerede stater: **AL AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC MK MT NL NO PL PT RO RS SE SI SK SM TR**

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(54) Benævnelse: **STYRINGSSTRUKTUR OG STYRINGSMETODE FOR EN VINDMØLLE**

(56) Fremdragne publikationer:
EP-A1- 2 365 215
EP-A1- 3 156 646
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US-A1- 2014 246 855
US-A1- 2015 292 483

The present invention relates to a controller structure for a wind turbine having an aerodynamic rotor with at least one rotor blade, to an associated control method and also to a wind turbine and to a wind farm.

Controller structures for operating wind turbines are known. The most widespread are so-called pitch-controlled wind turbines in which the rotor blades of the rotor of the wind turbine are adjustable about their longitudinal axis, the so-called pitch axis. By changing the pitch angle, an aerodynamic power of the rotor blades is changed, as a result of which it is possible to restrict the power to rated power when the nominal wind is reached. To this end, it is known to provide so-called rotation speed controllers, as are schematically shown in figure 2, in order to approximately adhere to a target rotation speed N_{target}. The rotation speed controller 200 is designed to establish the target rotation speed N_{target} as reference variable as far as possible, wherein an actual rotation speed N_{actual} measured by the wind turbine 100 is fed back and the deviation is converted by means of a P controller 210 and a D controller 220 into a pitch rate to be set. The pitch rate is set to a target pitch rate 240 in a manner limited by a pitch rate limiter 230, the target pitch rate then being used to operate the wind turbine 100.

The quality of control of the rotation speed directly influences the shear loads of important components of the wind turbine, such as the tower and the rotor blades for example.

The German Patent and Trademark Office has searched the following prior art in the priority application relating to the present application: DE 10062025 C1, DE 2903819 A1, DE 10213792 A1, DE 102017105165 A1, US 2014/0246855 A1, US 2015/0130187 A1, EP 2933477 B1.

Additionally, US 2015/292483 A1 describes a system and method for dynamically controlling a wind turbine. The method includes operating the wind turbine based on a thrust set point and a speed set point. A next step includes determining a desired change in actual speed of the wind turbine in response to control actuations starting from an instantaneous operating point. The method also includes determining a desired change in thrust of the wind turbine in response to control actuations starting from the instantaneous operating point. Next, the method determines at least one parameter set point that achieves the desired change in speed and the desired change in thrust and controls the wind turbine based on the parameter set point so as to maintain the actual thrust and the actual speed of the wind turbine within a certain tolerance of the thrust set point and the speed set point, thereby regulating loads acting on the wind turbine while simultaneously maintaining optimal or near optimal power output.

Against this prior art, it was an object of the present invention to provide a controller structure for rotation speed control, which controller structure allows a reduction in the loads on the wind turbine.

According to a first aspect, the object is achieved by a controller structure for a wind turbine according to claim 1.

Designing the rotation speed control arrangement as a cascade control arrangement allows the slow, outer rotation speed control arrangement to allow, as a result, more rapid control by the provision of the inner control loop which has a reference variable that can be rapidly established. This creates the basis for effectively reducing loads acting on the wind turbine. In other words, the sluggish reference variable of the outer control loop is maintained, but the speed of the controller is compensated for by a rapidly changing reference variable of the inner control loop.

In one embodiment, a controlled variable of the outer control loop is provided as reference variable of the inner control loop. The manipulated variable of the outer control loop is accordingly a change in the rotation speed, an acceleration of the rotation speed, a function of the change in the rotation speed and/or a function of the acceleration of the rotation speed.

In one embodiment, the outer control loop is designed to limit a target value of the inner control loop, in particular the change in the rotation speed, the acceleration of the rotation speed, the function of the change in the rotation speed and/or the function of the acceleration of the rotation speed. Therefore, it is advantageously possible to limit a maximum acceleration acting on the rotor and also associated loads.

The input signal of the inner control loop comprises a rotor acceleration power or a rotor acceleration torque, wherein the rotor acceleration power or the rotor acceleration torque describes the portion of a power received by the rotor of the wind turbine or of a torque that is converted into an acceleration of the rotor.

Here and below, the terms “power” and “torque” are used interchangeably since they can be converted one into the other by extremely simple conversions using the rotation speed.

Accordingly, descriptions and advantages which are explained with respect to a power by way of example are likewise applicable to the associated torque, and vice versa.

In one embodiment, the input signal of the inner control loop comprises an aerodynamic power received by the rotor, wherein the aerodynamic power received by the rotor comprises a sum of a rotor acceleration power and at least one power received by a further component of the wind turbine, in particular a generator power of a generator of the wind turbine, wherein the rotor acceleration power describes the portion of a power received by the rotor of the wind turbine that is converted into an acceleration of the rotor.

In one embodiment, the outer control loop determines a deviation of an actual rotation speed of the rotor from a target rotation speed of the rotor as a system deviation.

Therefore, the outer control loop acts in a manner corresponding to a conventional rotation speed control arrangement of the wind turbine, wherein considerably more rapid establishment of the desired variables is rendered possible by the configuration according to the invention as a cascaded control arrangement.

In one embodiment, the outer control loop generates a target value of a power or of a torque as manipulated variable. This power is preferably the acceleration power of the rotor or the received aerodynamic power. Similarly, consideration, as mentioned, with associated torques instead of with powers is possible.

The outer control loop preferably always generates, as target value, the physical variable which serves as an input signal for the inner control loop. This physical input signal generally comprises a change in the rotation speed, an acceleration of the rotation speed, a function of the change in the rotation speed, a function of the acceleration of the rotation speed, a rotor acceleration power, a rotor acceleration torque and/or an aerodynamic power.

In one embodiment, the target value of the power is limited upward and downward. Therefore, excessive control by the inner control loop, which can in turn lead to high loads for example, is avoided.

In one embodiment, the target value of the power is asymmetrically limited upward and downward. Therefore, for example, an acceleration power can be restricted to a value other than the braking power, this in turn resulting in a reduction in the loads which can occur at a maximum.

In one embodiment, the power comprises a rotor acceleration power, wherein the rotor acceleration power is limited to a rated power of the wind turbine, in particular to at most 20% of the rated power of the wind turbine. By limiting the rotor acceleration power, an excessive load acting due to the acceleration is avoided.

In one embodiment, the power comprises an aerodynamic rotor power, wherein the aerodynamic rotor power is limited to twice a rated power of the wind turbine, in particular to at most 120% of the rated power of the wind turbine. The aerodynamic rotor power comprises, in particular, a sum of the generator power and of the rotor acceleration power.

In one embodiment, the inner control loop generates, as manipulated variable, a pitch angle or a rate of change in a pitch angle of at least one of the rotor blades of the rotor. The pitch angles or rates of change in the pitch angle can be provided individually for each rotor blade or else collectively for all of the rotor blades jointly as manipulated variable.

In one embodiment, the target value for the rate of change in the pitch angle is limited, in particular to a value of between -18°/s and 18°/s and particularly preferably to a value of between -5°/s and +5°/s.

In one embodiment, the outer control loop and/or the inner control loop have/has a P controller.

In particular when a pitch angle is output as the target value, the inner control loop has, as an alternative or in addition, an I controller. In particular, the controller can also be designed as a PI controller, advantageously particularly when the output is a blade angle instead of a pitch rate.

In one embodiment, the controller structure further has a calculation component which is designed to determine a rotor acceleration power from a change in a measured actual rotation speed of the wind turbine using the rotor inertia.

In one embodiment, the controller structure further has a pilot control arrangement for pilot control of a pitch angle of at least one rotor blade, which pilot control arrangement is designed to prespecify, parallel to the inner control loop, a pitch angle and/or a rate of change in the pitch angle.

The aerodynamic target power or the target rotor acceleration allows a target blade angle or target pitch angle to be determined therefrom, for example in order to be able to perform pilot control before strong, impending gusts, which target blade angle or target pitch angle is offset against the actual blade angle or actual pitch angle to give a pilot control pitch rate.

The two pitch rates, that is to say the rate of change in the pitch angle on account of the inner control loop and also the rate of change in the pitch angle on account of the pilot control, run preferably in parallel, so that they are superimposed. A matter of designing the wind turbine is then to determine which of the two prespecified rates is implemented in which way by the installation. Owing to the pilot control provided in this aspect, it is possible to at least partially absorb extreme loads, as occur in the case of gusts in particular.

According to a further aspect, the object is achieved according to the invention by a method for operating a wind turbine according to claim 12.

The method according to the invention allows the same advantages to be achieved as are described for the controller structure according to the invention. Similarly, the method, analogously and with associated advantages, can be combined with the refinements described according to the invention as preferred.

According to a further aspect, the object is achieved according to the invention by a wind turbine having a controller structure according to the invention.

According to a further aspect, the object is achieved according to the invention by a wind farm having a plurality of wind turbines according to the invention.

Further advantages and exemplary embodiments are described below with reference to the appended figures, in which:

figure 1 shows, schematically and by way of example, a wind turbine,

figure 2 shows, schematically and by way of example, a controller structure for rotation speed controllers of wind turbines, and

figure 3 shows, schematically and by way of example, a controller structure according to the invention.

Figure 1 shows a schematic representation of a wind turbine according to the invention. The wind turbine 100 has a tower 102 and a nacelle 104 on the tower 102. An aerodynamic rotor 106 with three rotor blades 108 and a spinner 110 is provided on the nacelle 104. During operation of the wind turbine, the aerodynamic rotor 106 is set in a rotational motion by the wind, and therefore also turns an electrodynamic rotor of a generator that is directly or indirectly coupled to the aerodynamic rotor 106. The electrical generator is arranged in the nacelle 104 and generates electrical energy. The pitch angles of the rotor blades 108 can be changed by pitch motors at the rotor blade roots of the respective rotor blades 108.

Fig. 3 shows, schematically and by way of example, a controller structure 300 according to the invention for a wind turbine 100, as is shown in figure 1 for example. The controller structure 300 is designed as a cascade control arrangement and has an outer control loop 310 and an inner control loop 350. The controller structure 300 controls a rotation speed in the wind turbine to a target value N_{target}. To this end, the outer control loop 310 compares the actual rotation speed N_{actual} with a target rotation speed N_{target} to be established and generates a target value 340 for the rotor acceleration power $P_{acceleration\_target}$ by means of a signal, limited by a limiter 330, of a P controller 320.

The inner control loop 350 now performs control to the rotor acceleration power $P_{acceleration}$ and accordingly attempts to set the rotor blades of the wind turbine 100 in such a way that the rotor 106 accelerates as little as possible. To this end, an actual acceleration power $P_{acceleration}$ is determined by means of a calculation unit 380, for example on the basis of the the change in the rotor rotation speed with respect to time dN_{actual}/dt by a calculation unit 380. The difference between the target value 340 of the acceleration power $P_{acceleration\_target}$ and the ascertained actual value $P_{acceleration}$ is converted by a P controller 360 into a pitch rate to be set or a blade angle, to be set, of the rotor blades 108. The pitch rate to be set or the pitch angle to be set is limited by a limiter 370 and is then passed as target value 390 to the control arrangement of the wind turbine 100.

In this example, the calculation unit 380 employs known physical relationships between the moment of inertia J known for the rotor, a torque M and rotation speed or angular velocity ω derived therefrom in order to calculate the actual acceleration power $P_{acceleration}$ from the change in the rotation speed.

Instead of the rotor acceleration power, as is described in the exemplary embodiment, it is also possible to use all of the aerodynamic power received by the rotor, that is to say with additional consideration of the power received by the generator. One advantage of the rotor acceleration power is, in many cases, that the variable is often usually already available for wind estimators used in control of wind turbines 100, that is to say extensive adaptation of the control of the wind turbine 100 is not required. Accordingly, it suffices merely to replace the known rotation speed controller with a controller structure 300 according to the invention. Wind estimators are known, for example, from the German patent publication DE 10 2017 105 165 A1.

As an alternative to powers, the controller structure 300 presented by way of example can also be implemented with torques or rotation speeds derived with respect to time. These solutions are identical apart from the aspect that the current rotation speed is included in the acceleration power. However, the way in which powers are converted into torques, and vice versa, is already sufficiently known.

The inner control loop 350 would alone lead to severe rotation speed errors over time, and therefore the outer control loop 310, which reacts considerably more slowly and sluggishly, generates a target value, which can deviate from 0 kW, for the acceleration power. If, for example, an excessive rotation speed situation prevails, that is to say that the actual rotation speed N_{actual} is greater than the target rotation speed N_{target}, the target value 340 would be, for example, -200 kW. In this case, the inner control loop 350 would establish an approximate rotor acceleration power $P_{acceleration}$ of -200 kW, so that the rotation speed of the rotor 106 is reduced as a result.

Limiting the output of the rotation speed controller by the limiter 330 or 370 allows the maximum acceleration power to be restricted, this likewise having a load-reducing effect.

The controller structure 300 schematically shown in figure 3 can be particularly advantageously supplemented with a pilot control arrangement arranged parallel to the inner control loop 350. The pilot control arrangement can perform pilot control, for example, on impending gusts and accordingly actively intervene in pitch angle adjustment in addition to the control. Therefore, extreme loads that occur, as are the result of strong gusts, can be particularly effectively avoided.

In summary, the controller structure according to the invention accordingly means a controller structure 300 for controlling the rotation speed to a rotation speed target value N_{target}. The inner control loop 350 receives the aerodynamic power received by the rotor 106 or the acceleration power or, in simplified terms, also merely the rotor acceleration as controlled variable, wherein the pitch rate or, as an alternative, also a target rotor blade angle serves as manipulated variable. The outer control loop 310 controls, as controlled variable, the rotor rotation speed N, wherein a target value of the aerodynamic power, of the acceleration power or else of the target rotor acceleration are generated as manipulated variable for the inner control loop 350.

Patentkrav

1. Reguleringsstruktur (300) til en vindmølle (100), der har en aerodynamisk rotor (106) med mindst et rotorblad (108), hvor reguleringsstrukturen (300) er udformet til at regulere en omdrejningshastighed (n) for rotoren (106) i vindmøllen (100), hvor
reguleringsstrukturen (300) er udformet som et kaskadereguleringsindretning og har en ydre reguleringskreds (310) og en indre reguleringskreds (350), hvori
den indre reguleringskreds (350) modtager et indgangssignal (340), som omfatter en ændring i omdrejningshastigheden, en acceleration af omdrejningshastigheden, en funktion af ændringen i omdrejningshastigheden og/eller en funktion af accelerationen af omdrejningshastigheden, **kendetegnet ved, at** indgangssignalet fra den indre reguleringskreds (350) omfatter en rotoraccelerationseffekt eller et rotoraccelerationsmoment, hvor
rotoraccelerationskraften eller rotoraccelerationsmomentet beskriver den del af en kraft eller drejningsmoment, der modtages af rotoren (106) på vindmøllen (100), som omdannes til en acceleration af rotoren (106).

2. Reguleringsstruktur (300) ifølge krav 1, hvor
en reguleringsvariabel af den ydre reguleringskreds (310) er tilvejebragt som referencevariabel for den indre reguleringskreds (350), hvor
den ydre reguleringskreds (310) er især udformet til at begrænse en målværdi for den indre reguleringskreds, især ændringen i omdrejningshastigheden, accelerationen af omdrejningshastigheden, funktionen af ændringen i omdrejningshastigheden og/eller funktionen af accelerationen af omdrejningshastigheden.

3. Reguleringsstruktur (300) ifølge et af de foregående krav, hvor
indgangssignalet fra den indre reguleringskreds (350) omfatter en aerodynamisk effekt, der optages af rotoren (106), hvor

den aerodynamiske effekt, der optages af rotoren (106), omfatter en sum af rotoraccelerationseffekten og mindst en effekt, der optages af en yderligere komponent af vindmøllen (100), især en generatoreffekt fra en generator af vindmøllen (100).

4. Reguleringsstruktur (300) ifølge et af de foregående krav, hvor
den ydre reguleringskreds (310) bestemmer en afvigelse af en faktisk rotationshastighed for rotoren (106) fra en målrotationshastighed for rotoren (106) som en reguleringsafvigelse.

5. Reguleringsstruktur (300) ifølge et af de foregående krav, hvor
den ydre reguleringskreds (310) genererer en målværdi (340) af en effekt eller af et drejningsmoment som manipuleret variabel, hvor målværdien (340) af effekten fortrinsvis er begrænset opad og nedad, og især er asymmetrisk begrænset opad og nedad.

6. Reguleringsstruktur (300) ifølge krav 5, hvor effekten omfatter en rotoraccelerationskraft,
hvor rotoraccelerationseffekten er begrænset til en nominel effekt af vindmøllen (100), især til højst 20% af den nominelle effekt af vindmøllen (100).

7. Reguleringsstruktur (300) ifølge et af kravene 5 eller 6, hvor effekten omfatter en aerodynamisk rotoreffekt,
hvor den aerodynamiske rotoreffekt er begrænset til to gange en nominel effekt af vindmøllen (100), især til højst 120% af den nominelle effekt af vindmøllen (100).

8. Reguleringsstruktur (300) ifølge et af de foregående krav, hvor
den indre reguleringskreds (350) genererer, som en manipuleret variabel, en stigningsvinkel eller en ændringshastighed i en stigningsvinkel på mindst et af

rotorbladene (108) på rotoren (106), hvor målværdien (340) for ændringshastigheden i stigningsvinklen fortrinsvis er begrænset, især til en værdi på mellem -18°/s og 18°/s og især fortrinsvis til en værdi mellem -5°/s og +5°/s.

9. Reguleringsstruktur (300) ifølge et af de foregående krav, hvor den ydre reguleringskreds (310) og/eller den indre reguleringskreds (350) har en P-regulator (320) og/eller en PI-regulator.

10. Reguleringsstruktur (300) ifølge et af de foregående krav, hvor reguleringsstrukturen (300) har yderligere en beregningskomponent, som er indrettet til at bestemme en rotoraccelerationseffekt ud fra en ændring i en målt faktisk rotationshastighed af vindmøllen (100) ved anvendelse af rotorinertien.

11. Reguleringsstruktur (300) ifølge et af de foregående krav, hvor reguleringsstrukturen (300) har yderligere en pilotreguleringsindretning til pilotstyring af en stigningsvinkel på mindst ét rotorblad (108), hvor pilotreguleringsindretningen er indrettet til at forud specificere, parallelt med den indre reguleringskreds (350), en stigningsvinkel og/eller en ændringshastighed i stigningsvinkel.

12. Fremgangsmåde til drift af en vindmølle (100) med en aerodynamisk rotor (106) med mindst ét rotorblad (108), hvor fremgangsmåden er udformet til at regulere en rotationshastighed af vindmøllens (100) rotor (106), hvor fremgangsmåden er udformet som en kaskadereguleringsindretning og har en ydre reguleringskreds (310) og en indre reguleringskreds (350), hvor fremgangsmåden omfatter følgende trin:
ved hjælp af den indre reguleringskreds (350) at opnå et indgangssignal, som omfatter en ændring i omdrejningshastigheden, en acceleration af omdrejningshastigheden, en funktion af ændringen i omdrejningshastigheden og/eller en funktion af accelerationen af omdrejningshastigheden, **kendetegnet ved, at**

indgangssignalet fra den indre reguleringskreds (350) omfatter en rotoraccelerationseffekt eller et rotoraccelerationsmoment, hvor rotoraccelerationskraften eller rotoraccelerationsmomentet beskriver den del af en effekt eller drejningsmoment, der optages af rotoren (106) på vindmøllen (100), som omdannes til en acceleration af rotoren (106).

13. Vindmølle (100) med en reguleringsstruktur (300) ifølge et af kravene 1 til 11.

14. Vindmøllepark med en flerhed af vindmøller (100) ifølge krav 13.

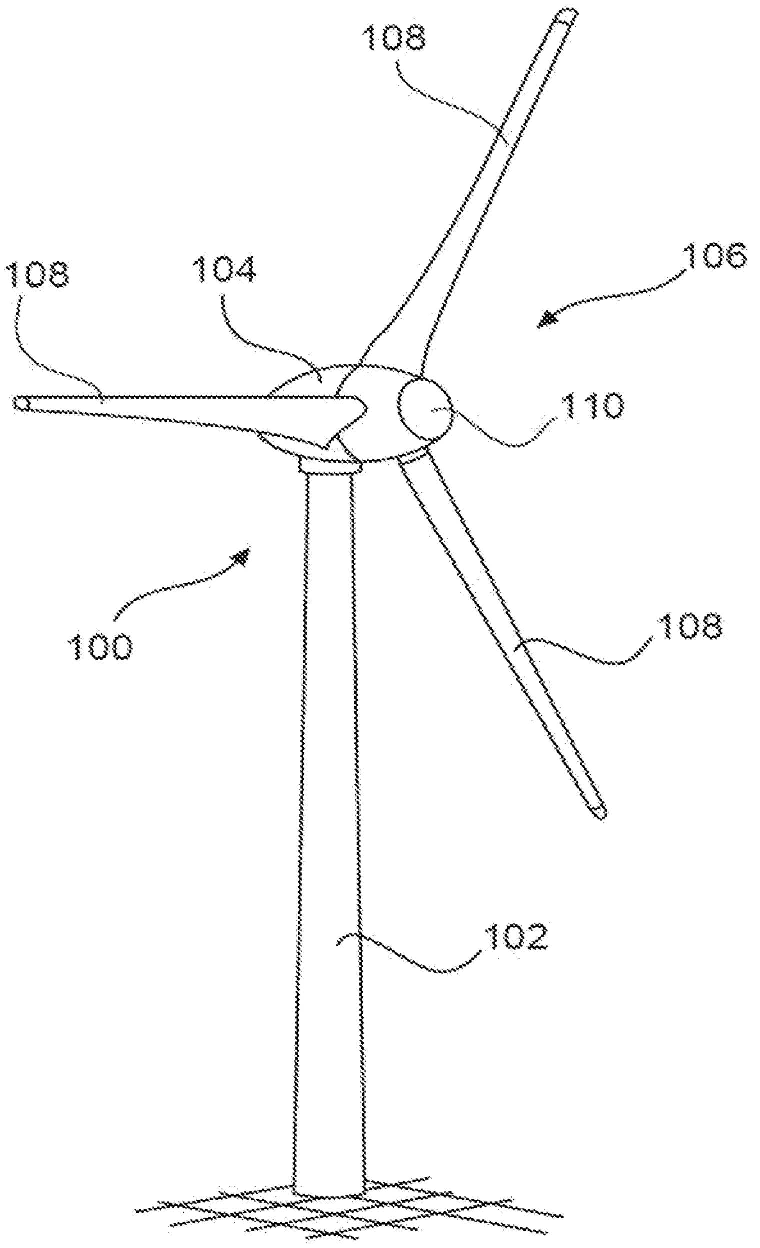

Fig. 1

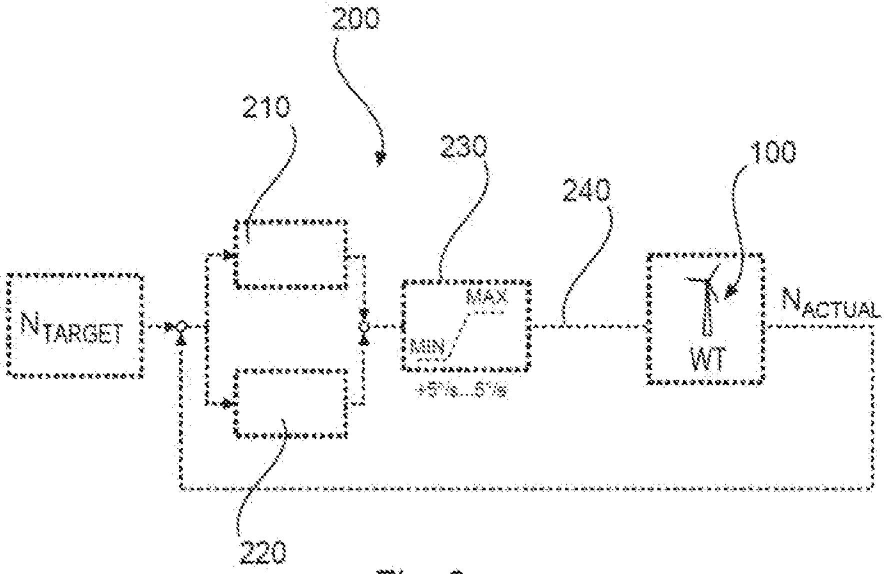
200
210
230
240
100
NTARGET
MAX
MIN
WT
NACTUAL
220

Fig. 2

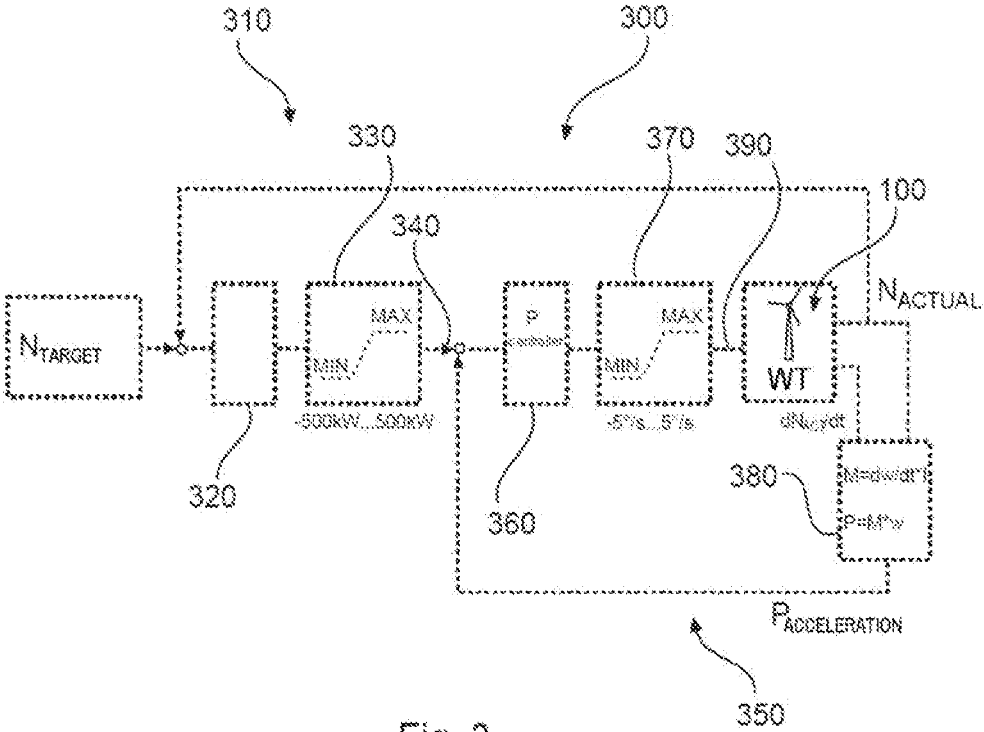
310
300
330
370
390
100
340
NTARGET
MAX
MIN
-500kW...500kW
P
MAX
MIN
-5°/s...5°/s
WT
NACTUAL
320
360
380
PACCELERATION
350

Fig. 3