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- (71) Applicant: NTNU TECHNOLOGY TRANSFER AS
[NO/NO]; Høgskoleringen 1, N-7491 Trondheim (NO).
- (72) Inventors: MOAN, Torgeir; Basunveien 35, N-7560 Vikhammer (NO). MULIAWAN, Mada Jaya; Søndre Berg 15C, N-7051 Trondheim (NO). KARIMIRAD,

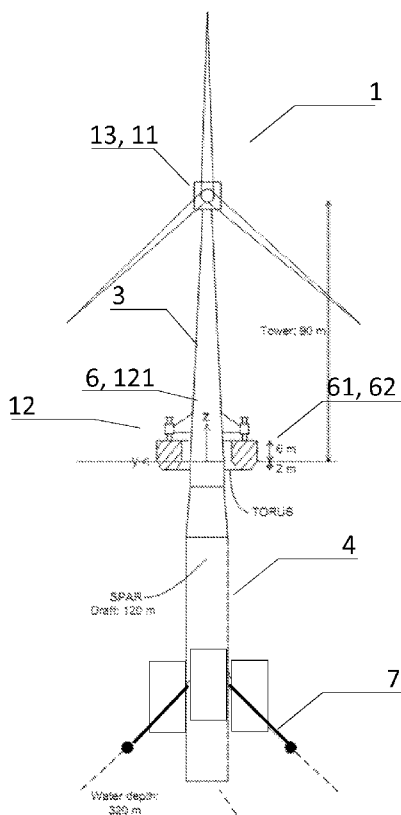
Madjid; Jonsvannsveien 93C, N-7050 Trondheim (NO).
GAO, Zhen; Brundalsgrenda 6, N-7058 Trondheim (NO).

- (74) Agent: FLUGES PATENT AS; Postboks 27, N-1629 Gamle Fredrikstad (NO).
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(54) Title: FLOATING WIND TURBINE WITH WAVE ENERGY CONVERTER

Fig. 2



(57) Abstract: The invention is a floating wind turbine comprising - a wind turbine rotor (1) mounted on a tower (3) of a spar and tower structure (4, 3) comprising a generally vertical buoyant and deep, ballasted spar (4) moored in a mooring (7), - said turbine rotor (1) connected to a first electrical power generator (11). The floating wind turbine comprises the following features: * that the spar and tower structure (4, 3) provided with a buoyant torus (62) arranged at mean water level about the spar and tower structure (4, 3); * that the torus (62) oscillates with sea waves in an axial direction with a motion relative to the spar and tower structure (4, 3), * that the torus (62) is provided with a power take-off system (120) coupled to a second electrical power generator (121). The so modified floating wind turbine will then be more efficient, particularly for the lower wind speed range.

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Introduction

The present invention relates to a wind turbine mounted on top of a tower supported on a floating spar buoy, particularly a ballasted spar buoy moored to the seafloor, wherein a wave energy converter is connected to the same spar buoy and tower structure at mean water level.

Background art

Wind turbines mounted on top of a tower supported on a floating spar buoy are known from WO2010/122316 which describes a controller for a floating wind turbine. The controller controls the rotor speed of the turbine by controlling the torque of a load on the rotor so as for the rotor speed to vary in response to wave-induced motion.

Wave energy generators are known from an axi-symmetric vertical floating structure comprising lower and upper coaxially and mutual vertically oscillating bodies of which the upper body is a torus and the lower body is a vertically oriented ballasted bob with almost neutral buoyancy, wherein the bodies have different heave frequencies. The relative motion is utilized through a hydraulic power transmission for generating electrical energy.

Such a wave energy generator is known from Norwegian patent NO324789 to Wavebob Ltd. It describes a device for converting wave energy. It comprises at least two devices each comprising a surface floater, whereas at least one of the surface floaters is fixedly connected to a submerged body. The movement of the two devices as a response to a passing wave may be utilized to achieve an energy conversion.

Brief summary of the invention

The invention is defined in the attached claim 1. Various embodiments of the invention is defined in the dependent claims.

Brief figure captions

The invention and its various embodiments are illustrated in the attached drawings, wherein

Fig. 1 is a simplified perspective view of the invention showing a wind turbine mounted in a nacelle on top of a tower on a floating spar, with a torus of a wave energy extractor arranged floating in the splash zone of the floating spar and tower structure, the torus arranged to ride on waves in the generally vertical, longitudinal axis of the structure.

In the right lower part of Fig. 1 is illustrated a mooring system for a spar and tower structure used in a modeled embodiment of the invention.

Fig. 2 is a simplified elevation view of the same and shows a section view of the torus with a guidance and stopper mechanism for the torus.

Fig. 3 shows a prior art wave energy converter comprising a torus riding on a vertical part of a deep draught ballasted buoy.

Fig. 4a shows vertical and horizontal sections through the torus part of the system of the invention, and a detail horizontal section of a wheel between the spar and the torus.

Fig. 4b shows vertical and horizontal sections of the torus' power take-off system in a hydraulic system embodiment, using several cylinders.

Fig. 4c is a very simplified vertical section of the hydraulic cylinders on either sides of the spar in an embodiment corresponding to the one of Fig. 4b.

Fig. 4d shows vertical and horizontal sections of an alternative embodiment of the torus' power take-off system in another hydraulic system embodiment, using one cylinder.

Fig. 4e is a very simplified vertical section of the hydraulic cylinders on either sides of the spar in the alternative embodiment corresponding to the one of Fig. 4d.

Fig. 5a is a pitch motion spectrum (left) of a "spar only" and an embodiment of the invention modeled for two different situations: without (spar only, continuous line) and with the auxiliary buoyant structure (broken line), an attenuated torus wave energy converter modifying the pitch characteristics.

Fig. 5b is a wind power production for a wind velocity example of 8 m/s, which is below the rated velocity for the model embodiment wind turbine. The power production is modeled for the same two different situations: a floating wind turbine without (continuous line) and with (broken line) the torus according to the invention. The time span of Fig. 5b is 100 seconds (from 2000 to 2100 seconds). The dominating wave period T_p is clearly visible in the power production, but more important is that the power production is higher with the invention.

Fig. 5c shows the wind power production as in Fig. 5b, but for a time span from 0 to 3600 seconds; one hour.

Fig. 6 shows a hinged embodiment of a torus which may be retrofitted and / or removed from a spar and tower structure at sea.

Fig. 7 shows, in the upper part: graphs of mean pitch (γ_s) and standard deviation (γ_{sSTD}) for a wind turbine generator on a "spar only", and as mean pitch (γ_c) and standard deviation (γ_{cSTD}) for a wind turbine on a spar with the invention, for abscissa values of mean wind velocity and wind power. In the lower part, Fig. 7 shows a graph of mean wind power production (P_c , P_s) and their STD (P_{cSTD} , P_{sSTD}) as function of wind velocity. The following parameters for wind and waves according to a JONSWAP spectrum have been used:

Case no.	Vmean (m/s)	Hs (m)	Tp (s)
1	8	2.5	9.8
2	11.2	3	10
3	14	3.6	10.2
4	17	4.2	10.5

Fig. 8 shows the possible survival modes for the combined floating wind turbine spar and buoyant torus converter in non-operational or extreme conditions when the wind turbine is parked and/or the power take-off system of the wave energy converter is released:

Fig. 8a illustrates a released mode, wherein the torus free to move in heave along the spar.

Fig. 8b illustrates a locked mode, wherein the torus is mechanically locked to the spar at the mean water level (MWL).

Fig. 8c illustrates a submerged mode, wherein the torus is

mechanically locked to the spar and ballasted to a submerged position.

Advantages of the invention

A first advantage of the invention is the utilization of common power cables for the transmission of electrical energy from each combined floating wind turbine and wave energy converter. The length of power cables required for an array of spars according to the invention is significantly reduced compared to an array of wave energy converters arranged inbetween the spars.

A second advantage of the invention is the utilization of a common mooring system already existing for the floating wind turbine.

A third advantage of the invention is the significantly reduced combined mass of the wave energy converter as it may ride on the already existing structure of the floating vertical spar and tower.

A fourth and very significant advantage of the invention is that the energy output of a device the invention is modeled to be higher than the energy output from the modeled wind generator and from the wave energy converter as counted separately. In this aspect, the power output of the combined device is higher than the sum of the energy output of the components taken separately. The energy output of the wind turbine part of the invention is higher with a working wave energy generator than without such a wave energy generator, please see Fig. 5b and Fig. 5c, but also Fig. 7. The curves illustrate pitch motion for spar only and for the invention indicated as "combined". The wind power in combined mode is

higher than wind power for "spar-only". The effect is most pronounced below a rated wind velocity of the wind turbine. This increased power production is a rather surprising effect of the invention.

Embodiments of the invention

The invention is illustrated in the attached drawings and a general illustration of the invention is given in Fig. 1 which shows the buoyant torus arranged at mean water level about the vertically floating combined spar and tower which carries a "windmill", i.e. a wind turbine on top of the tower, the wind turbine for generating electrical energy.

The invention illustrated is a floating wind turbine comprising a wind turbine rotor (1) on a tower (3) of a combined spar and tower structure (4, 3). The spar and tower structure comprises a generally vertical buoyant and deep, ballasted spar (4) kept on station by a mooring (7). Due to waves and wind the spar and tower will have mean tilt and dynamic pitch motion, which has to be closely monitored and controlled.

The turbine rotor (1) is connected to a first electrical power generator (11). In an embodiment the rotor may be connected through a mechanical gearbox to the axle of the first electrical power generator (11) which is then arranged in a nacelle at the top of the tower, but other solutions such as hydraulic transmission to the generator may be used, and then the electrical power generator (11) may be arranged anywhere in the tower or spar, below the nacelle.

The novel features of the invention comprises that the spar and tower structure (4, 3) is provided with a buoyant torus

(62) arranged at mean water level about the spar and tower structure (4, 3), please see Figs. 1 and 2.

The torus (62) is arranged for oscillating with sea waves in an axial direction, i.e. in the nearly vertical direction, in a motion relative to the motion of the spar and tower structure (4, 3). The torus (62) is provided with a power take-off system (120) which converts part of the energy of the relative motion and is coupled to a second electrical power generator (121).

In an embodiment of the invention the power output is transmitted via common a common power cable for the transmission of electrical energy from the combined floating wind turbine and wave energy converter of the invention. The common power cable is connected to a power grid.

The turbine rotor (1) is mounted on an axle supported in axle bearings (131) in a nacelle (13) on said tower (3). In an embodiment of the invention the nacelle (13) is arranged on a rotating bearing (132) with an axial rotation on said tower (3), which is necessary if the tower and spar structure is not allowed to turn azimuthally in its moorings.

As will be seen from Figs. 1 and 2, there is no sharp transition from the top of the spar to the bottom of the tower; it may be smooth or slightly conic. A tower base (31) of said tower (3) and a spar top portion (41) of said spar structure (4) form a generally smooth transition near said splash zone between said tower (3) and said spar (4). Please notice that I have used the term "combined spar and tower structure (4, 3)" in order to describe an axially aligned spar buoy cylinder supporting a tower.

In the modelling a sea water density (1025 kg/m³) is used. We have considered the spar (4) as the part of the spar and tower structure below the design water level, the "waterline", please see Fig. 2.

The embodiment of the combined spar and tower with the torus according to the invention is modelled as a two-body system. The modelled two-body system is modelled using features available in a computer program called SIMO developed by Marintek for simulating motions and station-keeping behaviour of complex systems of floating vessels and suspended loads. SIMO's essential feature for the present purpose is its flexible modelling of multi-body systems that accommodate the introduction of both mechanical and hydrodynamical coupling between the spar and tower structure and the torus.

the power take-off system is the coupling between the two main components of the system and is modelled in a simplified manner as an ideal linear damper (Bpto) and spring (Kpto) that couple the motion between the two bodies. The parameters have been set to Bpto = 8000 kN s/m and Kpto = 50 kN /m, please see the table below.

The total displaced volume of the floating wind turbine with the spar and tower structure is 8015 m³, with a total mass of 8216 tons (including tower, turbine, etc), disregarding the floating torus (62).

In the dynamically modeled invention, the following parameters have been used as an example embodiment:

Property	Value	Unit	
Torus (62)			
Outer diameter	20	m	

Inner diameter	10	m	
Draught	2	m	
height	8	m	
Displacement	408	m ³	
Mass	418	t (1000 kg)	
Centre of mass below sea level	0.9	m	
Moment of inertia I_{xx} about a horizontal axis	10760	t m ²	
Moment of inertia I_{zz} about a vertical axis	20560	t m ²	
Vertical stroke length of torus (62)	6	m	
Stiffness of upper end stop spring	10 ⁶	kN/m	
Stiffness of lower end stop spring	10 ⁶	kN/m	
Spar and tower structure:			
height of Tower (3) above waterline	90	m	
diameter at waterline of Spar (4)	6.5	m	
diameter at bottom of spar (4)	9.4	m	
Draught of spar (4) below waterline (combined draught and height 120m+90m=210m)	120	m	
<i>Displacement of spar (4)</i>	<i>8016</i>	<i>m³</i>	
Total mass of spar (4)	8216	t (1000 kg)	
Centre of mass, below waterline	78.5	m	
Moment of inertia i_{xx} about a horizontal (x) axis of spar and tower (4,3)	69840000	t m ²	
Moment of inertia i_{zz} about the long (z) axis of spar and tower	167800	t m ²	
Fairlead (mooring attachment) elevation below waterline	70	m	
Other parameters			
Wind turbine power output	5	MW	
Power take-off damper property	8000	kN s/m	
Power take-off stiffness	50	kN/m	

Water depth on site	320	m	
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As is seen from the table above, the torus (62) contributes insignificantly with an additional 10760 t m² to the moment of inertia i_{xx} **69840000** t m² of the combined spar and tower structure. However we shall see that the invention significantly affects the dynamic behaviour of the spar and tower structure so as to provide more produced power to a degree not expected.

For the mooring illustrated in Fig. 1, lower part, the following parameters have been used:

The properties of mooring system components

Property	Upper Line (UL)	Lower Line (LL)	Clump mass	End Line (EL)
Length (m)	300	600	2	370
Diameter (m)	0.09	0.09	1.67	0.09
Mass/Length (kg/m)	42.5	42.5	17253	42.5
Axial stiffness (EA) (kN)	384243	384243	384243	384243

Other dimensions of the spar, the tower, the maximum wind turbine power output, the torus, or the power take-off system and the mooring are envisaged, and the given parameters by no way shall limit the scope of the invention, as the inventors believe that the effect of the invention is not only present for the values of the parameters used in the modeling.

The modeling using the parameters of the example embodiment without a torus, indicated as "spar only" and for the invention indicated as "combined concept" may be summarized with the following power outputs as follows:

Power (kW)											
Case no.	Vmean(m/s)	Hs (m)	Tp (s)	Spar only				Combined concept			
				wind power ¹		wave power ²		wind power		wave power	
				Mean	STD	Mean	STD	Mean	STD	Mean	STD

1	8	2.5	9.8	1727.1	244.35	-	-	1820.07	233.2	275.4	379.9
2	11.2	3	10	4573.044	327.95	-	-	4874.972	296.46	420.9	576.2
3	14	3.6	10.2	4937.625	12.39	-	-	4947.001	13.13	622.62	852.79
4	17	4.2	10.5	4929.498	8.167	-	-	4939.5	8.713	883.45	1211

According to the modeling, the energy output of a device according to the invention is modeled to be higher than the energy output from the modeled wind generator and from the wave energy converter as counted separately. Details will be discussed below.

Please notice that the term "wave power" in the table above should be understood as "absorbed power" for the power output from the torus' wave power take-off system: is this the power absorbed by the dampened spring system and not necessarily the power output from the generator due to loss in the system, and should be multiplied throughout by some efficiency factor less than 1.

As an example well below a rated wind velocity for the modeled wind turbine, in which the turbine control system does not cut the power output, please see "case no. 1 above: For a mean wind speed of 8 m/s, and a wave state Hs of 2.5 m and a wave period of 9.8 s, the mean wind power output of the wind turbine driven generator alone, without the invention, is 1727 kW and its standard deviation is 244.35 kW, please see particularly Fig. 5b which shows the power production of 100 seconds, but also Fig. 5c which spans a time period of 1 hour. For the invention for the same wind and wave conditions, the wind power generator mean wind power output is 1820.07 kW, please also refer to Figs. 5b and 5c, and with a lower standard deviation: 233.2 kW, which is both more power and more stable power output than without a torus. In addition the potential wave-generated power output from the torus is

calculated to be 275.4 kW with a standard deviation of 379.9 kW, please refer to the table above.

For higher wind velocities the wind turbine control system will prevent an over rate rotor speed or over rate energy production (P_c , P_s) by controlling the pitch and / or the gear ratio, please see Fig. 7, lower graphs.

As an example near below a rated wind velocity for a wind turbine, near the wind velocity for which above the turbine control system starts cutting the power output, please see "case no. 2 above: For a mean wind speed of 11.2 m/s, and a wave state H_s of 3 m and a wave period of 10 s, the mean wind power output of the wind turbine driven generator alone, without the invention, is 4573 kW and its standard deviation is 328 kW. For the invention for the same wind and wave conditions, the wind power generator mean wind power output is 4875 kW with a lower standard deviation: 296.5 kW, which is both more power and more stable power output than without a torus. In addition the potential wave-generated power output from the torus is calculated to be 420.9 kW with a standard deviation of 576.2 kW.

The mean energy output of the wind turbine part of the invention is thus higher while using a working wave energy generator than without such a wave energy generator, please also see particularly Fig. 5b and Fig. 5c showing modeled wind turbine power production for a wind velocity of 8 m/s which is significantly below the rated velocity for the wind turbine. The wind power in combined mode is higher than wind power for "spar-only". This is a rather surprising effect of the invention.

Moreover, we see that the standard deviation for cases No. 1 and 2, wherein the standard deviation of the produced wind power is reduced from 244.35 and 327.95 to 233.2 and 296.46 respectively, this means that the power production stability from the wind generator is improved for lower wind speeds. The power production stability for the cases no. 3 and 4 for higher wind speeds is very high both without and with the invention due to the effect of the control system, with negligible RMS values of 12.39 kW and 8,167 kW without a torus, and 13.13 kW and 8.713 kW with a torus. Anyway, the increased wind power production stability for lower wind speeds is another advantage of the invention.

The tension force on the mooring lines has been calculated and shows an insignificant increase for all sea states.

In an embodiment of the invention the torus (62) is provided with **guide wheels (64)** for running along said spar and tower structure (4, 3) in its axial, generally vertical direction. The dimension and the number of the **guide wheels (64)** will depend on the interface force between said spar and tower structure (4,3) and torus (62).

In an embodiment of the invention, the power take-off system (120) comprises a hydraulic power take-off system (63) for converting the relative motion into hydraulic energy for running the second electrical power generator (121), please see below.

Fig. 4b shows vertical and horizontal sections of the torus' power take-off system in a hydraulic system embodiment, using several cylinders, and in a further embodiment sharing support

structure with the end stop structures extending out radially from the lower part of the tower.

Fig. 4c is a very simplified vertical section of the hydraulic cylinders (67) on either sides of the spar in an embodiment corresponding to the one of Fig. 4b, wherein each hydraulic cylinder (67) is connected via a control manifold (68) to a closed hydraulic circuit (69) with a hydraulic motor (70), preferably with displacement control, driving an electrical generator (121).

Fig. 4d shows vertical and horizontal sections of an alternative embodiment of the torus' power take-off system in another hydraulic system embodiment, using one cylinder (67), with the one cylinder having a separate support structure (71) extending radially out from the lower part of the tower, independent of the end stop structures.

Fig. 4e is a very simplified vertical section of the hydraulic cylinders on either sides of the spar in the alternative embodiment corresponding to the one of Fig. 4d, wherein the single hydraulic cylinder (67) is connected via a control manifold (68) to a closed hydraulic circuit (69) with a hydraulic motor (70), preferably with displacement control, driving an electrical generator (121).

According to an alternative embodiment of the power take-off system (120) it may comprise an electromagnetic inductive system (123) utilizing part of the relative motion between said auxiliary buoyant structure (61) and said spar and tower structure (4, 3). The electromagnetic inductive system may comprise a static inducing coil (122) in the spar, and a reactive moving coil (123) in the torus, so as for generating electric energy in the static coil which may thus constitute a

part of the second electric generator (121) from which energy may be exported to the grid via the power cable otherwise used for transporting away the energy from the wind turbine.

In an embodiment of the invention the floating wind turbine's power take-off system (120) comprises said guide wheels (64) coupled directly or indirectly to said second electrical power generator (121).

In an embodiment of the invention, heave motion characteristics of the buoyant structure (61) are tuned relative to heave motion characteristics of the tower and spar structure (3, 4) so as for improving the energy output of said second electrical power generator (12).

The torus (62) may comprise a ballast tank (611). The ballast tank (611) may be constituted as the torus (62) as such, and provided with a valve and pump system (612) arranged for adjusting its ballast by pumping sea water in or out. The ballasting may be part of the tuning. Other parameters for tuning the torus' relative motion with regard to the spar and tower structure comprise adjusting the power take-off systems force characteristics and the upper and lower end springs' characteristics.

In an embodiment of the invention the first and the second electrical power generators (11, 12) are combined into one generator. This is particularly useful if using a hydraulic transmission to the generator and the generator is arranged in the tower and spar structure. Such a combination may thus further increase the power output of the combined device according to the invention without significantly increasing the weight and cost of the generator system.

Survivability of the spar and torus combined system (STC) in severe wind and wave conditions is crucial. In non-operational or extreme conditions, the wind turbine (1), the wave energy converter (WEC) (62) or the entire spar and torus combined system will not produce electricity.

Such conditions might be the conditions in which the mean wind speed is larger than the cut-out speed of the wind turbine wherein the wind turbine is parked by pitching the blades such that the blade profiles point in the direction up against the wind or in the wind direction. Such conditions might also refer to the conditions in which the significant wave height is larger than the operational limit of the wave energy converter and the power take-off system (120) of the wave energy converter is released.

It is important to introduce a survival mode for both the wind turbine and the wave energy converter WEC to reduce the environmental loads. The survival modes for the wind turbine and the wave energy converter WEC may be triggered independently. It is therefore possible that the wind turbine is still in operation while at the same time the wave energy converter WEC is not in operation, and vice versa. However, in extreme conditions, both the wind turbine and the wave energy converter WEC might be set in survival modes.

The following strategies have been considered as options for the spar and tower combined system STC survival modes with respect to the wave energy converter WEC and its power take-off system PTO, please see Fig. 8.

- (a) Released mode: the torus (62) is allowed to move freely in heave along the spar (4) and the motions are only limited by the end stops (66).

- (b) Locked mode: the torus (62) is mechanically locked to the spar (4) by the braking system (65) at the mean water level (MWL) and moves together with the spar as a one-body system.
- (c) Submerged mode: the torus (62) is mechanically locked to the spar (4), submerged to a new position and moves together with the spar as a one-body system. This may be achieved by ballasting the torus using the active ballast system (612).

The released mode (option (a)) requires the least effort among the survival options. However, one may expect that the mechanical connections (guide wheels (64) and end stop systems (66)) will experience large loads in this mode in extreme conditions.

To reduce the loads on the mechanical connections, a braking system (65) is added in option (b) so that the torus (62) is locked to the spar (4). Since the spar is enclosed by the torus at the mean water level, ship collision is not expected to induce significant damage to the spar structure itself, as long as the torus is designed to absorb most of the collision energy and it could be damaged. Moreover, even if the torus is completely flooded, the entire system will not sink. However, by locking the two bodies at the mean water level, they will be exposed to large wave forces and will move significantly due to possible resonant heave motions. On the other hand, since the draught of the torus is relatively small, bottom slamming might occur on the torus in extreme waves.

Therefore, the submerged mode (option (c)) has been introduced to reduce the wave loads that act on the STC. The submerged mode could be achieved by adding ballast water to the torus (62). When the torus volume is fully loaded with seawater, the

spar and torus combined system STC will be lowered up to 14 m from its initial position. In this position, the wave loads on the system will be significantly reduced. However, a sufficient air gap between the blade tip and the mean water level must be taken into account in the design to avoid wave slamming forces on the wind turbine blade.

Moreover, options (a), (b) and (c) might be selected with respect to the severity of sea state. Option (a) might be considered for moderate non-operational sea states, while options (b) or (c) might be considered for extreme sea states.

A broader aspect of the invention

As seen in a broader perspective aspect the buoyant structure (61) can be considered as a pitch attenuator (12) which modifies the dynamic motion of the spar; at least the pitch dynamic motion of the spar and tower structure (4, 3). Thus the invention may be defined as a floating wind turbine with a turbine rotor (1) in a tower (3) of a combined spar and tower structure (4, 3) comprising generally vertical buoyant and deep, ballasted spar (4) moored in a mooring (7), said turbine rotor (1) connected to a first electrical power generator (11), wherein said spar and tower structure (4, 3) is provided with an auxiliary buoyant structure (61) arranged in the splash zone of said spar and tower structure (4, 3); the said buoyant structure (61) oscillating with sea waves in a relative motion in an axial direction of said spar and tower structure (4, 3), said buoyant structure (61) provided with an attenuator (12) modifying at least a pitch dynamic motion of said spar and tower structure (4, 3). In this very broad, general definition of the invention, the buoyant structure actually is not necessarily yet used to generate electrical energy; the wind turbine alone produces more energy even without regard to any power output of the wave energy

converter part (6) of the buoyant structure (61), and is an advantage in itself. please see Fig. 5 and Fig. 7 which shows that the energy output from the wind generator alone is higher with an operating torus than without. Please notice that the "attenuator" (12) in this definition is not merely a mechanical damper, but which converts the otherwise pitch energy through the power take-off system to electrical energy. The attenuator (12) in this context is provided with the wave energy converter (6) comprising the power take-off system (120) coupled to the second electrical power generator (121).

Claims:

1. A floating wind turbine comprising
- a wind turbine rotor (1) mounted on a tower (3) of a spar and tower structure (4, 3) comprising a generally vertical buoyant and deep, ballasted spar (4) moored in a mooring (7),
- said turbine rotor (1) connected to a first electrical power generator (11),

characterized in that

* said spar and tower structure (4, 3) provided with a buoyant torus (62) arranged at mean water level about said spar and tower structure (4, 3);

* said torus (62) oscillating with sea waves in an axial direction with a motion relative to said spar and tower structure (4, 3),

* said torus (62) provided with a power take-off system (120) coupled to a second electrical power generator (121).

2. The floating wind turbine of claim 1, said torus (62) provided with guide wheels (64) for running along said spar and tower structure (4, 3) in its axial generally vertical direction.

3. The floating wind turbine of claims 1 or 2, said power take-off system (120) comprising a hydraulic power take-off system (63) for converting said relative motion into hydraulic energy for running said second electrical power generator (121).

4. The floating wind turbine of any of the preceding claims, said power take-off system (120) comprising an electromagnetic inductive system (123) utilizing the relative motion between

said auxiliary buoyant structure (61) and said spar and tower structure (4, 3).

5. The floating wind turbine of claim 2, said power take-off system (120) comprising said guide wheels (64) coupled directly or indirectly to said second electrical power generator (121).

6. The floating wind turbine of any of the preceding claims, wherein heave motion characteristics of said buoyant structure (61) being tuned relative to heave motion characteristics of said tower and spar structure (3, 4) so as for improving the energy output of said second electrical power generator (12).

7. The floating wind turbine of any of the preceding claims, said torus (62) comprising a ballast tank (611).

8. The floating wind turbine of claim 7, said ballast tank (611) constituted as said torus (62) as such, and provided with a valve and pump system (612) arranged for adjusting its ballast by pumping sea water in or out.

9. The floating wind turbine of any of the preceding claims, a tower base (31) of said tower (3) and a spar top portion (41) of said spar structure (4) forming a generally smooth transition near said mean water level between said tower (3) and said spar (4).

10. The floating wind turbine of any of the preceding claims, wherein said turbine rotor (1) is mounted on an axle supported in axle bearings (131) in a nacelle (13) on said tower (3).

11. The floating wind turbine of claim 10, wherein said nacelle (13) is arranged on a rotating bearing (132) with an axial rotation on said tower (3).

12. The floating wind turbine of claim any of the preceding claims, wherein said first and said second electrical power generators (11, 12) being combined into one generator driven by said wind turbine (1) and said buoyant torus (62).

13. The floating wind turbine of claim 2, comprising brakes (65) for said guide wheels (64).

14. The floating wind turbine of claim 13, said brakes (65) arranged for locking said torus (62) to said spar (4).

15. The floating wind turbine of claim 3, said power take-off system (63) comprising a hydraulic cylinder (67) connected via a control manifold (68) to a closed hydraulic circuit (69) with a hydraulic motor (70) driving a second electrical power generator (121).

16. The floating wind turbine of claim 15, comprising a support structure (71) for said hydraulic cylinder (67), said support structure (71) extending out radially from the lower part of the tower, said support structure (71) provided with end stops (66).

17. The floating wind turbine of claim 15, said second hydraulic motor (121) provided with a displacement control.

Fig. 1

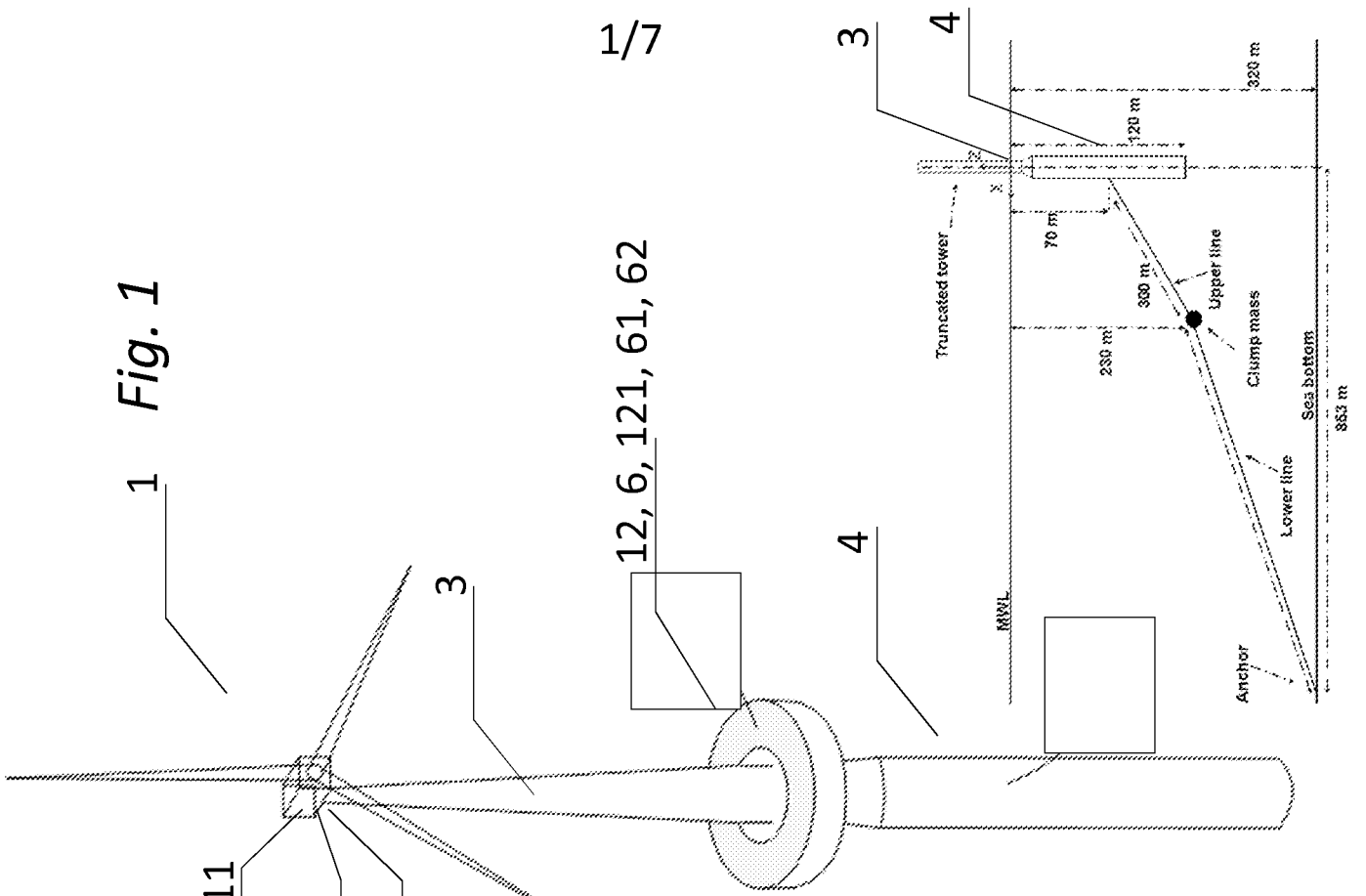


Fig. 2

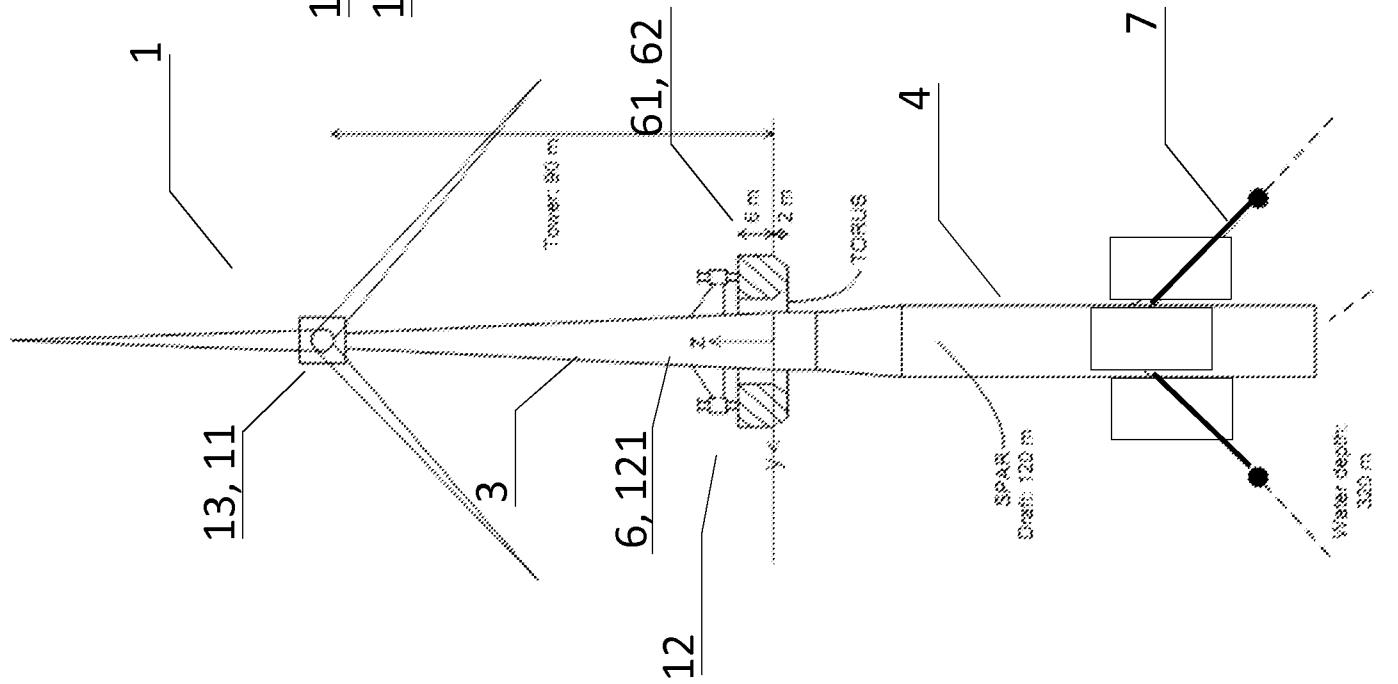


Fig. 3 (Prior art)

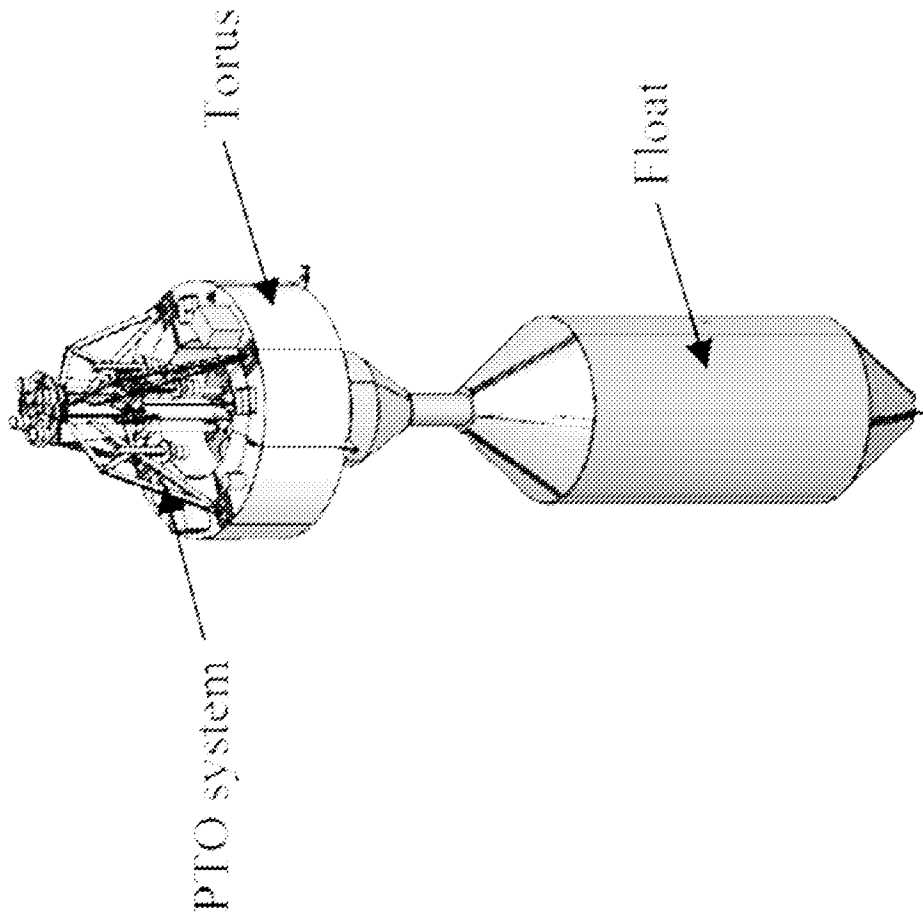


Fig. 4a

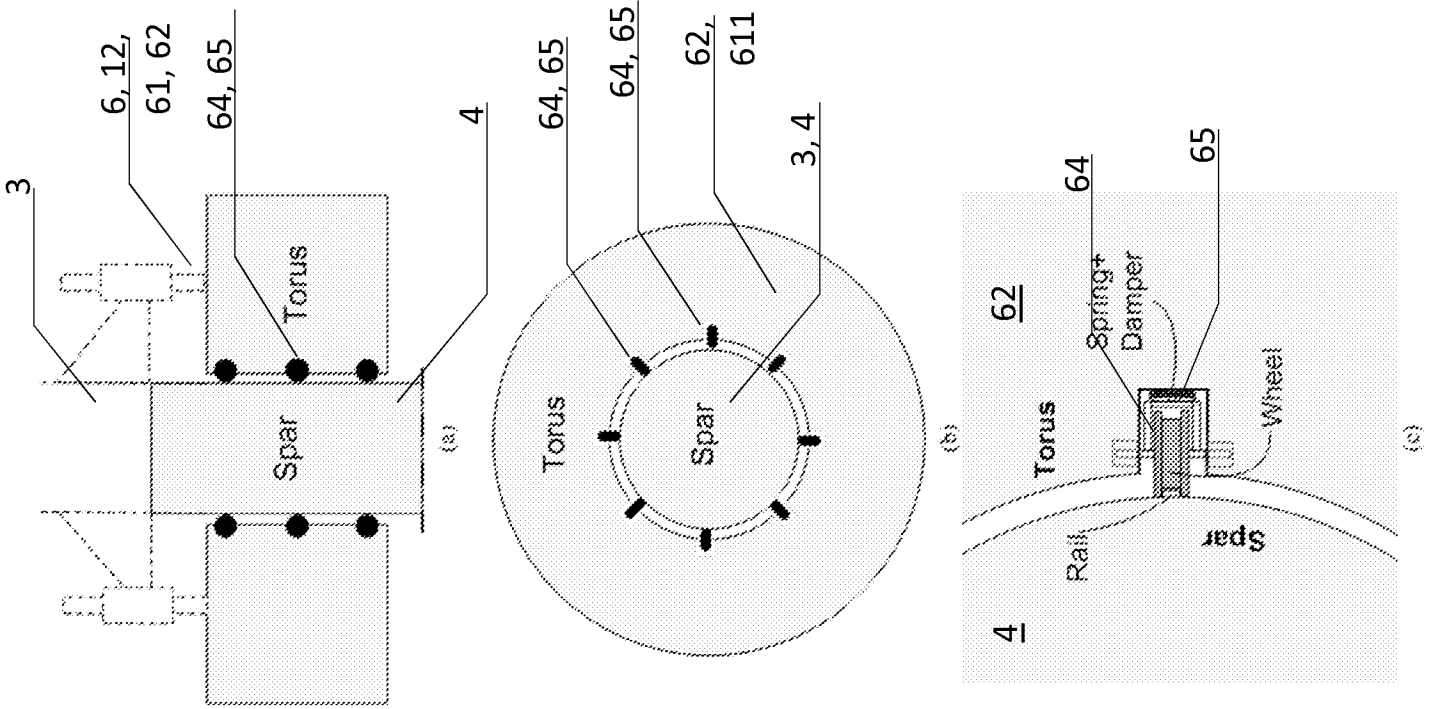


Fig. 4b

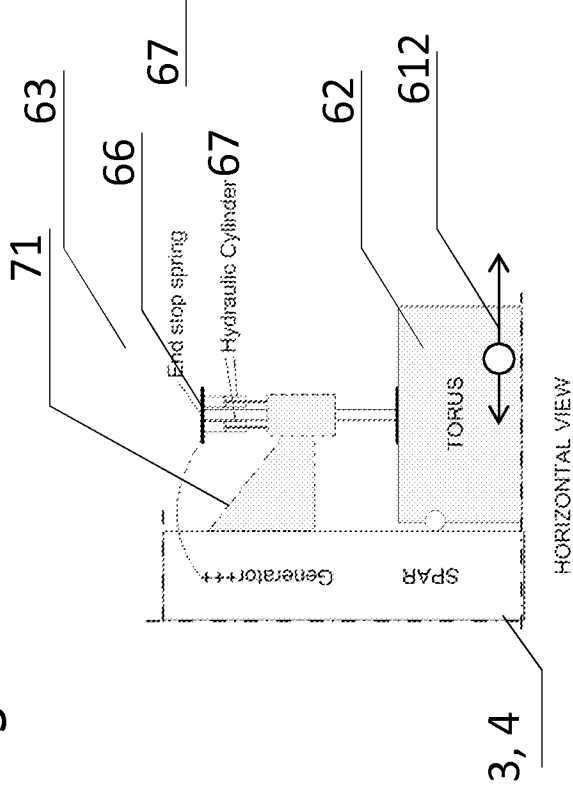
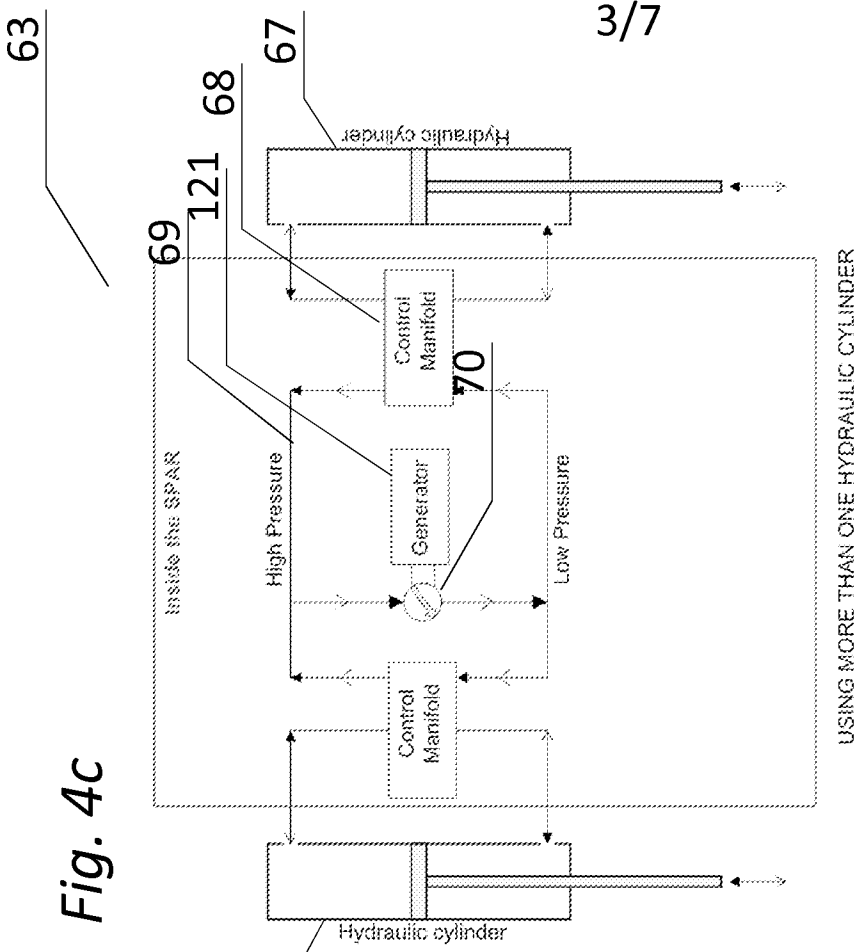
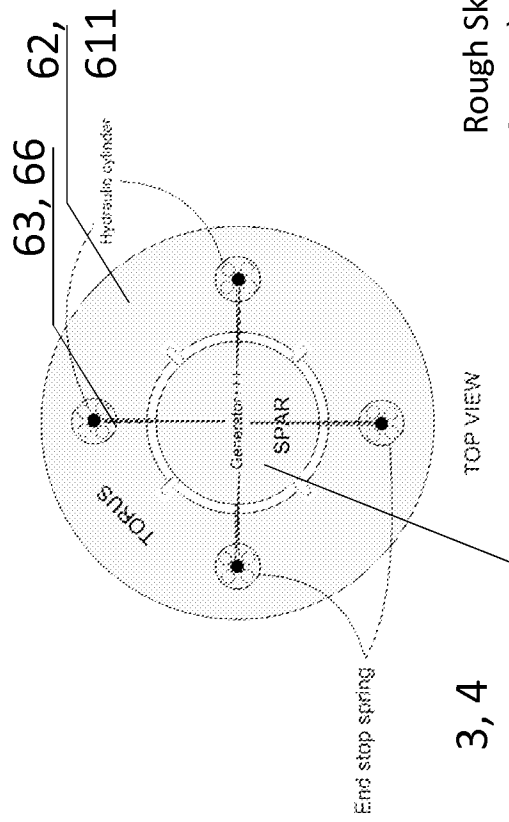


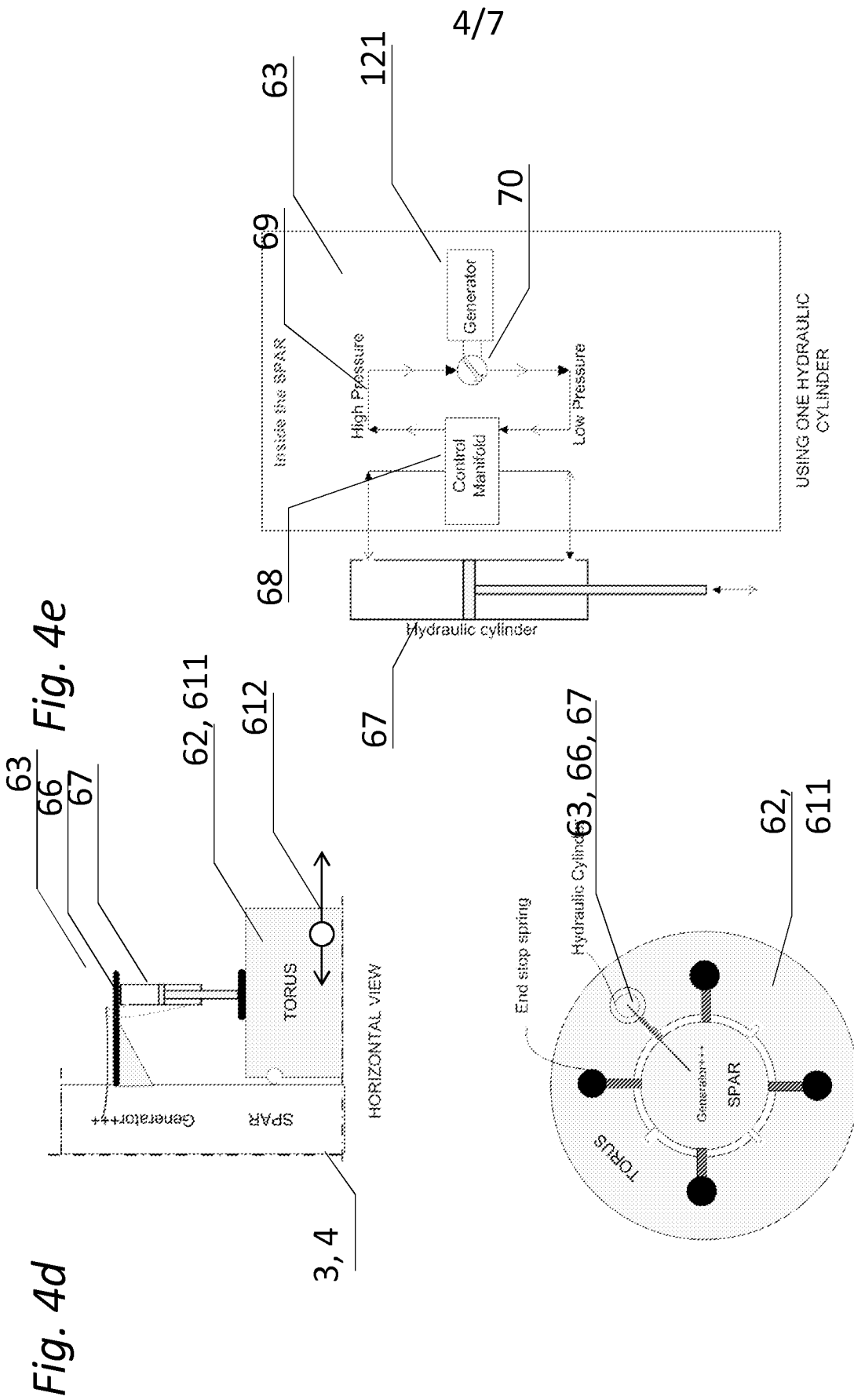
Fig. 4c



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Rough Sketch of WEC Power Take-Off System (Hydraulic System)- using several cylinder, sharing support structure with End Stop (Alt.1)



Rough Sketch of WEC Power Take-Off System (Hydraulic System)- using one cylinder, dedicated support structure (Alt.2)

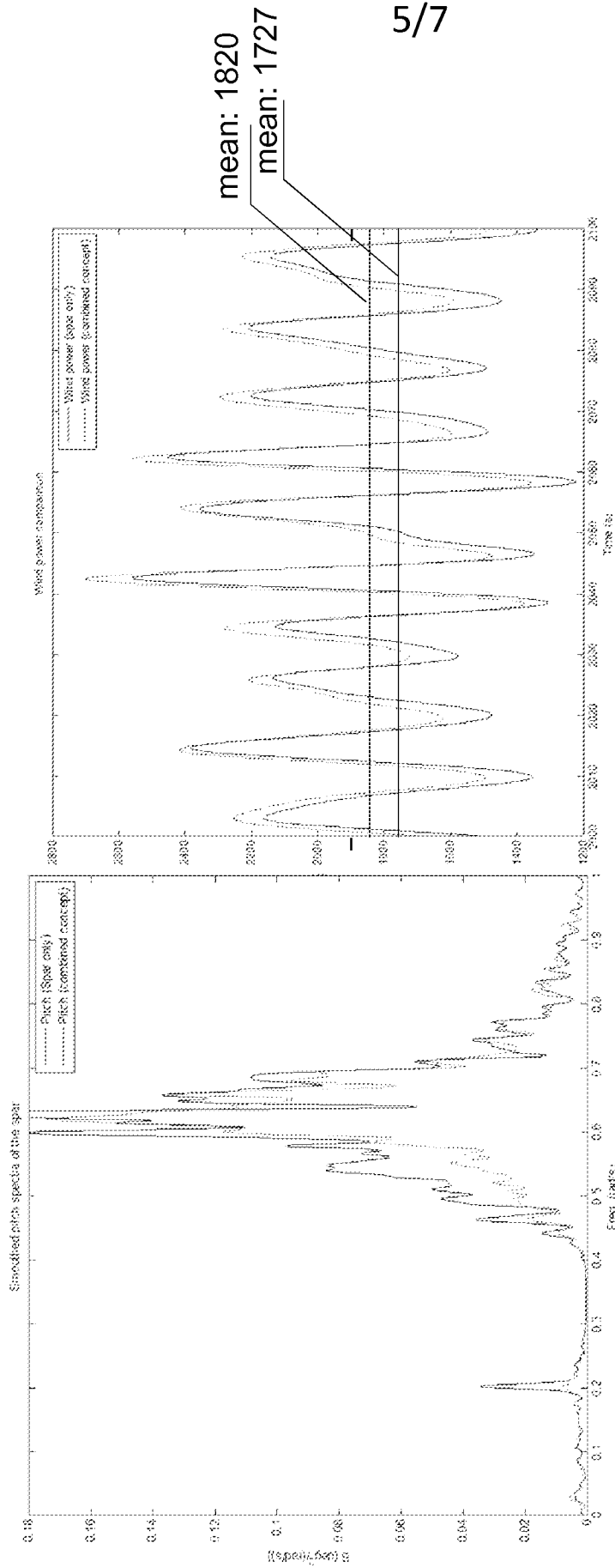


Fig. 5a: pitch motion spectrum and Fig. 5b: wind power production for a wind velocity 8 m/s, below the rated wind velocity for the modeled wind turbine. The spectra are modeled for two different situations: -without any torus ("spar only") and with the torus, indirectly modifying the motion characteristics of the spar and tower structure. The wind power productions modeled are given for a period between 2000 and 2100 seconds.

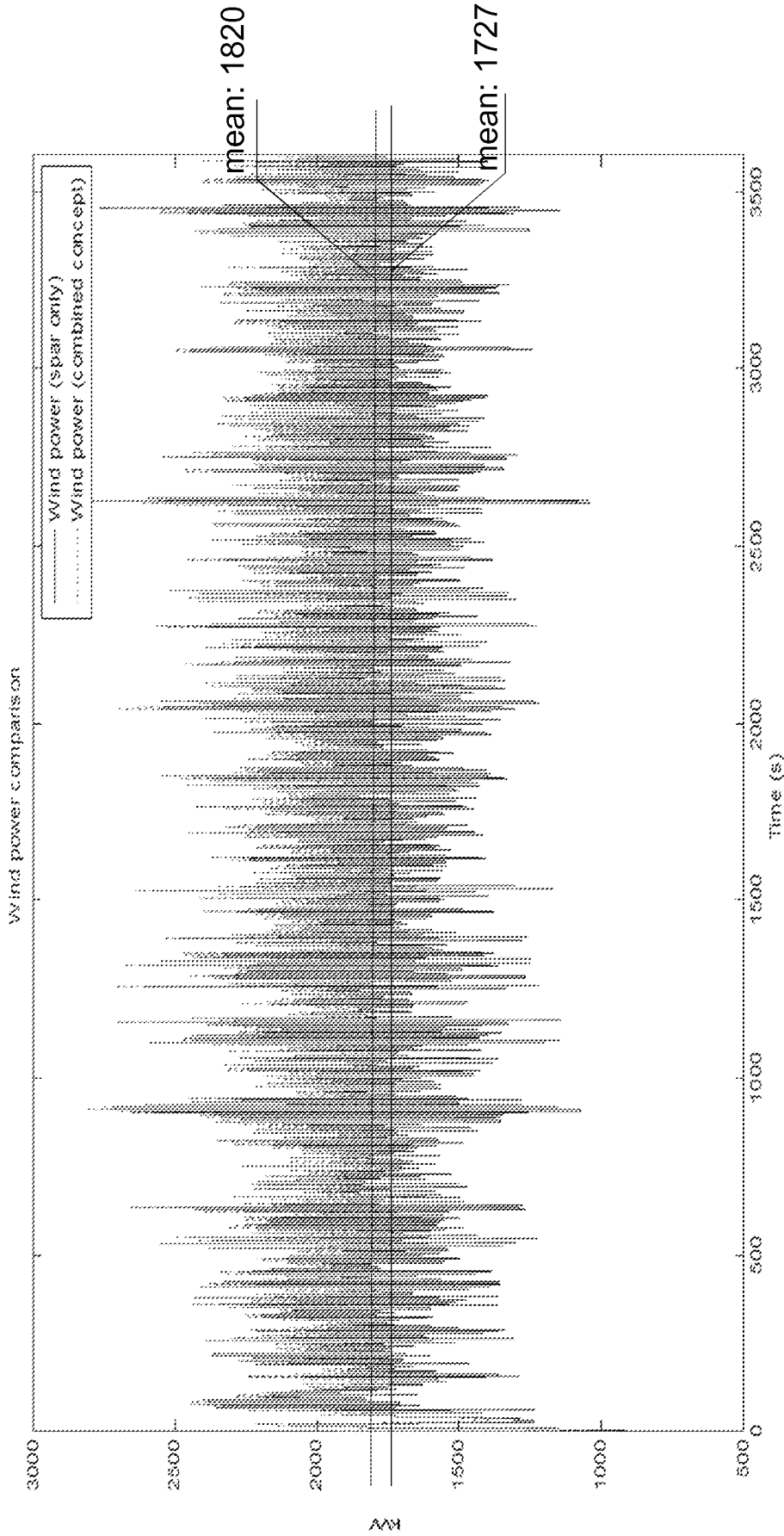


Fig. 5c: wind power production modeled for a period between 0 and 3600 seconds (1 hr) for the "below rated wind velocity" case of 8 m/s. The "over rated" cases will produce same power due to wind turbine's control system, and are thus not relevant for displaying differences in production rate.

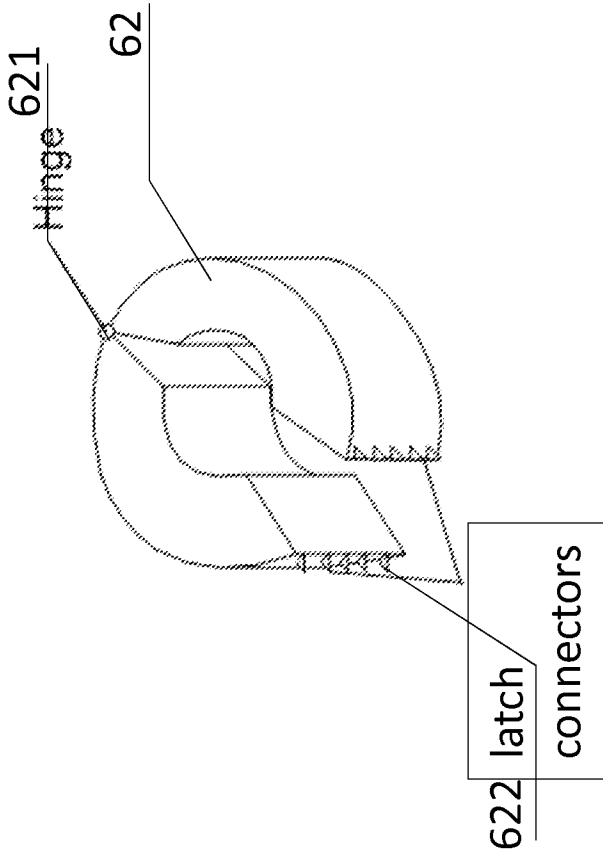
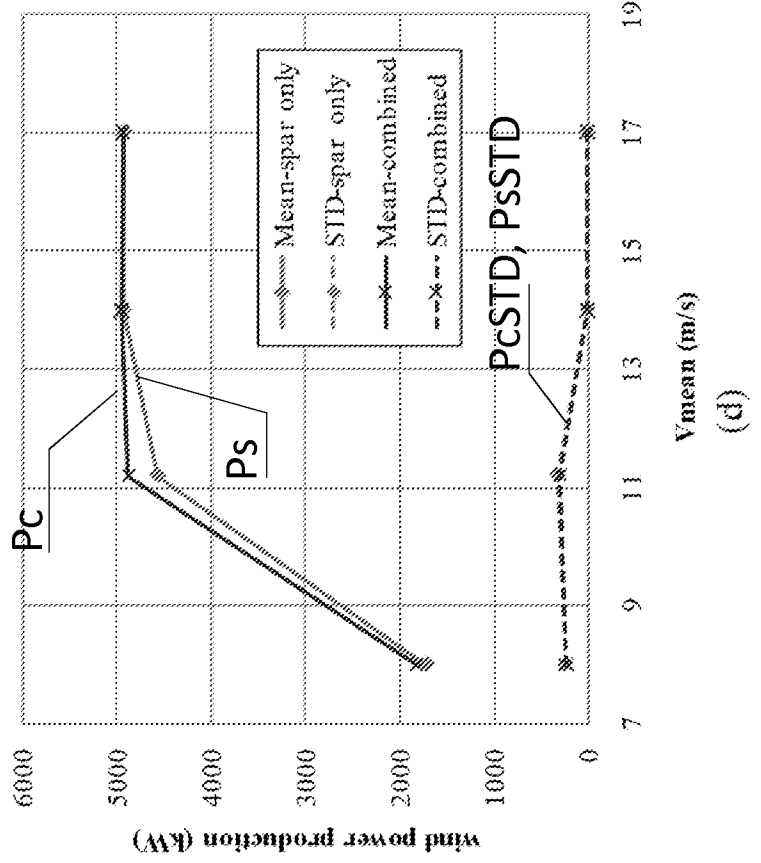
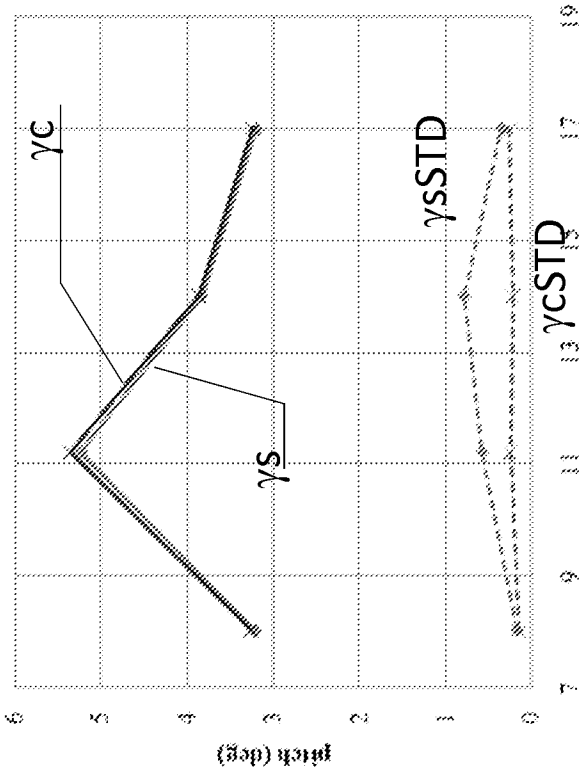
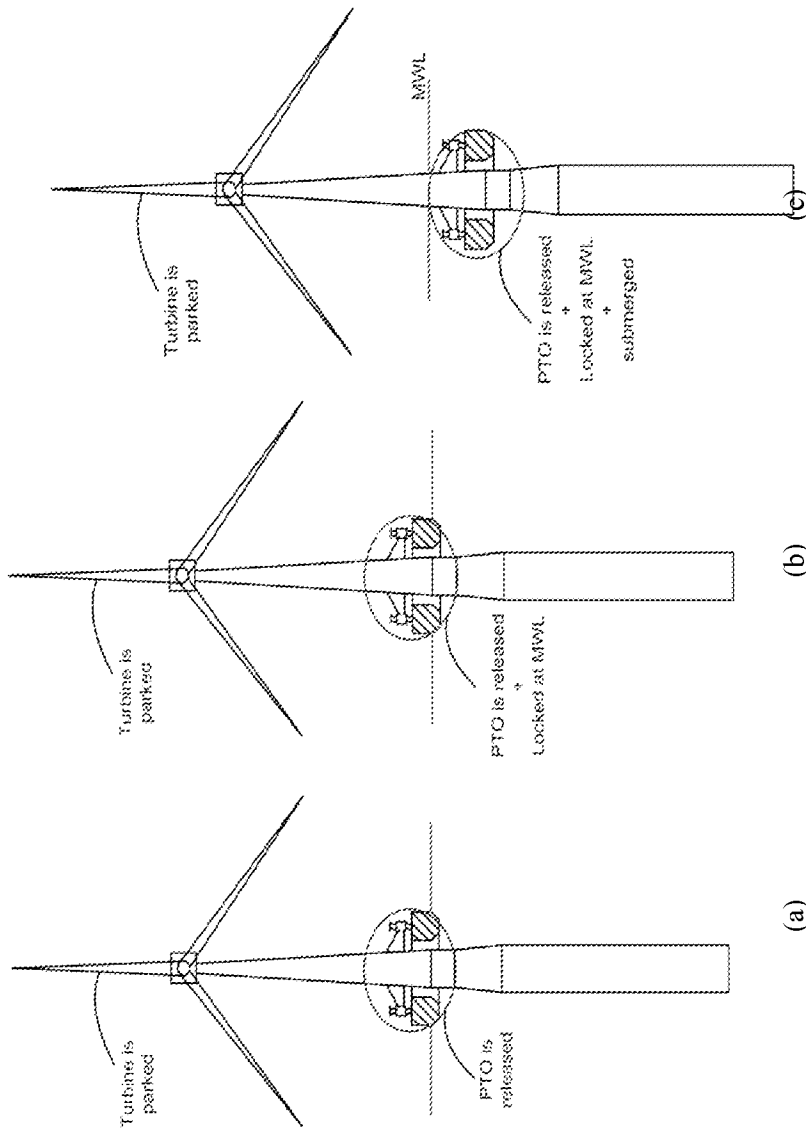


Fig. 6: an embodiment of the torus for transport and connection / disconnection on a spar and tower structure

Fig. 7:

Upper: graphs of mean pitch (γ_s) and standard deviation (γ_{sSTD}) for a wind turbine generator on a "spar only", and as mean pitch (γ_c) and standard deviation (γ_{cSTD}) for a wind turbine on a spar with the invention, for abscissa values of mean wind velocity and wind power. Lower: mean wind power production (Pc, Ps) and their STD (PcSTD, PsSTD) as function of wind velocities.



(a)

(b)

(c)

Fig. 8:

Possible survival modes for spar-torus combination in non-operational or extreme conditions when the wind turbine is parked and/or the power take-off system of the wave energy converter is released:

- (a) Released mode, the torus free to move in heave along the spar,
- (b) Locked mode, the torus mechanically locked to the spar at the mean water level (MWL), and
- (c) Submerged mode, the torus mechanically locked to the spar and ballasted to a submerged position.

INTERNATIONAL SEARCH REPORT

International application No
PCT/N02013/050050

A. CLASSIFICATION OF SUBJECT MATTER
INV. F03D9/00 F03B13/20
ADD.

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 F03B

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)

EPO-Internal, WPI Data

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Y	page 4, line 9 - page 5, line 10 page 5, line 15 - page 6, line 13 page 9, line 3 - line 5 figures 1-5	6-8
Y	----- DE 101 03 894 A1 (KOLDIN HANS [DE]) 14 August 2002 (2002-08-14) paragraph [0005] - paragraph [0006] paragraph [0017] figure 1 -----	6-8
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Further documents are listed in the continuation of Box C.

See patent family annex.

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Date of the actual completion of the international search

12 July 2013

Date of mailing of the international search report

23/07/2013

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer

Westermayer, Philipp

INTERNATIONAL SEARCH REPORT

International application No

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