The development of conceptual options to the construction of ice-resistant floating wind power plants

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Abstract. This paper addresses the conceptual engineering solutions for a Marine Floating Power Plant which uses the Wind energy and is designed to supply electrical power to Russian Arctic coastal and island territory. The analysis of different types current Wind Turbines (WT) made a basis for a construction configuration for sea based Arctic Marine Floating Wind Power Plants and helped define the main wind, wave and ice loads influencing Marine Floating Wind Power Plants in Arctic conditions. Also, different types of Marine Floating Wind Power Plant substructures were analyzed. Numerical modelling of the behavior of the considered conceptual options of Marine Floating Wind Power Plants was carried out. Strength analysis of substructures for Arctic offshore wind power plant options in question has been performed.

Introduction

Russian grid energy is traditionally based on major hydraulic, nuclear and thermal power plants. However, offshore, island, and coastal areas of the Arctic Ocean have significant Wind Energy Resources [1, 2]. Using them through building Autonomous Offshore Marine Floating Wind Power Plants, Coastal Wind Power Plants, and Wind-Diesel Power Plants can significantly decrease deliveries of diesel fuel to the Northern Territories and improve power supply [1]. The work examines Marine Floating Wind Power Plants in more detail, possessing high mobility, can be quickly transported to a particular water area and provide the electrical power to the development of industrial projects on these remote territories.

Commercial exploitation of sea based Wind Turbines (WTs), designed for electric power generation, started in the 1990s. The depths allowing WT to be set become much deeper. Shallow depth WT are usually placed on fixed substructures. However, the cost of WP fixed substructures, set deeper than 50 meters underwater, is inadequately higher than the profit from the WT. There is already the current global experience in carrying out Marine Floating Wind Power Plant projects. Except that the known projects were carried out for ice-free seas, which means almost no experience in carrying out Marine Floating Wind Power Plants in ice conditions. The following problems are of great current interest and in need of scientific evidence: the problems related to finding reliable and energetic types and WT parameters adapted to Arctic conditions; the problems related to the development of optimal design shapes of Marine Floating Wind Power Plants substructure receiving wind, wave and ice loads; the problems related to the minimizing metal consumption and Marine Floating Wind Power Plants costs; the problems related to drilling of the towing technologies and schematics, positioning and anchorage of Marine Floating Wind Power Plants as well as the problems related to the transportation of the electrical power to the shore [3].

In the Marine Floating Wind Power Plants, already constructed or being designed, it is usually suggested to use three main types of substructures of floating WTs: SPAR type (*Hywind* project [4]); TLP type (*GICON* project [5]); and semi-submersible substructures (*WindFloat* project [6]).

The present work discusses some conceptual Marine Floating Wind Power Plant options for relatively shallow sea depths so the options of exploiting substructures of SPAR type, which are usually designed for depths over 100 meters, haven't been analyzed.

The choice of a floating substructure for a Marine Floating Wind Power Plant was based on the following requirements:

- Stability of the floating Marine Floating Wind Power Plant substructure.
- Acceptable Marine Floating Wind Power Plant oscillation parameters (linear and angular displacements) under the action of environmental loads while producing electrical power or a standstill due to storms.
- Acceptable linear and angular displacement of Marine Floating Wind Power Plant under the influence of ice features in the extreme ice impact mode.
- Acceptable metal consumption of the structure options and the minimum cost of their production.
- Maximum constructability.

1. Conceptual options of marine floating wind power plant construction

The present work offers conceptual options of Marine Floating Wind Power Plant with a capacity of 1.5 MW having different types of substructures and the exploitation of current WT types:

– Concept 1 – single-column MFWPP-1 with one horizontal axial WT and ice-resistant TLP substructure (Figure 1).

– Concept 2 – three-column MFWPP with three vertical axial WT with ice-resistant semisubmersible substructure (Figure 2).

From a structural point of view, a single-column MFWPP-1 substructure consists of a supporting column with the diameter of 5 m and three main buoyancy volumes interconnected with the column by tubular braces with the diameter of 2,5 m. To reduce ice loads on the facility in the ice belt area the diameter of the support column in reduced to 3 m. The overall height of the substructure is 47 m.

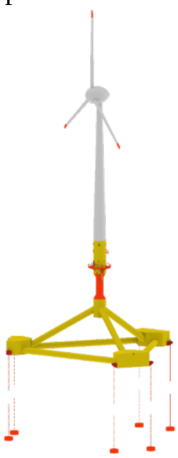

Figure 1. MFWPP-1.

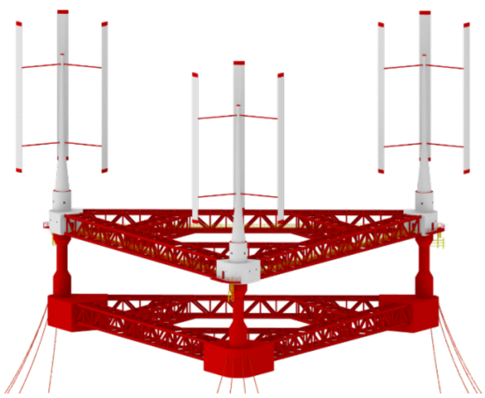

Figure 2. MFWPP -2.

MFWPP-1 hull can be conditionally divided into two main components:

— Bottom frame of Marine Floating Wind Power Plant hull being a triangle substructure with the overall size equal to or below 60 m. The main buoyancy blocks are placed in the construction corners; each corner has ballast tanks for receiving and pumping liquid ballast while Marine Floating Wind Power Plant positioning and displacement from the base. At each side wall of the Marine Floating Wind Power Plant main buoyancy blocks, there are cantilevered hull structures for installation of mooring chain tension devises and one tow pad eye. The main buoyancy volumes are interconnected by non-watertight structures.

— The WT tower foundation is cylinder-shaped. The WT substructure's lower part is connected with the main buoyancy blocks by watertight cylinder-shaped constructions. WT Tower foundation of the single-column Marine Floating Wind Power Plant with one horizontal axial wind-powered generator can be conditionally vertically divided into 3 belts:

a) lower belt of the foundation is cylinder-shaped. The lower belt is divided into two levels. There is a sealed cable termination for electric power supply to shore in the flooring of the lower level;

b) ice breaking belt is cylinder-shaped with conical parts at the top and bottom parts designed to take ice impacts;

c) the top of the WT tower foundation is cylinder-shaped. The main Marine Floating Wind Power Plant electrical equipment is placed in the top belt of the WT tower foundation: switchgears, a transformer, a WT control and state monitoring cabinet and converters;

For a single-column MFWPP-1, a 1.5 MW capacity horizontal axial WT is set. All main equipment, i.e. generator set, gear, system of swinging to the wind, blade rotation system, control system, auxiliary service board, etc. is located inside the cradle.

WT Tower consists of meta tapered tubes, with cradle rotation gear attached to the top part and the bottom part attached to the substructure body.

The Marine Floating Wind Power Plant anchor mooring system comprises tensioned mooring lines. These mooring lines are fixed to cantilevered chain tension gears located at side walls of the Marine Floating Wind Power Plant main buoyancy blocks. Mooring lines are mooring chains. Gravity or pile-type anchors may be applied depending on soil type.

Structurally, the MFWPP-2 substructure consists of three cylindrical support columns with diameter of 5 m, placed within 100 m apart from each other and interconnected by spatial horizontal trusses and braces which, in their turn, consist of built-up double T-beams. Both top and bottom parts of each column are provided with three-dimensional structures to connect the trusses and the column. And these bottom three-dimensional structures are used as buoyancy volumes. In order to decrease ice loads on the facility, the diameter of the support columns in the ice belt area was reduced.

The MFWPP-2 hull with three wind turbines is a triangle support structure; in its corners there are three WT Towers support foundations. Three-column Marine Floating Wind Power Plant hull may be conditionally divided into three main components:

– Bottom frame of the hull that is a triangle structure with overall dimension of about 100 m. Ballast tanks are located in each of three frame fixation areas. Mooring system pad eyes are located on side panels of truss fixation areas at the Marine Floating Wind Power Plant hull bottom frame;

– Top frame of the hull that is a triangle structure. Each of frame truss fixation areas accommodates rooms for Marine Floating Wind Power Plant main electrical equipment;

– Three WT Tower foundations are cylinder-shaped. WT Tower foundations are integrated into truss fixation volumes both at the top and bottom frame. WT Tower foundation of the three-column MFWPP may be conditionally divided into three vertical belts as follows:

1) WT foundation bottom belt is cylinder-shaped. This belt is divided into two levels, with the lower level integrated into the truss fixation volumes at the Marine Floating Wind Power Plant hull bottom frame. Pump room serving the ballast tanks is located at the lower level. The pump room flooring is equipped with a sealed subsea cable termination for electric power supply to shore. The second level accommodates ballast system manifold room.

2) ice breaking belt is cylinder-shaped with conical parts in the top and bottom parts designed to take ice impacts;

3) WT Tower foundation top belt is cylinder-shaped. Bottom part of this belt is integrated into the truss fixation volumes at the floating Marine Floating Wind Power Plant hull top frame.

The WT Tower foundation top belt houses the electrical equipment. For the three-column MFWPP-2 the vertical axial WTs of Darrieus type are set; their capacity is 0,5 MW and they possess an H-shaped wind wheel with swept surface diameter of 30 meters and of blade width of 42 meters. WT Towers consist of three tapered tubes that have main WT bearings inside.

Mooring system of the three-column MFWPP-2 comprises slugged mooring lines. The bundles are located at the substructure corners at the area of bottom column frame. Mooring lines are mooring chains. Also, gravity or pile-type anchors may be applied depending on soil type.

Mass of MFWPP-2 substructure is almost 4 times greater than the mass of the MFWPP-1 substructure.

2. Mathematical modelling of marine floating wind power plant behavior under effects of environmental loads

Buoyancy and stability of the Marine Floating Wind Power Plant was ensured based on its structural analysis. In order to analyze Marine Floating Wind Power Plant behavior under the environmental loads and to select Marine Floating Wind Power Plant mooring system parameters, mathematical modelling of their behavior under effects of environmental loads has been performed.

The environmental conditions that Marine Floating Wind Power Plant was designed for included varying parameters of current and wind velocity, wave and ice parameters typical for expected conditions of Marine Floating Wind Power Plant deployment. The Marine Floating Wind Power Plant is expected to operate in working mode with extreme wind velocity up to 25 m/s. Wind velocity is combined with current velocity (up to 1.5 m/s) and moderate storm (the height of the waves with 3% probability – 6.0 m, the average period of 9.0 s) or ice effects (the thickness of the level ice being 1.0 m and a compressive strength bring 1.5 MPa). Thus, such combination of factors describes the extreme conditions for operational mode.

Generation and calculation of wind stream induced loads and moments for horizontal axial WT and vertical axial WT considering static and dynamic components have been determined according to the proprietary methodology [7]. During design of WT as a part of the Marine Floating Wind Power Plant, all the most typical design cases and load combinations that may occur from a floater-based WT operating in severe climatic conditions have been studied. Design combinations of static and dynamic loads used for checking static strength and stability, fatigue strength and stiffness, both from WT structure and acting on the already vibrating under wave effects floater, have been studied for the following design cases: WT working mode; WT emergency operation; transportation, installation and maintenance. In addition, loads related to WT operation in severe climatic conditions (icing of structures and blades) have been taken into account.

In all WT design cases, the following requirements are applied to civil-engineering structures of WT: static strength and stability when WT members are affected by ultimate loads; WT member fatigue strength where loads are specified versus time; WT structure stiffness, i.e. provision of its members' vibrations where natural frequencies of the WT and its members are beyond the structural resonance zone.

Two factor combinations were taken as an extreme mode of survival with respect to wind and wave effects. The first combination included extreme wind velocity with 100-year return period (40 m/s), extreme current velocity (up to 1.5 m/s), and moderate storm (the height of the waves with 3% probability – 6.0 m, the average period of 9.0 s). The second combination included extreme storm with 100-year return period (the height of the waves with 3% probability – 12.3 m, the average period of 11.0 s), extreme wind (up to 40 m/s), and moderate current (0.5 m/s). In this survival mode, Marine Floating Wind Power Plant does not generate electrical power but shall withstand environmental loads and keep the mooring system undamaged.

In extreme mode with respect to ice load, extreme wind (up to 40 m/s) was combined with effect of ice with maximum thickness (1.0 m) and strength (1.5 MPa). The selected ice movement speed was moderate speed since maximum forces could be expected at very low ice drift speed, but very low drift speeds are unlikely due to high wind velocity that partially affects this speed.

For analysis and generalization of environmental conditions affecting installation and operation of Marine Floating Wind Power Plants, coastal areas of the Kara Sea, the Barents Sea, and the Okhotsk

Sea have been selected, where energy infrastructure development is especially relevant in view of execution of major projects related to development of the Russian continental shelf mineral resources.

Design loads from level ice acting on a vertical cylindrical barrier were calculated according to procedures given in Russian SP 38.13330.2012 [8] and ISO 19906 [9] for the specified ice thickness and compression strength.

Ice and wave load calculation approaches have been integrated into *Anchored Structures* [10] software package. The same software package was used for calculation of current- and wave-induced loads, and hydrodynamic characteristics of Marine Floating Wind Power Plants. The software package was also used for time domain simulation of Marine Floating Wind Power Plant behavior under environmental loads.

For the systematic study of Marine Floating Wind Power Plant options' behavior, a design case matrix has been developed that allows, by means of subsequent mathematical modelling, selecting mooring systems for Marine Floating Wind Power Plant options in question, studying their behavior under various combinations of environmental conditions, estimating viability of structural designs with various directions of environmental impacts and various water depth at site.

Some cases of mathematical modelling of Marine Floating Wind Power Plant behavior under environmental impacts are shown in Figures 3–6.

Analysis of mathematical modelling results for a single-column MFWPP-1 reveals the following: behavior of Marine Floating Wind Power Plant with vertically tensioned lines under wind, current, waves, and ice effects meets regulatory requirements of the Russian Maritime Register of Shipping (RMRS) at typical water depths.

Analysis of mathematical modelling results for a three-column MFWPP-2 reveals the following:

1. In operational mode at waves, the facility's motions do not exceed design values and the three-column Marine Floating Wind Power Plant maintains its operability at typical water depth.
2. At minimum installation water depth, the facility losses its stability during heavy storms and its bottom touches the seabed.

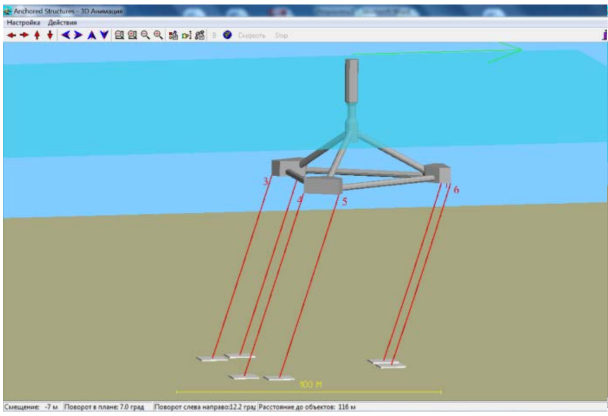

Figure 3. Position of floating wind power plant with vertically tensioned lines under ice load impact.

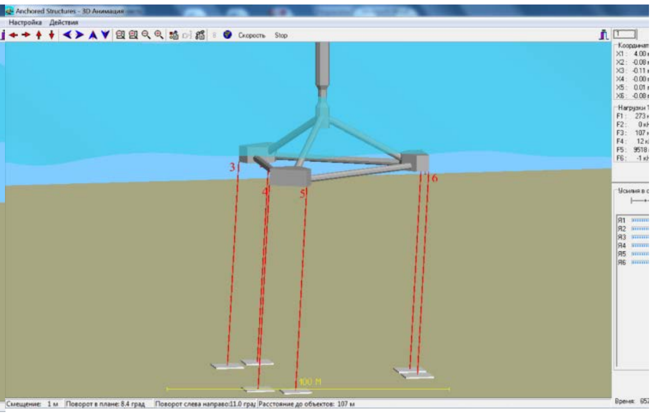

Figure 4. Position of Marine Floating Wind Power Plant with vertically tensioned lines under wave load impact.

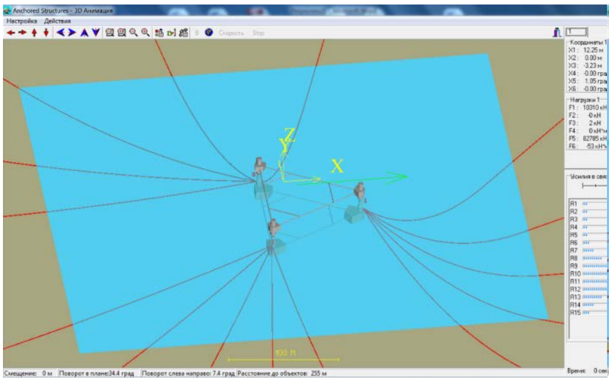

Figure 5. Position of three-column marine floating wind power plant under ice load impact.

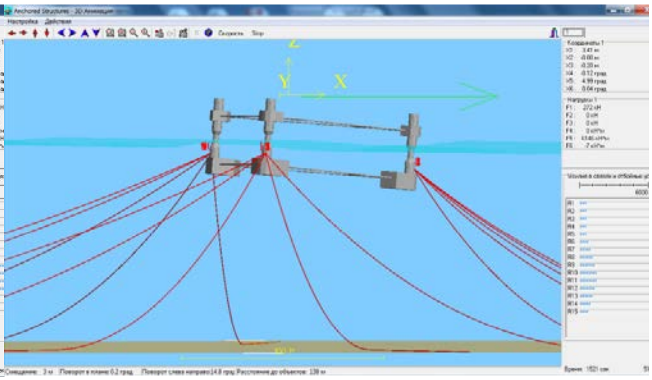

Figure 6. Position of three-column marine floating wind power plant under wave load impact.

3. Estimations of marine floating wind power plant structural member strength

Strength estimations considered the worst environmental load combinations that may cause maximum structural stresses [10]. Structural member ultimate strength criterion for the operating mode complies with regulations of RMRS [11] and was determined using the following equations:

$$\sigma \leq \eta_1 \cdot R_d; \quad \tau \leq 0{,}57\ \eta_1 \cdot R_d; \qquad (1)$$

where σ and τ are the highest normal and tangential stresses in structural members; η_1 is safety factor; R_d is material design yield strength.

The studied substructure members are referred to the main criticality category according to the RMRS Rules for MODU/FOR (η_1=0.68 in working operation mode). During design stage, steel grade and dimensions of Marine Floating Wind Power Plant members were selected based on this criterion.

Strength estimations for the developed substructure designs were performed considering the following three design cases:

- Design case 1. Structural dead weight effects;
- Design case 2. Structural dead weight effects and loads from WT on the floater mating surface;
- Design case 3. Structural dead weight and ice field effects.

Stressed and strained state of the substructure for various load cases was determined by means of FE analysis using ANSYS software package.

Maximum values of effective structural stresses in the substructures obtained from the above estimations do not exceed the allowable limits.

Conclusions

The obtained study results allow to conclude the following:

1. WT types and parameters preferable for application as an energy component of Marine Floating Wind Power Plants have been analysed.
2. Main combinations of static and dynamic loads and moments acting on Marine Floating Wind Power Plants from WT of various configurations under normal operational and extreme working conditions have been determined.
3. Developed Marine Floating Wind Power Plants conceptual options maintain their operability under wind-wave and ice effects typical for the Russian Northern seas.
4. Design values of stresses in structural members under extreme conditions do not exceed allowable limits. Marine Floating Wind Power Plants substructures presented in this paper meet the required stability factors.
5. Both studied substructure options are able to operate at water depths from 50 to 100 meters.

6. Floating substructures at water depth less than 50 meters are not reasonable. These water depths require fixed substructures.

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