

(51) International Patent Classification:
F03D 7/06 (2006.01) *F03D 11/00* (2006.01)(21) International Application Number:
PCT/CN2015/073639(22) International Filing Date:
4 March 2015 (04.03.2015)

(25) Filing Language: English

(26) Publication Language: English

(71) Applicant: **GENERAL ELECTRIC COMPANY**
[US/US]; 1 River Road, Schenectady, New York 12345 (US).

(72) Inventors; and

(71) Applicants (for US only): **SOURI, Ramy Michael** [US/US]; 300 Garlington Road, Brookfield Ste 300, Greenville, South Carolina 29615 (US). **SLACK, Robert Peter** [US/US]; 11113 Northeast 33rd Place, Bellevue, Washington 98004 (US). **MASHTARE, Dale Robert** [US/US]; 300 Garlington Road, Brookfield 3rd Floor, Greenville, South Carolina 29615 (US). **RISDON, Ryan Andrew** [US/US]; 300 Garlington Road, Greenville, South Carolina 29615 (US). **AGARWAL, Pranav** [IN/US]; One Research Circle, Niskayuna, New York 12309 (US). **GU, Shuang** [CN/CN]; 1800 Cai Lun Road, CTC2C047, No., Shanghai 201203 (CN).(74) Agent: **CHINA PATENT AGENT (H.K.) LTD.**; 22/F., Great Eagle Center, 23 Harbour Road, Wanchai, Hong Kong (CN).

(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— with international search report (Art. 21(3))

(54) Title: SYSTEM AND METHOD FOR MITIGATING LOADS ON A WIND TURBINE

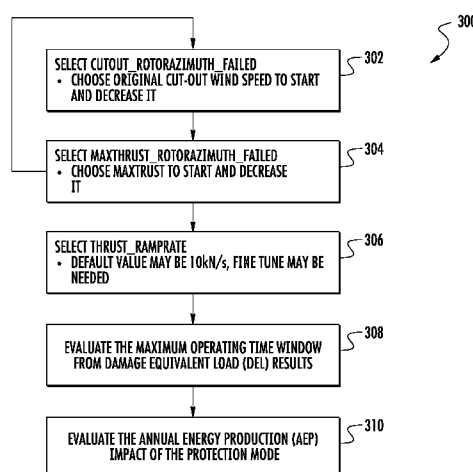


FIG. 11

(57) Abstract: A method for mitigating loads of a wind turbine (10) in response to one or more load sensors (65,66,67) failures. The method includes operating the wind turbine (10) in a standard operating mode through a controller (26), and monitoring loads of the wind turbine (10) through one or more load sensors (65,66,67). The standard operating mode includes a predetermined thrust set point and a predetermined cut-out wind speed set point. In response to detecting one or more load sensors (65,66,67) failures, the method includes enabling a protection operating mode in the controller (26) for a predetermined time period. More specifically, the protection operating mode includes reducing the predetermined thrust set point and the predetermined cut-out wind speed set point. A system for mitigating loads of a wind turbine (10) is also disclosed.

SYSTEM AND METHOD FOR MITIGATING LOADS ON A WIND TURBINE

FIELD OF THE INVENTION

[0001] The present subject matter relates generally to wind turbines and, more particularly, to systems and methods for mitigating loads on a wind turbine in response to one or more load sensor failures.

BACKGROUND OF THE INVENTION

[0002] Wind power is considered one of the cleanest, most environmentally friendly energy sources presently available and wind turbines have gained increased attention in this regard. A modern wind turbine typically includes a tower, a generator, a gearbox, a nacelle, and one or more rotor blades. The rotor blades are the primary elements for converting wind energy into electrical energy. The blades typically have the cross-sectional profile of an airfoil such that, during operation, air flows over the blade producing a pressure difference between its sides. Consequently, a lift force, which is directed from the pressure side towards the suction side, acts on the blade. The lift force generates torque on the main rotor shaft, which is connected to a generator for producing electricity.

[0003] Typically, wind turbines are designed to operate at a rated power output over an anticipated operating life. For instance, a typical wind turbine is designed for a 20-year life. However, in many instances, the operating life is limited based on the fatigue life (or damage equivalent loads (DELs)) of one or more of the wind turbine components and/or extreme loads acting on the wind turbine. Thus, conventional wind turbines implement various control technologies to curtail loads acting on various turbine components so as to maximize the operating life. For example, various systems utilize a plurality of load sensors to detect loads acting on the wind turbine and limit turbine operation accordingly. More specifically, U.S. Patent Number 7,160,083 entitled "Method and Apparatus for Wind Turbine Load Control" describes a method of utilizing a plurality of proximity sensors to determine and mitigate loads for a wind turbine and is incorporated herein by reference in its entirety. Further control systems simply shut down the wind turbine when wind speeds exceed a certain value.

[0004] Shutting down the wind turbine completely, however, results in an undesired reduction in power output and a significant annual energy production (AEP) loss. In addition, for systems that utilize sensors to determine and mitigate loads, it would be desirable to account for time periods of sensor down-time or failure, which can provide unreliable data for determining actual loads on the turbine. Further, prior art systems do not necessarily reduce peak loads, which are often observed at the middle or knee region of the power curve, i.e. typically from about 10 meters/second to about 15 m/s, however the knee region may vary depending on the capacity factor of the wind turbine.

[0005] Accordingly, a system and method for mitigating loads of a wind turbine that addresses the aforementioned issues would be desired in the art. For instance, a system and method for operating a wind turbine that reduces loads during normal operation in the event of sensor down-time or failure would be advantageous.

BRIEF DESCRIPTION OF THE INVENTION

[0006] Aspects and advantages of the invention will be set forth in part in the following description, or may be obvious from the description, or may be learned through practice of the invention.

[0007] In one aspect, the present subject matter is directed to a method for mitigating loads of a wind turbine. In one embodiment, the method includes operating, via a controller, the wind turbine in a standard operating mode. The standard operating mode includes a predetermined thrust set point and a predetermined cut-out wind speed set point. The method also includes monitoring loads of the wind turbine via one or more load sensors. In response to detecting one or more load sensor failures, the method includes enabling a protection operating mode in the controller for a predetermined time period. More specifically, the protection operating mode includes reducing the predetermined thrust set point and/or the predetermined cut-out wind speed set point.

[0008] In additional embodiments, the one or more load sensors may include any suitable sensors, including but not limited to a rotor blade azimuth sensor, a yaw azimuth sensor or encoder, one or more proximity sensors, and/or or a blade strain

sensor. Thus, in one embodiment, the method also includes disabling a rotor imbalance function within the controller in response to detecting one or more proximity sensor failures. More specifically, the rotor imbalance function includes calculating one or more loads of the wind turbine during the standard operating mode caused by yawing or nodding using the one or more load sensors. Thus, if a proximity sensor failure is detected, then the controller can disable the rotor imbalance function and operate the wind turbine using the protection operating mode instead.

[0009] Similarly, in certain embodiments, the method may also include disabling a constrained rotor imbalance function within the controller in response to detecting a rotor blade azimuth sensor failure since the rotor blade azimuth sensor(s) can be more critical to load estimations. The constrained rotor imbalance function includes calculating one or more loads of the wind turbine during a shut-down mode caused by yawing or nodding using the one or more load sensors. Thus, if a rotor blade azimuth sensor failure is detected, then the controller can disable the constrained rotor imbalance function and operate the wind turbine using the protection operating mode instead.

[0010] In another embodiment, the method may include disabling the protection operating mode after the predetermined time period and reverting to the standard operating mode, e.g. if the sensor failure is cleared. More specifically, in certain embodiments, the step of reverting to the standard operating mode may include resetting at least one of the predetermined thrust set point or the predetermined cut-out wind speed set point or enabling the rotor imbalance function.

[0011] In further embodiments, the method may include selecting a ramp rate for reducing the predetermined thrust set point. As such, the method may also include reducing the predetermined thrust set point based on the ramp rate. In particular embodiments, the method may further include tuning the ramp rate by starting with the predetermined thrust set point and incrementally reducing the predetermined thrust set point until one or more loads of the wind turbine are below design limits.

[0012] In various embodiments, the load sensors as described herein are configured to measure at least one of the following: a rotor load (e.g. an asymmetric rotor loading), a wind turbine thrust, a main-shaft deflection, one or more vibrations, a

blade loading, a tower loading or acceleration, a shaft loading, a nacelle loading, a pitch bearing loading, a yaw bearing loading, a hub loading, a pitch- or yaw-bearing loading, and/or similar, or any combinations thereof. In another aspect, the present disclosure is directed to a method for protecting a wind turbine in response to one or more load sensor failures. The method includes monitoring loads of the wind turbine via the one or more load sensors, wherein the one or more load sensors are configured to detect at least one of an asymmetric rotor load or a tower acceleration. In response to detecting one or more load sensor failures, the method also includes activating a protection operating mode in a wind turbine controller for a predetermined time period. More specifically, in certain embodiments, the protection operating mode includes reducing a predetermined thrust set point and/or a predetermined cut-out wind speed set point stored in the controller. It should be understood that the method may further include any of the additional steps and/or features described herein.

[0013] In yet another aspect, the present subject matter is directed to a system for mitigating loads of a wind turbine. The system includes one or more load sensors configured to monitor loads of the wind turbine and a processor configured to perform one or more operations. More specifically, the operations include operating the wind turbine in a standard operating mode having a predetermined thrust set point and a predetermined cut-out wind speed set point and in response to detecting one or more load sensor failures, enabling a protection operating mode for a predetermined time period. Further, the protection operating mode includes reducing the predetermined thrust set point and/or the predetermined cut-out wind speed set point. It should be understood that the system may further be configured to with any of the features described herein.

[0014] These and other features, aspects and advantages of the present invention will become better understood with reference to the following description and appended claims. The accompanying drawings, which are incorporated in and constitute a part of this specification, illustrate embodiments of the invention and, together with the description, serve to explain the principles of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] A full and enabling disclosure of the present invention, including the best mode thereof, directed to one of ordinary skill in the art, is set forth in the specification, which makes reference to the appended figures, in which:

[0016] FIG. 1 illustrates a perspective view of one embodiment of a wind turbine according to the present disclosure;

[0017] FIG. 2 illustrates a graph of one embodiment of a power curve of a wind turbine according to the present disclosure, particularly illustrating the various operating regions of the wind turbine from the cut-in wind speed to the cut-out wind speed;

[0018] FIG. 3 illustrates a schematic view of one embodiment of suitable components that may be included within a turbine controller of the wind turbine shown in FIG. 1;

[0019] FIG. 4 illustrates a schematic view of one embodiment of a wind farm according to the present disclosure;

[0020] FIG. 5 illustrates a perspective view of one embodiment of a wind turbine according to the present disclosure, particularly illustrating various axes of rotation and corresponding forces and moments acting on the wind turbine;

[0021] FIG. 6 illustrates a schematic view of one embodiment of a system for mitigating loads of a wind turbine during a time period of sensor failure according to the present disclosure;

[0022] FIG. 7 illustrates a graph of one embodiment of thrust versus time of a wind turbine, particularly illustrating the thrust during a protection operating mode of the wind turbine according to the present disclosure;

[0023] FIG. 8 illustrates a graph of one embodiment of the collective thrust value and the pitch command of a wind turbine as the controller of the wind turbine transitions from a standard operating mode to a protection operating mode according to the present disclosure;

[0024] FIG. 9 illustrates a graph of one embodiment of the collective thrust value and the pitch command of a wind turbine as the controller of the wind turbine transitions from a protection operating mode to a standard operating mode according to the present disclosure;

[0025] FIG. 10 illustrates a graph of one embodiment of a power curve of a wind turbine, particularly illustrating the effect on the power output of the wind turbine in response to a reduction in the thrust set point according to the present disclosure; and

[0026] FIG. 11 illustrates a flow diagram of one embodiment of a tuning process for a rotor blade azimuth sensor according to the present disclosure.

DETAILED DESCRIPTION OF THE INVENTION

[0027] Reference now will be made in detail to embodiments of the invention, one or more examples of which are illustrated in the drawings. Each example is provided by way of explanation of the invention, not limitation of the invention. In fact, it will be apparent to those skilled in the art that various modifications and variations can be made in the present invention without departing from the scope or spirit of the invention. For instance, features illustrated or described as part of one embodiment can be used with another embodiment to yield a still further embodiment. Thus, it is intended that the present invention covers such modifications and variations as come within the scope of the appended claims and their equivalents.

[0028] Generally, the present subject matter is directed to a system and method for mitigating loads of a wind turbine during a period of sensor failure. During normal operation of the wind turbine, a plurality of sensors coupled to a controller monitor loads acting on the wind turbine to ensure that the loads remain within their respective design envelopes. If one or more of the sensors fail, the loads of the wind turbine may exceed design limits, thereby causing damage to the wind turbine. As such, the present disclosure is directed to mitigating loads in response to a sensor failure. More specifically, the system of the present disclosure includes a controller that is configured to operate the wind turbine in a standard operating mode having a predetermined thrust set point and a predetermined cut-out wind speed set point. Thus, the controller monitor loads of the wind turbine via one or more load sensors during the standard operating mode. If the controller detects one or more load sensor failures, the controller is configured to enable a protection operating mode for a predetermined time period. More specifically, during the protection operating mode, the controller is configured to reduce the predetermined thrust set point and the

predetermined cut-out wind speed set point by a certain amount to ensure that loads acting on the wind turbine remain within their design envelopes until the sensors are repaired or replaced.

[0029] The present system and method provides many advantages not present in the prior art. For example, the present disclosure utilizes a combination of reduced cut-out wind speed and thrust to reduce the peak values of most load sensors, thereby allowing the turbine to produce full power in the wind speed region when loads are smaller than the load envelope. More specifically, reducing the thrust level at the knee region of the power curve has resulted in peak loads reduction. In addition, reducing the cut-out wind speed results in blade root and imbalance loads reduction. As such, the present disclosure provides less power loss than prior art systems that simply de-rate power or shut down the wind turbine to control loads. Further, the present disclosure is capable of quantifying life consumption of the turbine based on a fatigue loads analysis. Accordingly, the life consumption can be communicated to the turbine controller such that any necessary operating conditions may be applied to impose further limitations on turbine operation as needed.

[0030] Referring now to the drawings, FIG. 1 illustrates a perspective view of one embodiment of a wind turbine 10 configured to implement the control technology according to the present disclosure. As shown, the wind turbine 10 generally includes a tower 12 extending from a support surface 14, a nacelle 16 mounted on the tower 12, and a rotor 18 coupled to the nacelle 16. The rotor 18 includes a rotatable hub 20 and at least one rotor blade 22 coupled to and extending outwardly from the hub 20. For example, in the illustrated embodiment, the rotor 18 includes three rotor blades 22. However, in an alternative embodiment, the rotor 18 may include more or less than three rotor blades 22. Each rotor blade 22 may be spaced about the hub 20 to facilitate rotating the rotor 18 to enable kinetic energy to be transferred from the wind into usable mechanical energy, and subsequently, electrical energy. For instance, the hub 20 may be rotatably coupled to an electric generator (not shown) positioned within the nacelle 16 to permit electrical energy to be produced.

[0031] The wind turbine 10 may also include a wind turbine controller 26 centralized within the nacelle 16. However, in other embodiments, the controller 26 may be located within any other component of the wind turbine 10 or at a location

outside the wind turbine. Further, the controller 26 may be communicatively coupled to any number of the components of the wind turbine 10 in order to control the operation of such components and/or to implement a corrective action. As such, the controller 26 may include a computer or other suitable processing unit. Thus, in several embodiments, the controller 26 may include suitable computer-readable instructions that, when implemented, configure the controller 26 to perform various different functions, such as receiving, transmitting and/or executing wind turbine control signals.

[0032] Accordingly, the controller 26 may generally be configured to control the various operating modes of the wind turbine 10 (e.g., start-up or shut-down sequences), de-rate the wind turbine 10, and/or control various components of the wind turbine 10. For example, as shown in FIG. 2, the controller 26 may operate the wind turbine 10 according to the illustrated power curve. As shown, at very low wind speeds, there is insufficient torque exerted by the wind on the rotor blades 22 to make the blades 22 rotate. However, as the speed increases, the wind turbine 10 begins to rotate and generate electrical power. More specifically, once the wind speed reaches the cut-in wind speed (i.e. the speed at which the turbine 10 first starts to generate power), the controller begins to operate the wind turbine 10 in a standard operating mode. The cut-in wind speed may vary between wind turbines, but is typically from about 3 meters/second (m/s) to about 4 m/s. As the wind speed increases from the low wind speed region to the middle wind speed region (e.g. the knee region), the power produced by the wind turbine 10 increases to a rated power. The rated power generally refers to the maximum amount of power that can be produced by the generator, therefore, once the rated power is reached, the controller 26 is designed to limit the power to this maximum level, e.g. by pitching the blades 22. More specifically, in certain embodiments, the controller 26 may control the blade pitch (i.e., an angle that determines a perspective of the rotor blades 22 with respect to the direction of the wind) by adjusting an angular position of at least one rotor blade 22 relative to the wind. For instance, the controller 26 may control the pitch angle of the rotor blades 22 by rotating the rotor blades 22 about a pitch axis 28, either individually or simultaneously, by transmitting suitable control signals to a pitch drive or pitch adjustment mechanism (not shown) of the wind turbine 10. Still referring to

FIG. 2, as the wind speed continues to increase above the rated output wind speed (e.g. in the high wind speed region), the loads on the wind turbine 10 also continue to increase, which can cause damage the wind turbine components. As a result, the controller 26 is configured to de-rate or shut down the wind turbine 10 (e.g. via a braking system) when a predetermined cut-out wind speed is reached to prevent loads from surpassing allowable limits. The cut-out wind speed may also vary between wind turbines, but is typically around 25 m/s.

[0033] Referring now to FIG. 3, a block diagram of one embodiment of suitable components that may be included within the controller 26 is illustrated in accordance with aspects of the present subject matter. As shown, the controller 26 may include one or more processor(s) 58 and associated memory device(s) 60 configured to perform a variety of computer-implemented functions (e.g., performing the methods, steps, calculations and the like disclosed herein). As used herein, the term “processor” refers not only to integrated circuits referred to in the art as being included in a computer, but also refers to a controller, a microcontroller, a microcomputer, a programmable logic controller (PLC), an application specific integrated circuit, and other programmable circuits.

[0034] Additionally, the memory device(s) 60 may generally comprise memory element(s) including, but are not limited to, computer readable medium (e.g., random access memory (RAM)), computer readable non-volatile medium (e.g., a flash memory), a floppy disk, a compact disc-read only memory (CD-ROM), a magneto-optical disk (MOD), a digital versatile disc (DVD) and/or other suitable memory elements. Further, the controller 26 may also include a communications module 62 to facilitate communications between the controller 26 and the various components of the wind turbine 10. For instance, the communications module 62 may include a sensor interface 64 (e.g., one or more analog-to-digital converters) to permit the signals transmitted by one or more sensors 65, 66, 67 (e.g. load sensors) to be converted into signals that can be understood and processed by the controller 26. It should be appreciated that the sensors 65, 66, 67 may be communicatively coupled to the communications module 62 using any suitable means. For example, as shown in FIG. 3, the sensors 65, 66, 67 are coupled to the sensor interface 64 via a wired connection. However, in other embodiments, the sensors 65, 66, 67 may be coupled

to the sensor interface 64 via a wireless connection, such as by using any suitable wireless communications protocol known in the art. As such, the processor 58 may be configured to receive one or more signals from the sensors 65, 66, 67.

[0035] The sensors 65, 66, 67 of the wind turbine 10 may be any suitable sensors configured to measure any operating or loading condition at or near the wind turbine. For example, the sensors may include blade sensors for measuring a pitch angle of one of the rotor blades 22 or for measuring a loading acting on one of the rotor blades 22; generator sensors for monitoring the generator (e.g. torque, rotational speed, acceleration and/or the power output); and/or various wind sensors 65 for measuring various wind parameters. More specifically, in certain embodiments, the sensors 65, 66, 67 may include load sensors, including but not limited to one or more rotor blade azimuth sensors, one or more yaw azimuth sensors or encoders, one or more proximity sensors, and/or one or more blade strain sensors. For example, in certain embodiments, the sensors 65, 66, 67 may include similar sensors as those described in U.S. Patent Number 7,160,083 entitled “Method and Apparatus for Wind Turbine Load Control” which is incorporated herein by reference in its entirety. As such, in particular embodiments, the sensors 65, 66, 67 may be configured to measure at least one of the following: a rotor load (e.g. an asymmetric rotor loading), a wind turbine thrust, a main-shaft deflection, one or more vibrations, a blade loading, a tower loading or acceleration, a shaft loading, a nacelle loading, a pitch bearing loading, a yaw bearing loading, a hub loading, a pitch- or yaw-bearing loading, or similar or any combination thereof. Accordingly, the sensors 65, 66, 67 are configured to measure fatigue and/or extreme loads acting on the wind turbine 10 and/or its various components. Fatigue loads are typically caused by the cyclic movement of the wind turbine and/or constant loads that cause damage over time and are often referred to as damage equivalent loads (DELs), whereas extreme loads are typically caused by storm loads and/or extreme turbulence intensity levels that occur in short intervals.

[0036] In addition, the sensors 65, 66, 67 may be located near the ground of the wind turbine, on the nacelle, or on a meteorological mast of the wind turbine. It should also be understood that any other number or type of sensors may be employed and at any location. For example, the sensors may be accelerometers, pressure sensors, angle of attack sensors, vibration sensors, MIMU sensors, camera systems,

fiber optic systems, anemometers, wind vanes, Sonic Detection and Ranging (SODAR) sensors, infra lasers, Light Detecting and Ranging (LIDAR) sensors, radiometers, pitot tubes, rawinsondes, other optical sensors, and/or any other suitable sensors. It should be appreciated that, as used herein, the term “monitor” and variations thereof indicates that the various sensors of the wind turbine may be configured to provide a direct measurement of the parameters being monitored or an indirect measurement of such parameters. Thus, the sensors 65, 66, 67 may, for example, be used to generate signals relating to the parameter being monitored, which can then be utilized by the controller 26 to determine the actual condition.

[0037] Referring now to FIG. 4, the system and method as described herein may also be combined with a wind farm controller 222 of a wind farm 200. As shown, the wind farm 200 may include a plurality of wind turbines 202, including the wind turbine 10 described above. For example, as shown in the illustrated embodiment, the wind farm 200 includes twelve wind turbines, including wind turbine 10. However, in other embodiments, the wind farm 200 may include any other number of wind turbines, such as less than twelve wind turbines or greater than twelve wind turbines. In one embodiment, the controller 26 of wind turbine 10 may be communicatively coupled to the farm controller 222 through a wired connection, such as by connecting the controller 26 through suitable communicative links 226 (e.g., a suitable cable). Alternatively, the controller 26 may be communicatively coupled to the farm controller 222 through a wireless connection, such as by using any suitable wireless communications protocol known in the art.

[0038] Referring now to FIG. 5, an exploded view of one embodiment of a wind turbine 10 is shown, particularly illustrating the various axes of rotation and corresponding forces and moments acting on the wind turbine 10. The peak loads of the wind turbine 10 may vary between turbines, but in general, typically correspond to at least one of the following: the blade root resultant moment (e.g. M_{rB} , which includes pitch and hub loads M_{xB} , M_{yb} , and M_{zb}), main shaft loads (e.g. M_{yr} , M_{zr}), main bearing loads (e.g. M_{xr} , M_{yr}), yaw drive loads (e.g. M_{xk}), yaw bolts/bearing/flange loads (e.g. M_{yk} , M_{zk}) or tower bending loads (e.g. M_{xt} , M_{yt} , and M_{zt}). It should be understood that the peak loads as described herein may also include any additional loads experienced by the wind turbine 10 and that the loads

illustrated in FIG. 5 are provided for example purposes only. As such, when one or more sensors associated with one of the aforementioned loads fails, the system of the present disclosure is configured to implement the control technology as described herein so as to mitigate loads of the wind turbine 10 until the sensor is repaired or replaced.

[0039] More specifically, as shown in FIG. 6, a schematic view of one embodiment of the system 100 for mitigating loads of the wind turbine 10 in response to a sensor failure according to the present disclosure is illustrated. Thus, the system 100 is configured to reduce extreme loads to within the design envelopes, reduce fatigue loads (DELs), reduce AEP loss during failure time, and/or limit the additional turbine life consumption during failure time. More specifically, as shown, the system 100 is configured to choose a certain operating mode according to the type of sensor failure. For example, some load sensors may be more crucial than others for accurate load estimates, thereby requiring additional protection steps and/or a more aggressive approach if such sensor fails. Thus, in certain embodiments, the system 100 can modify the protection mode according to the severity of the failed sensor on load estimations. More specifically, in one embodiment, the system 100 can follow a first control path if a proximity sensor fails and a different control path should a rotor blade azimuth sensor fail. Once the processor 58 detects a sensor failure, certain signals may be set to false to initiate the control scheme of FIG. 6. For example, as shown at 102, the processor 58 is configured to set the ProxSen_Available signal to false if a proximity sensor fails or RotorAzim_Err to false if the rotor blade azimuth sensor fails. It should be understood that these sensor signals are provided for illustrative purposes only and are not meant to be limiting. Rather, any other sensor signals may be detected and received by the processor 58 such that the processor 58 can determine whether the sensor is operating properly.

[0040] As shown at 124, the processor 58 is configured to activate the protection operating mode in response to a sensor failure. In contrast, if a sensor failure is not detected, the processor 58 continues operating in the standard operating mode according to MaxThrust 110, which corresponds to the predetermined thrust set point. Though the MaxThrust 110 may be any suitable thrust value and may vary between

different wind turbines, an example thrust value may be from about 300 kilo-Newtons (kN) to about 400 kN.

[0041] For purposes of illustration, it is assumed that a sensor failure has been detected by the processor 58 such that that protection operating mode has been activated. Thus, during the protection operating mode, the processor 58 is configured to reduce the predetermined thrust set point to a new reduced value (e.g. ThrustSetPoint_ProxSen_Failed or ThrustSetPoint_RotorAzimuth_Failed) depending on the type of sensor failure as shown at 104. For example, in the event of a proximity sensor failure, the original thrust set point (e.g. MaxThrust 110) may be decreased to a reduced thrust set point (e.g. MaxThrust 108). More specifically, in certain embodiments, the MaxThrust 110 may be reduced by about 10% to about 20% of its original value. In further embodiments, the MaxThrust 110 may be reduced by less than 10% or more than 20% of its original value. Similarly, in the event of a rotor blade azimuth sensor failure, the original thrust set point (e.g. MaxThrust 110) may be decreased to a reduced thrust set point (e.g. MaxThrust 108). For example, in particular embodiments, the MaxThrust 110 may be reduced by about 15% to about 25% of its original value since the rotor blade azimuth sensor is typically more crucial than other sensors for accurate load estimations. In further embodiments, the MaxThrust 110 may be reduced by less than 15% or more than 25% of its original value. As such, the processor 58 can select the appropriate reduced thrust set point via switch 112 depending on the type of sensor failure.

[0042] The processor 58 is also configured to reduce the cut-out wind speed in addition to reducing the thrust set point in response to a sensor failure. More specifically, as shown at 114 and 116, the processor 58 is configured to lower the predetermined cut-out wind speed according to Cutout_ProxSen_Failed 116 or Cutout_RotorAzimuth_Failed 114 depending on the type of sensor failure via switch 118. For example, in the event of a proximity sensor failure, the original cutout wind speed (e.g. of about 25 m/s) may be decreased to the reduced cut-out wind speed (e.g. CutOut_ProxSen_Failed). More specifically, in certain embodiments, the original cutout wind speed may be reduced by about 10% to about 20% of its original value. In further embodiments, the original cutout wind speed may be reduced by less than 10% or more than 20% of its original value. Similarly, in the event of a rotor blade

azimuth sensor failure, the original cutout wind speed may be decreased to a reduced cut-out wind speed (e.g. CutOut_RotorAzimuth_Failed). More specifically, in particular embodiments, the original cutout wind speed may be reduced by about 15% to about 25% of its original value. In further embodiments, the original cutout wind speed may be reduced by less than 15% or more than 25% of its original value.

[0043] In addition, as shown at 106, the processor 58 is configured to reduce the predetermined thrust set point according to a ramp rate (e.g. Thrust_RampRate). More specifically, as shown in FIG. 7, the ramp rate may be from about 5 kilo-Newtons/second (kN/s) to about 15 kN/s, more preferably about 10 kN/s. In further embodiments, the ramp rate may be more than 15 kN/s or less than 5 kN/s. As such, when a sensor failure is detected as shown at 109, the controller 108 is configured to ramp down the thrust level according the ramp rate until the thrust value reaches a reduced thrust set point. In certain embodiments, the reduced thrust set point may be from about 225 kN to about 325 kN, more preferably from about 250 kN to about 300 kN. After a certain time period (e.g. T_1), the failed sensor may be repaired or replaced as shown at 111, therefore, the controller 108 may ramp up the thrust level to its original value as shown at 113.

[0044] Referring back to FIG. 6, some wind turbine control systems may include a rotor imbalance function within the controller 108. More specifically, the rotor imbalance function generally includes an algorithm that is configured to calculate, using the one or more load sensor signals, loads of the wind turbine 10 during the standard operating mode caused by yawing or nodding. In such an embodiment, as shown at 120, the controller 108 is configured to disable the rotor imbalance function within the controller 108 in response to detecting one or more load sensor failures since properly operating sensors are required to accurately calculate a rotor imbalance.

[0045] In addition, some controllers may include a constrained rotor imbalance function that generally includes an algorithm configured to calculate, using one or more load sensors, loads of the wind turbine during a shut-down mode caused by yawing or nodding. In such an embodiment, as shown at 122, the controller 108 is configured to disable the constrained rotor imbalance function within the controller 108 in response to detecting one or more load sensor failures (e.g. a rotor blade

azimuth sensor failure represented by DynCtl_RotorAzim_Err = false) since properly operating sensors are required to accurately calculate a rotor imbalance during shut down.

[0046] During the protection operating mode, when the rotor imbalance function (and possibly the constrained rotor imbalance function) has been switched off, the imbalance loads at high wind speed typically drive extreme loads. Therefore, reducing the cut-out wind speed according to the present disclosure effectively reduces such loads. In addition, reducing the maximum thrust limit during the protection operating mode can reduce loads of key sensors to be within their respective design envelopes. Though reducing the thrust level and cut-out wind speed may reduce the extreme load values, the reduction in the thrust set point and the cut-out wind speed may not necessarily reduce fatigue loads to be within the design envelopes since the rotor imbalance function(s) is disabled and therefore cannot effectively handle and mitigate the imbalance loads. Therefore, in certain embodiments, the controller 108 may also be configured to limit the length of the protection operating mode to a predetermined time period such that fatigue loads do not surpass a certain limit. As such, if the failed sensor(s) are not repaired or replaced within the predetermined time period, the controller 108 may de-rate or shut down the wind turbine 10 to protect the wind turbine components from excessive loading.

[0047] In additional embodiments, if the failed sensors are repaired or replaced, the controller 108 is configured to revert back to the standard operating mode of normal power production. More specifically, if the ProxSen_Available signal becomes true or the DynCtl_ProxRotorAzim_Err goes to false again, the controller 108 can implement a recovery mode to return operation of the turbine 10 back to the standard operating mode from protection operating mode. More specifically, the controller 108 is configured to complete one or more of the following steps to return to the standard operating mode: reset the reduced thrust set point to MaxThrust 110, reset the reduced cut-out wind speed set point to the original predetermined cut-out wind speed set point, and/or enable the rotor imbalance or the constrained rotor imbalance functions.

[0048] Referring now to FIGS. 8 and 9, various graphs illustrating the collective thrust value and pitch command from the standard operating mode to the protection

operating mode (FIG. 8) and recovery from the protection operating mode to the standard operating mode (FIG. 9) are shown. More specifically, FIGS. 8 and 9 illustrate the thrust curve in the transient time when the protection mode is on (curve 152) and off (curve 150). As shown, curve 150 is provided for comparison to curve 152 to illustrate that the thrust value is reduced when the protection mode is activated. Further, curves 154, 156 illustrate the difference in the pitch angle when the protection mode is on (curve 156) and off (curve 154). In addition, as shown in FIG. 9, when the controller 108 reverts back to the standard operating mode from the protection operating mode, the thrust acting on the wind turbine 10 increases.

[0049] After operation of the wind turbine 10 in the protection operating mode, the controller 108 may also determine the impact of such operation on the turbine life. For example, in certain embodiments, the Palmgren-Miner rule may be used to calculate the additional life cost of operating the wind turbine 10 in the protection operating mode. More specifically, the controller 108 may use a concept of equivalent time to quantify additional time cost of the protection operating mode. As used herein, the “equivalent time” concept generally refers to the idea that running the turbine in the protection operating mode when one or more sensor fails for n_{days} time will have the same accumulated damage loads as running the turbine in the standard operating mode for n_{eqtime} time. For example, as shown in Equation (1) below, if S_2 is the fatigue load (e.g. the damage equivalent load (DEL)) of the protection operating mode and $S_{\text{env(ref)}}$ is the load envelope value for the DEL, the equivalent time can be calculated as follows:

$$n_{\text{eqtime}} = n_{\text{days}} \cdot \frac{N_{\text{ref}}}{N_2} = n_{\text{days}} \cdot \left(\frac{S_2}{S_{\text{env(ref)}}} \right)^m \quad \text{Equation (1)}$$

where N_{ref} is the number of reference cycles of stress of a wind turbine for 20 years, N_2 is number of cycles to failure when the stress equals S_2 in the wind turbine's S-N curve, and

m is the S-N curve exponent.

[0050] The controller is also configured to calculate the maximum operating time period for the protection operating mode. More specifically, in certain embodiments, the controller 108 may use Equation (2) below to calculate the maximum operating

time period, n_{maxdays} , for the protection operating mode, assuming the protection operating mode will consume an additional 5% of the turbine life.

$$n_{\text{maxdays}} = \frac{5\% \times 365 \times 20}{\left(\frac{s_2}{s_{\text{env(ref)}}}\right)^m - 1} \quad \text{Equation (2)}$$

where m is the S-N curve exponent.

[0051] Referring now to FIG. 10, a graph illustrating the effect that reducing the thrust set point has on power as compared to prior art systems is illustrated. The power output during the standard operating mode is represented by line 160, the power output during the protection operating mode of the present disclosure is represented by line 162, and the power output of prior art protection systems is represented by line 164. As shown, operating the wind turbine 10 in the protection operating mode results in an annual energy production (AEP) loss as compared to the standard operating mode, however, the AEP loss is much less than the loss experienced by prior art systems since many prior art systems typically de-rate or shut down the wind turbine 10 during sensor failures. More specifically, many prior art systems experience a power loss of up to 70% or greater, whereas the power loss of the present disclosure is substantially less, e.g. about 5%.

[0052] In addition, the AEP loss of the present disclosure can be evaluated by incorporating the sensor's unavailability. More specifically, the controller 108 can determine the actual AEP (i.e. AEP_{real}) and the AEP loss (i.e. AEP_{loss}) based on Equations (3) and (4) below:

$$\text{AEP}_{\text{real}} = (1 - \text{unavailability}) \times \text{AEP}_{\text{nominal}} + \text{unavailability} * \text{AEP}_{\text{PS}} \quad \text{Equation (3)}$$

$$\text{AEP}_{\text{loss}} = \frac{\text{AEP}_{\text{nominal}} - \text{AEP}_{\text{real}}}{\text{AEP}_{\text{nominal}}} \quad \text{Equation (4)}$$

where $\text{AEP}_{\text{nominal}}$ is the AEP value in normal condition (i.e. no sensor failure occurs), AEP_{PS} is the AEP value in the protection mode, and unavailability is the percentage of unavailability of sensors.

[0053] Referring now to FIGS. 6 and 11, the controller 108 may also be configured to tune the protection operating mode control strategy. More specifically, as shown, a flow chart 300 of one embodiment of a tuning process for the case of a

rotor blade azimuth sensor is illustrated. As shown at 302, the controller 26 selects the CutOut_RotorAzimuth_Failed signal and chooses the original cut-out wind speed as a starting point and begins to incrementally decrease it. At 304, the controller 26 selects the MaxThrust_RotorAzimuth_Failed signal and chooses the predetermined thrust set point (e.g. MaxThrust) as a starting point and begins to incrementally decrease it. Accordingly, steps 302 and 304 can be used to evaluate extreme and fatigue loads and AEP. Further, the controller 26 may be configured to choose the reduced cut-out wind speed and thrust by balancing the loads reduction and AEP loss. Further, at 306, the controller 26 is configured to select the Thrust_RampRate and tune the ramp rate as needed. In addition, during this step, the controller 26 is configured to operate the wind turbine 10 in the standard operating mode with set/unset values for DynCtl_ProxRotorAzim_Err at different times to check if the transient behaviors are stable. More specifically, as shown, the default ramp rate may be 10 kN/s, however, this value can be tuned to smooth the procedure to enter or exit the protection operating mode. At 308 and 310, the controller 26 is configured to use the methods described herein to evaluate the maximum operating time and the total AEP loss during the tuning process. More specifically, as shown, the controller 26 is configured to evaluate the maximum operating time window from the fatigue/DEL analysis and evaluate the AEP impact of the protection operating mode.

[0054] This written description uses examples to disclose the invention, including the best mode, and also to enable any person skilled in the art to practice the invention, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the invention is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims if they include structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal languages of the claims.

WHAT IS CLAIMED IS:

1. A method for mitigating loads of a wind turbine, the method comprising:
 - operating, via a controller, the wind turbine in a standard operating mode, the standard operating mode comprising a predetermined thrust set point and a predetermined cut-out wind speed set point;
 - monitoring loads of the wind turbine via one or more load sensors; and,
 - in response to detecting one or more load sensor failures, enabling a protection operating mode in the controller for a predetermined time period, wherein the protection operating mode comprises reducing at least one of the predetermined thrust set point or the predetermined cut-out wind speed set point.
2. The method of claim 1, further comprising reducing the predetermined thrust set point and the predetermined cut-out wind speed set point.
3. The method of claim 1, wherein the one or more load sensors comprise at least one of a rotor blade azimuth sensor, a yaw azimuth sensor, one or more proximity sensors, or a blade strain sensor.
4. The method of claim 1, further comprising disabling a rotor imbalance function within the controller in response to detecting one or more load sensor failures, wherein the rotor imbalance function comprises calculating one or more loads of the wind turbine during the standard operating mode caused by yawing or nodding using the one or more load sensors.
5. The method of claim 4, further comprising disabling a constrained rotor imbalance function within the controller in response to detecting one or more rotor blade azimuth sensor failures, wherein the constrained rotor imbalance function comprises calculating one or more loads of the wind turbine during a shut-down mode caused by yawing or nodding using the one or more load sensor failures.
6. The method of claim 1, further comprising disabling the protection operating mode after the predetermined time period and reverting to the standard operating mode.
7. The method of claim 6, wherein reverting to the standard operating mode further comprises resetting at least one of the predetermined thrust set point or

the predetermined cut-out wind speed set point or enabling the rotor imbalance function.

8. The method of claim 1, further comprising:

selecting a ramp rate for reducing the predetermined thrust set point; and
reducing the predetermined thrust set point based on the ramp rate.

9. The method of claim 8, further comprising tuning the ramp rate by starting with the predetermined thrust set point and incrementally reducing the predetermined thrust set point until one or more loads of the wind turbine are below design limits.

10. The method of claim 1, wherein the load sensors are configured to measure at least one of the following: a rotor load, a wind turbine thrust, one or more vibrations, a blade loading, a tower loading or acceleration, a shaft loading, a nacelle loading, a pitch bearing loading, a yaw bearing loading, a hub loading, or a pitch- or yaw-bearing loading.

11. A method for protecting a wind turbine in response to one or more load sensor failures, the method comprising:

monitoring loads of the wind turbine via the one or more load sensors, wherein the one or more load sensors are configured to detect at least one of an asymmetric rotor load or a tower acceleration; and,

in response to detecting one or more load sensor failures, implementing a protection operating mode in a wind turbine controller for a predetermined time period, wherein the protection operating mode comprises:

reducing at least one of a predetermined thrust set point or a
predetermined cut-out wind speed set point stored in the controller.

12. The method of claim 11, wherein the load sensors comprise at least one of a rotor blade azimuth sensor, a yaw azimuth encoder, one or more proximity sensors, or a blade strain sensor.

13. The method of claim 11, further comprising disabling a rotor imbalance function within the controller in response to detecting one or more load sensor failures, wherein the rotor imbalance function comprises calculating one or more loads of the wind turbine during the standard operating mode caused by yawing or nodding using the one or more load sensors.

14. The method of claim 13, further comprising disabling a constrained rotor imbalance function within the controller in response to detecting one or more rotor blade azimuth sensor failures, wherein the constrained rotor imbalance function comprises calculating one or more loads of the wind turbine during a shut-down mode caused by yawing or nodding using the one or more load sensor failures.

15. A system for mitigating loads of a wind turbine, the system comprising:

one or more load sensors configured to monitor loads of the wind turbine;

a processor configured to perform one or more operations, the operation comprising:

operating the wind turbine in a standard operating mode, the standard operating mode comprising a predetermined thrust set point and a predetermined cut-out wind speed set point;

in response to detecting one or more load sensor failures, enabling a protection operating mode for a predetermined time period, wherein the protection operating mode comprises reducing at least one of the predetermined thrust set point or the predetermined cut-out wind speed set point.

16. The system of claim 15, wherein the one or more load sensors comprise at least one of a rotor blade azimuth sensor, a yaw azimuth sensor, one or more proximity sensors, or a blade strain sensor.

17. The system of claim 16, wherein the processor is further configured to disable a rotor imbalance function within the controller in response to detecting one or more load sensor failures, wherein the rotor imbalance function comprises calculating one or more loads of the wind turbine during the standard operating mode caused by yawing or nodding using the one or more load sensors.

18. The system of claim 17, wherein the processor is further configured to disable a constrained rotor imbalance function within the controller in response to detecting one or more rotor blade azimuth sensor failures, wherein the constrained rotor imbalance function comprises calculating one or more loads of the wind turbine during a shut-down mode caused by yawing or nodding using the one or more load sensor failures.

19. The system of claim 15, further comprising disabling the protection operating mode after the predetermined time period and reverting to the standard operating mode, wherein reverting to the standard operating mode further comprises resetting at least one of the predetermined thrust set point or the predetermined cut-out wind speed set point or enabling the rotor imbalance function.

20. The system of claim 15, further comprising:
selecting a ramp rate for reducing the predetermined thrust set point; and
reducing the predetermined thrust set point based on the ramp rate.

1/9

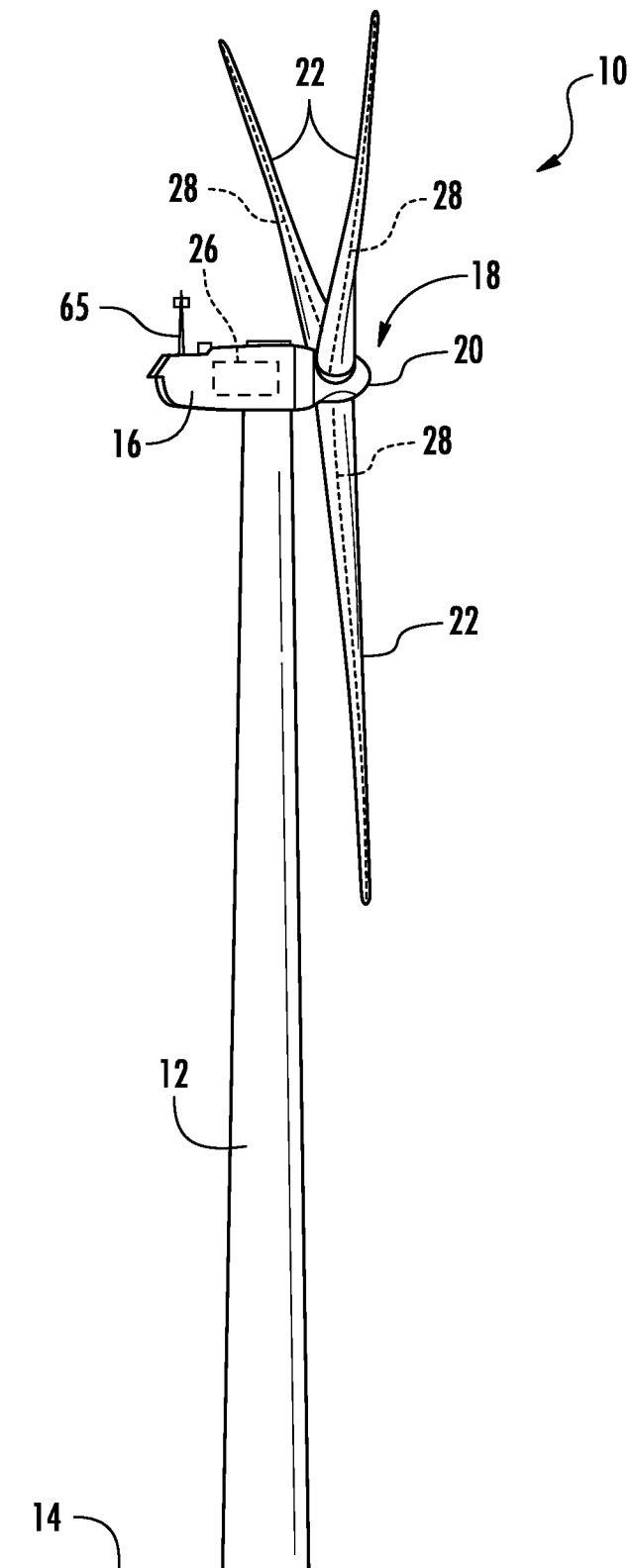


FIG. 1

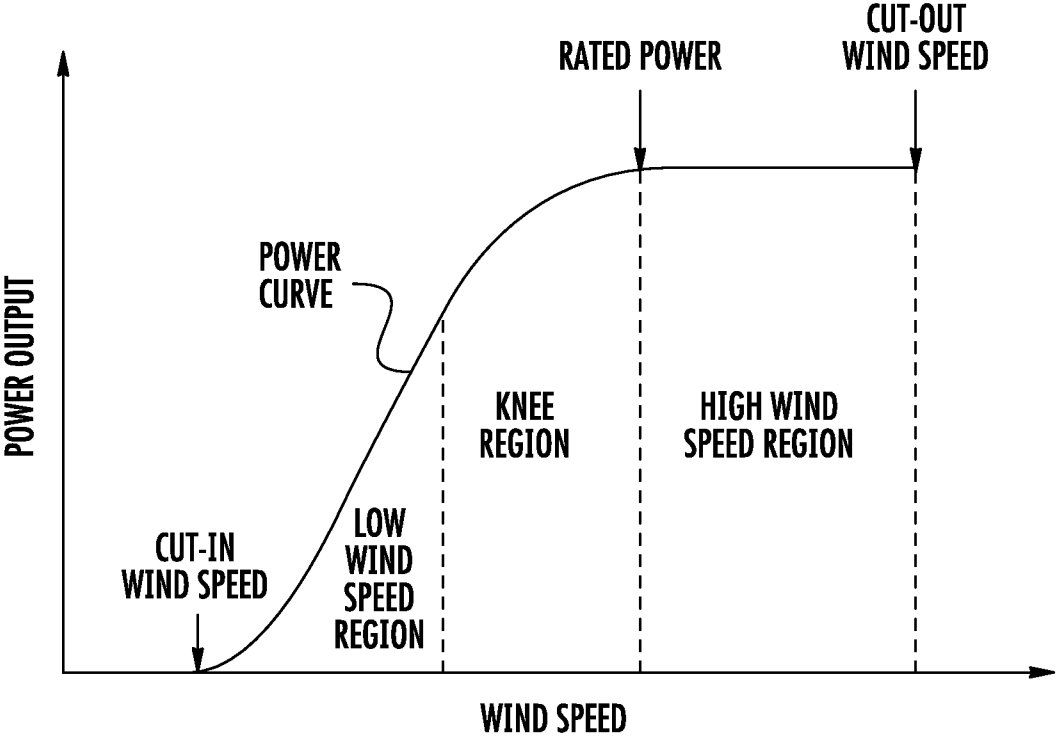
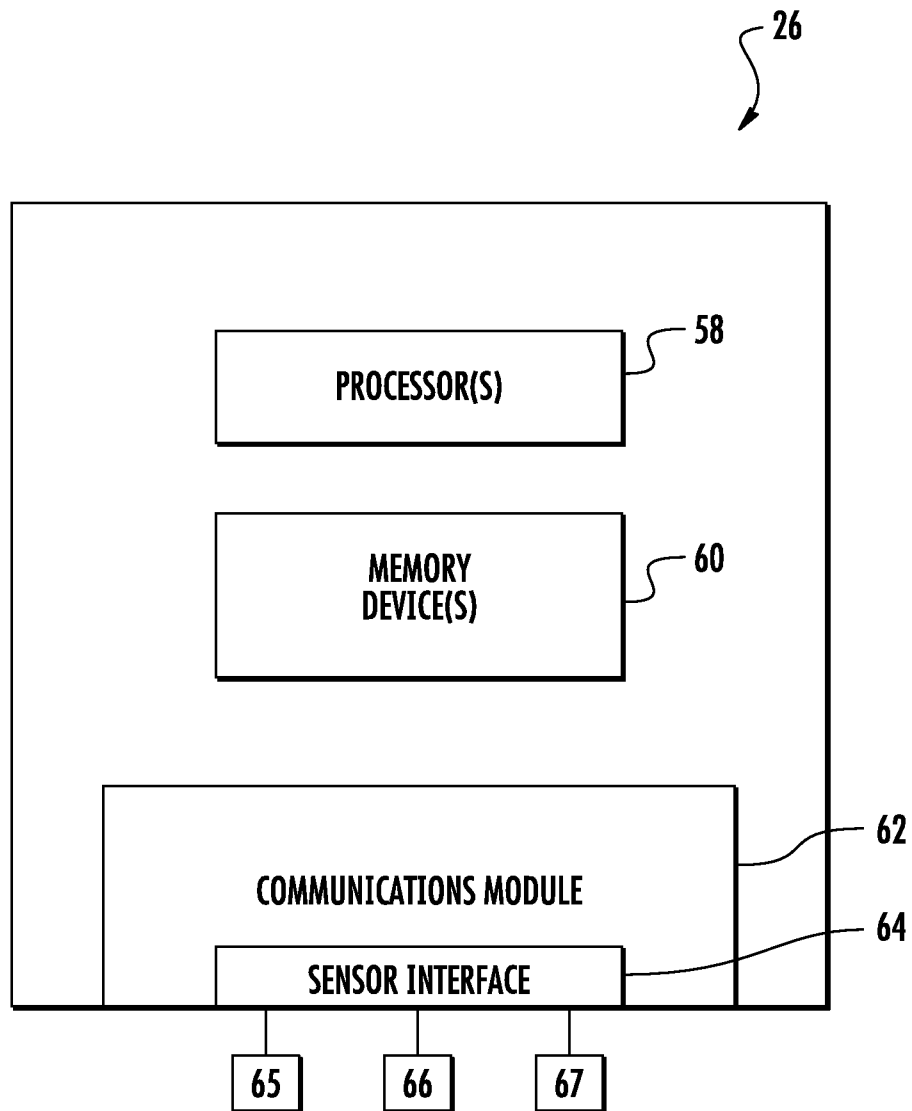
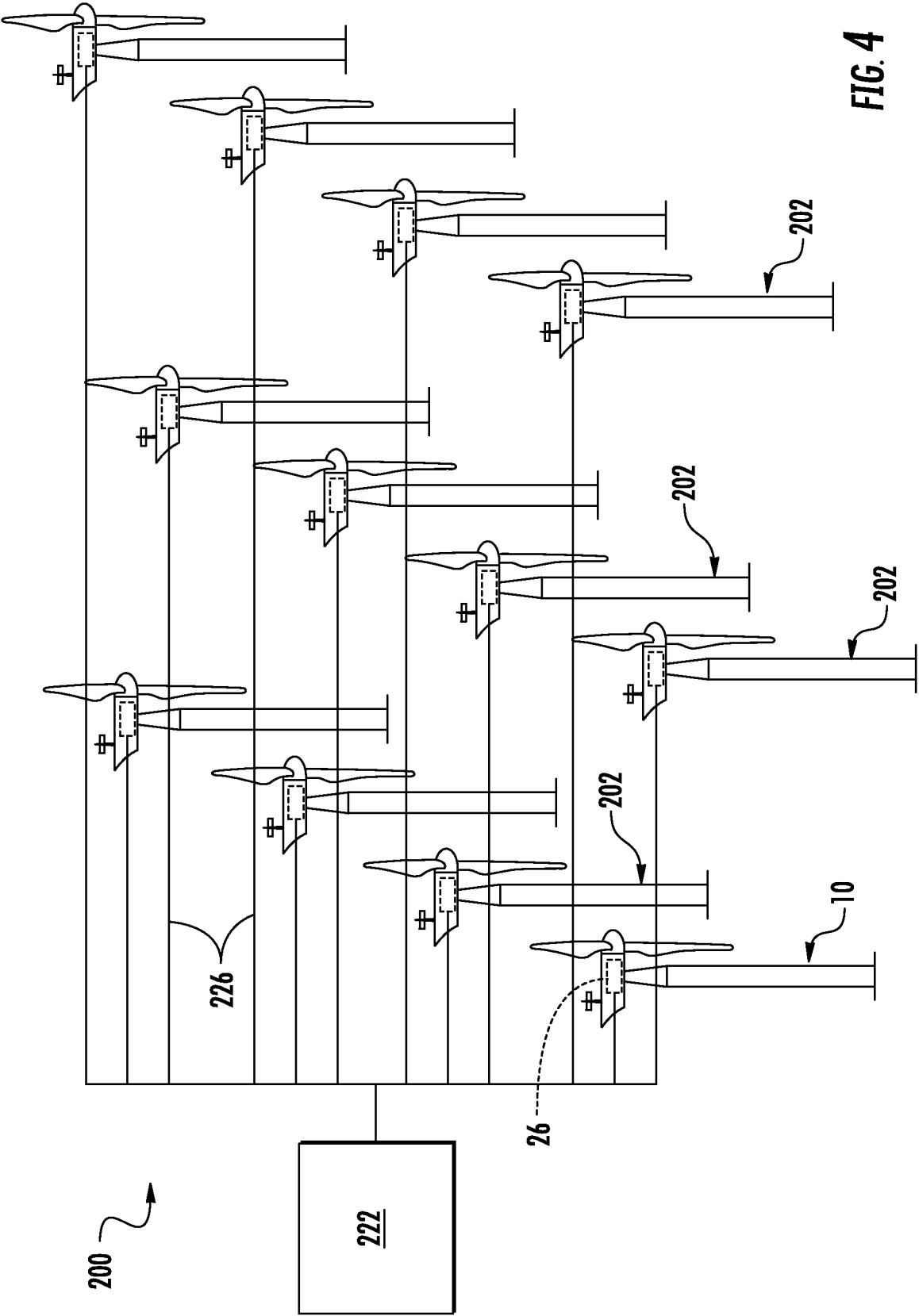


FIG. 2

3/9

**FIG. 3**



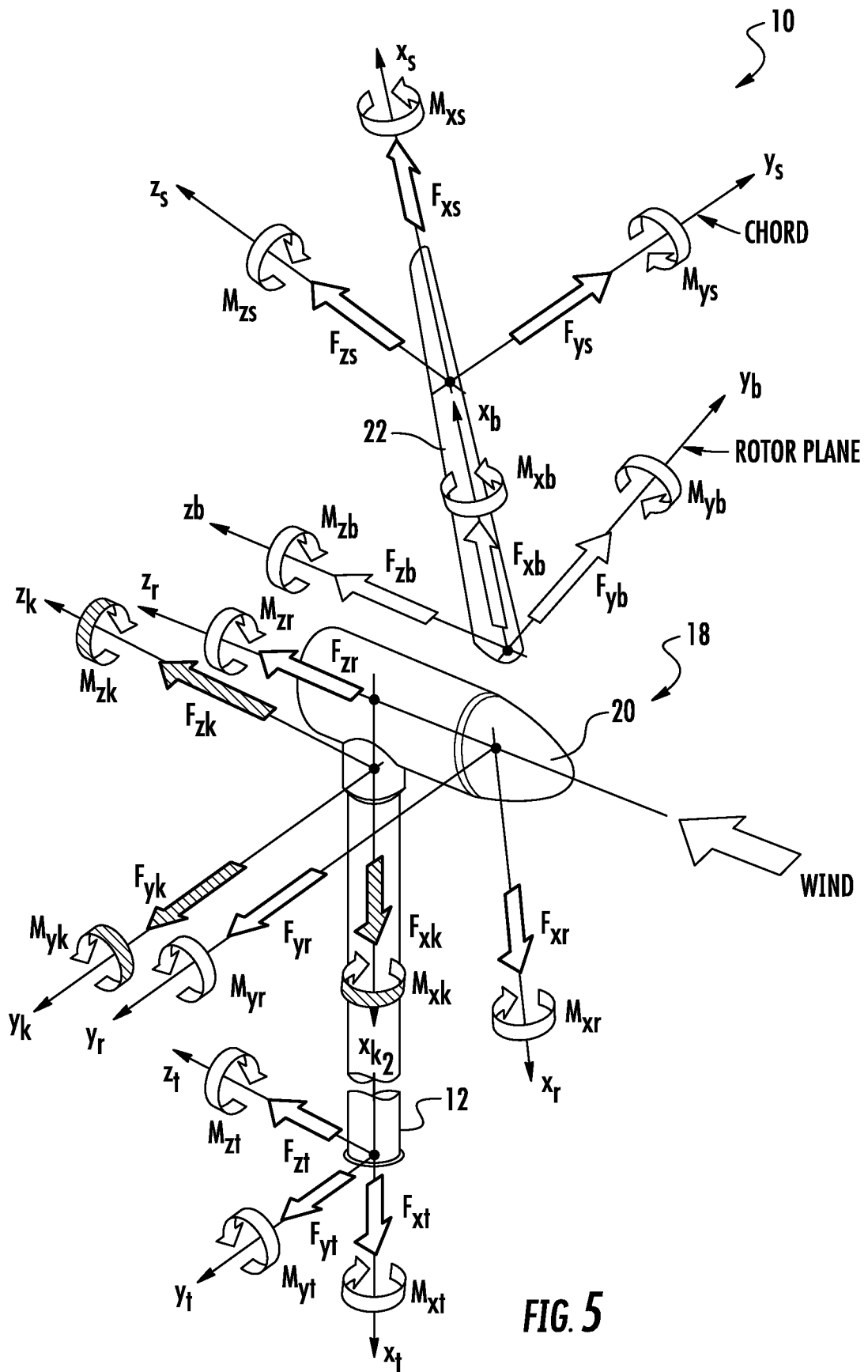


FIG. 5

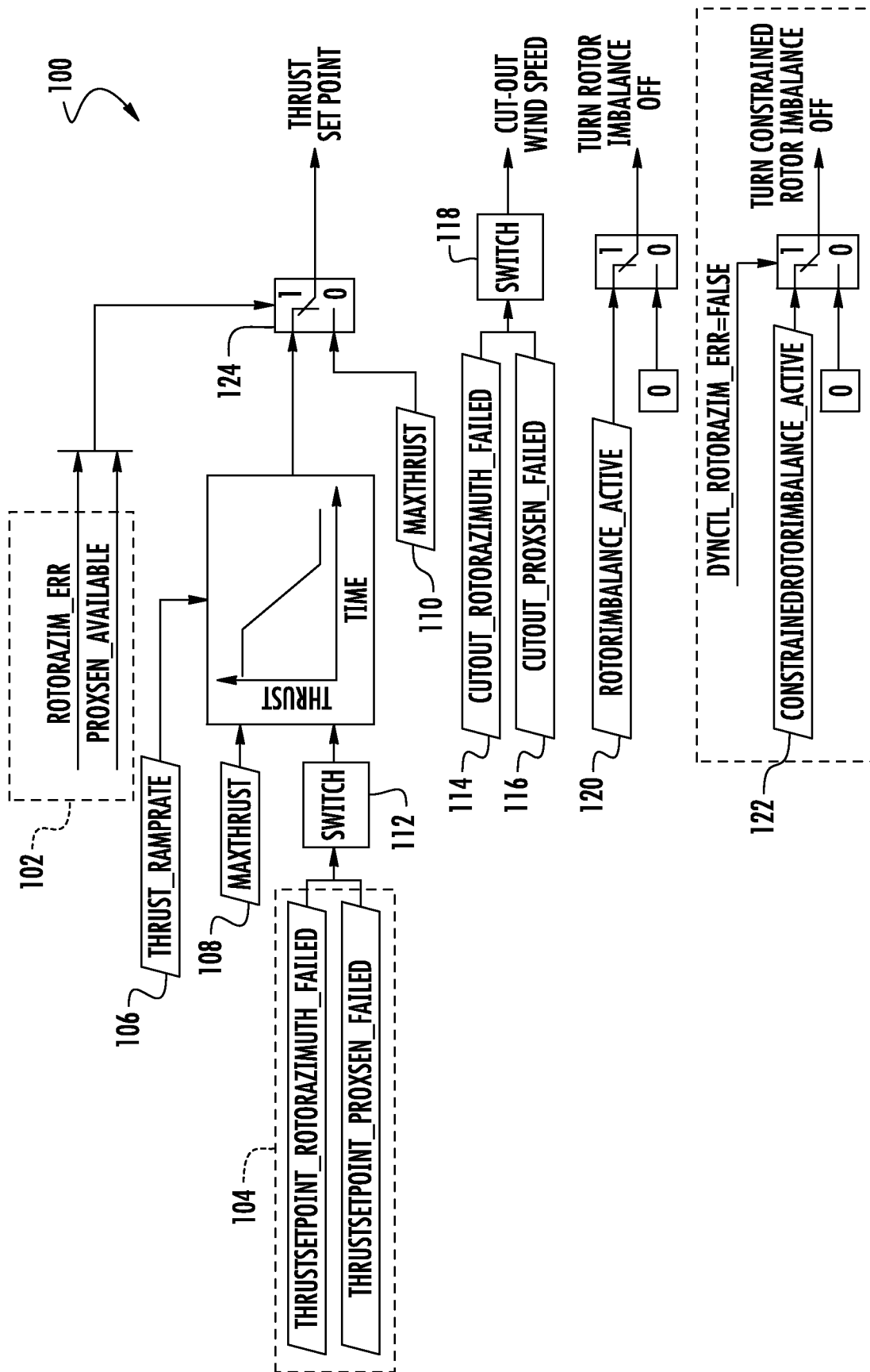


FIG. 6

7/9

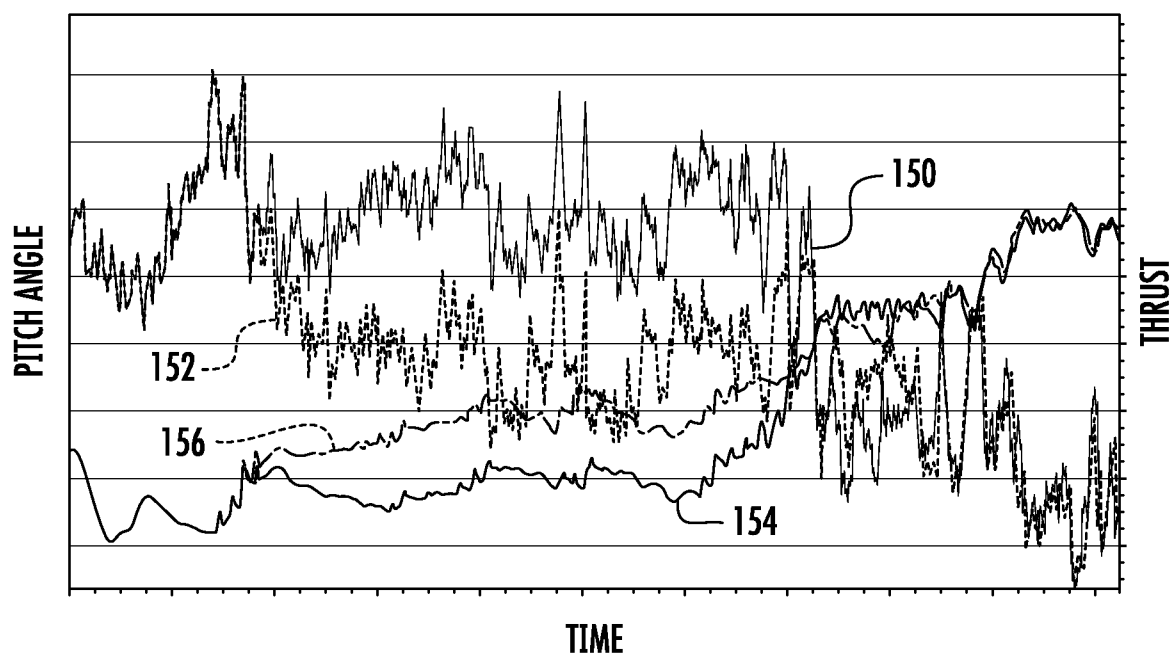
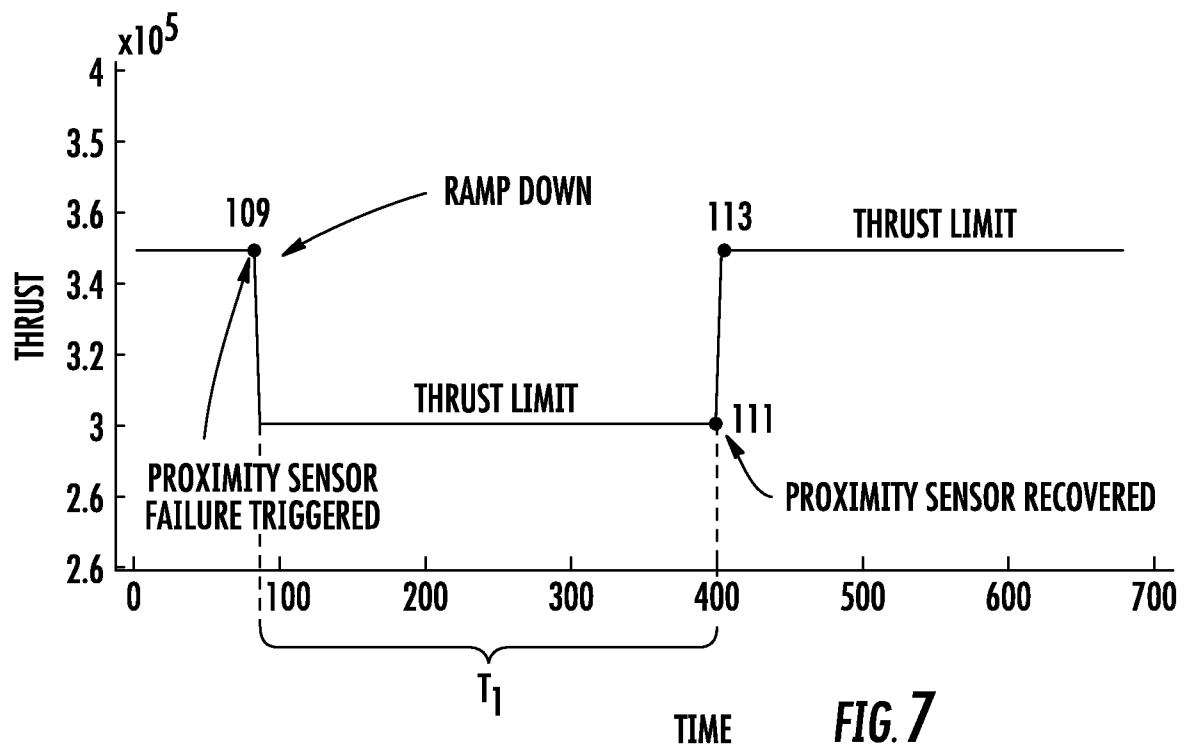


FIG. 8

8/9

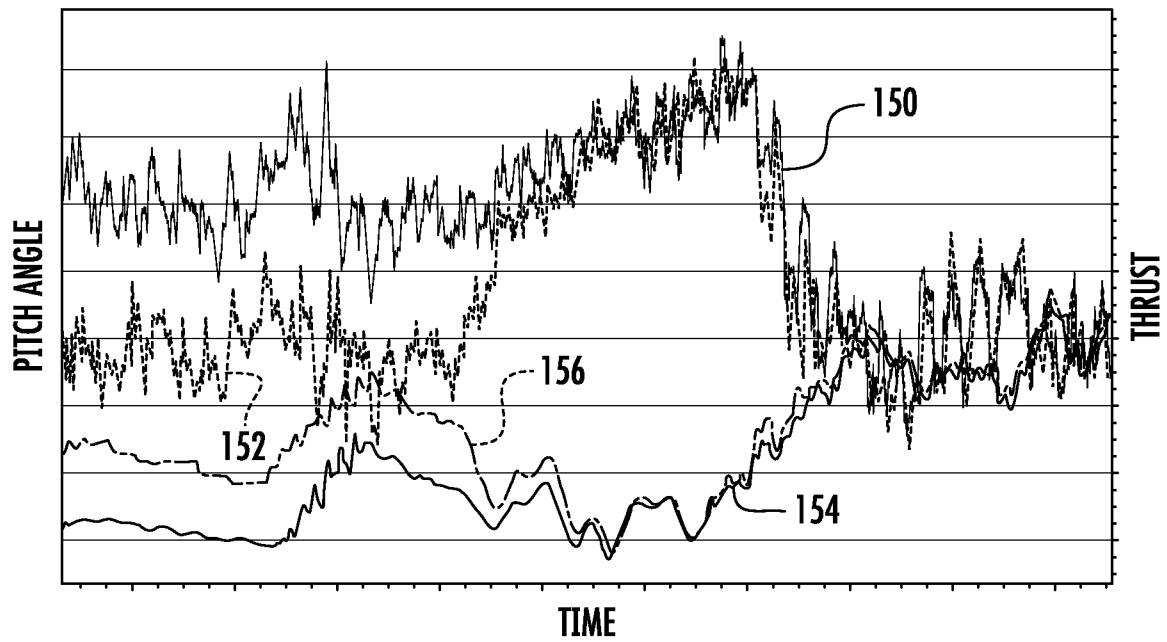


FIG. 9

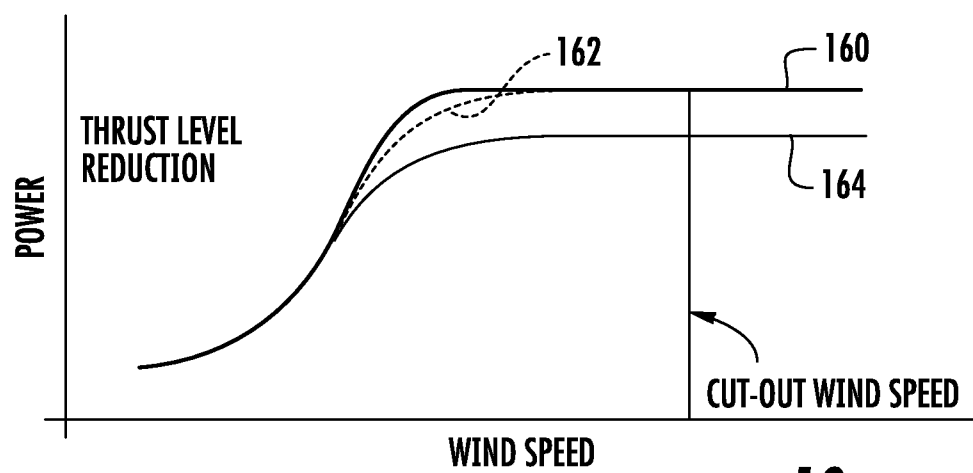
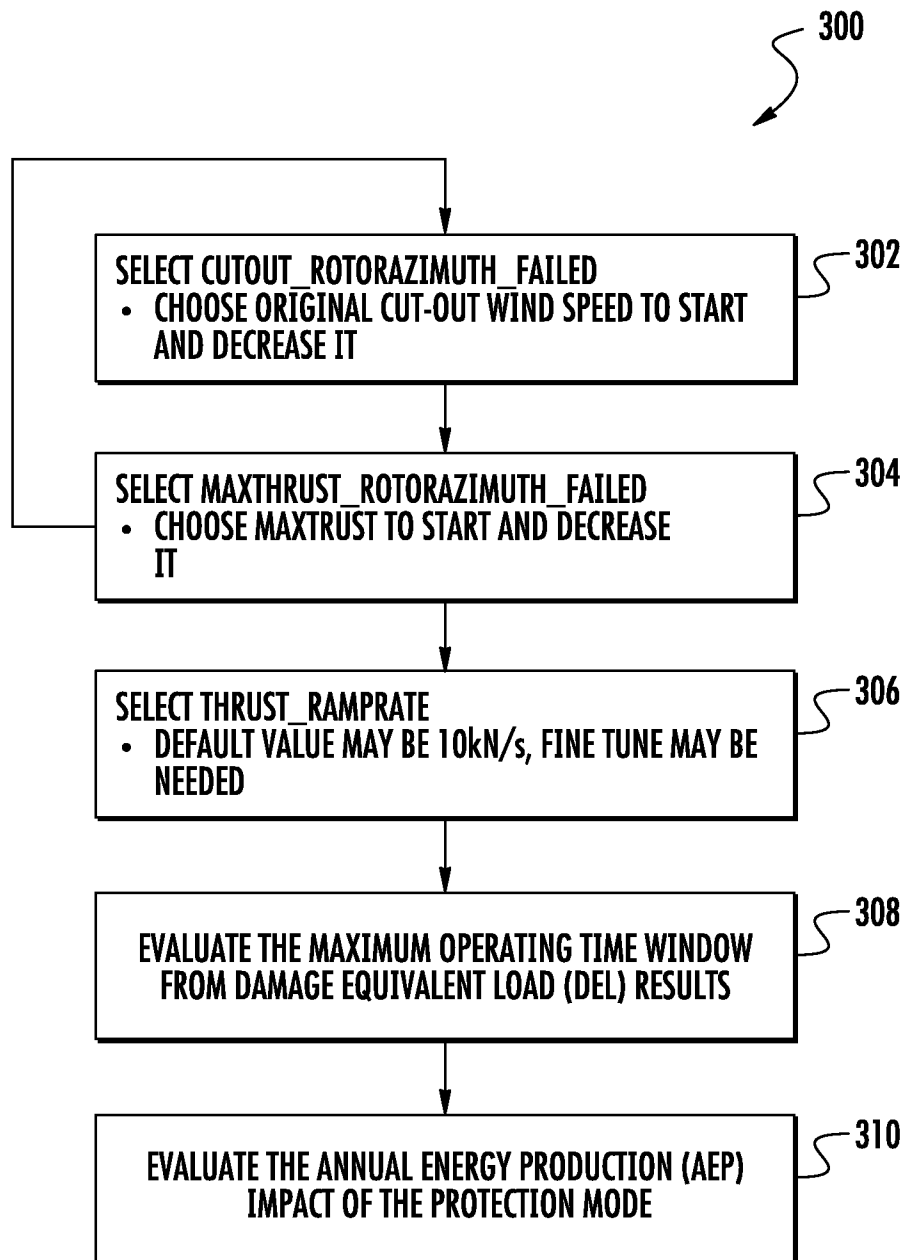


FIG. 10

9/9

**FIG. 11**

INTERNATIONAL SEARCH REPORT

International application No.

PCT/CN2015/073639

A. CLASSIFICATION OF SUBJECT MATTER

F03D 7/06(2006.01)i; F03D 11/00(2006.01)i

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

F03D

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

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

CPRSABS;CNKI;SIPOABS;VEN: fault, mitigat+, load, failure, sensor, wind w turbine, 故障, 失效, 负载

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	KR 101466082 B1 (SAMSUNG HEAVY IND) 27 November 2014 (2014-11-27) description, paragraph 0021-0045, abstract and figure 3	1-20
A	CN 102792012 A (三菱重工业株式会社) 21 November 2012 (2012-11-21) the whole document	1-20
A	CN 102619684 A (华锐风电科技集团股份有限公司) 01 August 2012 (2012-08-01) the whole document	1-20
A	US 7160083 B2 (GEN ELECTRIC) 09 January 2007 (2007-01-09) the whole document	1-20
A	WO 2013002256 A1 (MITSUBISHI HEAVY IND LTDET AL.) 03 January 2013 (2013-01-03) the whole document	1-20
A	US 2012134813 A1 (NIES JACOB JOHANNES ET AL.) 31 May 2012 (2012-05-31) the whole document	1-20



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:

“A” document defining the general state of the art which is not considered to be of particular relevance

“E” earlier application or patent but published on or after the international filing date

“L” document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

“O” document referring to an oral disclosure, use, exhibition or other means

“P” document published prior to the international filing date but later than the priority date claimed

“T” later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

“X” document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

“Y” document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

“&” document member of the same patent family

Date of the actual completion of the international search

26 November 2015

Date of mailing of the international search report

17 December 2015

Name and mailing address of the ISA/CN

STATE INTELLECTUAL PROPERTY OFFICE OF THE
P.R.CHINA
6, Xitucheng Rd., Jimen Bridge, Haidian District, Beijing
100088, China

Facsimile No. (86-10)62019451

Authorized officer

WEI, Hong

Telephone No. (86-10)62089633

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.

PCT/CN2015/073639

Patent document cited in search report			Publication date (day/month/year)	Patent family member(s)			Publication date (day/month/year)
KR	101466082	B1	27 November 2014	None			
CN	102792012	A	21 November 2012	EP	2685096	B1	14 October 2015
				AU	2011202348	A1	27 September 2012
				US	2012061962	A1	15 March 2012
				US	8523520	B2	03 September 2013
				KR	20120135005	A	12 December 2012
				CN	102792012	B	06 May 2015
				EP	2685096	A1	15 January 2014
				KR	101253014	B1	15 April 2013
				EP	2685096	A4	12 November 2014
				JP	5237455	B2	17 July 2013
				WO	2012124023	A1	20 September 2012
				CA	2741597	A1	11 September 2012
				IN	201101045	P3	14 September 2012
CN	102619684	A	01 August 2012	CN	102619684	B	09 July 2014
US	7160083	B2	09 January 2007	US	2004151577	A1	05 August 2004
WO	2013002256	A1	03 January 2013	EP	2728175	A1	07 May 2014
				JP	2013011200	A	17 January 2013
				EP	2728175	A4	25 March 2015
US	2012134813	A1	31 May 2012	None			