

# REVIEW ON THE POSSIBILITIES OF USING OF UNDERWATER VERTICAL AXIS TURBINES ARRAYS FOR CLEAN ENERGY HARVESTING

Olena Haisha<sup>1</sup>, Eugen Rusu<sup>1</sup>, Oleksandr Haisha<sup>2\*</sup>

<sup>1</sup>Dunarea de Jos University of Galati, Galati, Romania

<sup>2</sup>Institute of Marine Sciences, Barcelona, Spain

\*Corresponding author: [oleksandrgaysha1982@gmail.com](mailto:oleksandrgaysha1982@gmail.com)

*The article presents the concept of an array of modular vertically oriented turbines that are installed under the water surface to harvest energy from water flows. Such modular technical decisions may be of more interest and total economic efficiency in some specific conditions rather than giant wind turbines with hundred-meter blades. Particularly module structure is more appropriate under war threats, natural catastrophic events caused by a climate changes, relocation of production due to economic and political reasons, etc. The geometric parameters of one device are justified, and, on their basis, an estimated calculation of the possible generated power is made. There are pointed out the paths for the development of the technology for production of the proposed modules, in particular, with using modern integrated printing systems (industrial 3D printers), instead of environmentally unfavorable composites (which are used to make turbine blades of modern wind energy stations). The issues of ensuring the static stability of one module, as well as the features of the electrical part of the entire system, are also considered.*

*Keywords: marine energy stations, water flow energy, modular system, grid of small-sized modules, vertical rotor, Savonius rotor, helicoid rotor*

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## Introduction

The relevance of scientific papers devoted to the problems of harvesting renewable energy is beyond doubt given the accelerating process of global warming. For today the most widely used decision, which is relatively safe for the environment is using of horizontal axis wind turbines (HAWT). In this branch may be observed some type of a vicious circle: to decrease Levelized Cost of Energy (LCOE) larger blades of the turbine should be realized. And to produce huge blades (which for modern HAWT tends to be about hundred meters) strong composite materials should be used. For the moment there is no effective technology of such composite blades recycling and, as it is known, they just buried in a ground, which is obviously not good for the environment. And even in the future, when such recycling technologies are developed, they are likely to be accompanied by significant CO<sub>2</sub> emissions.

Note that small wind turbines can be made of traditional, easily recyclable materials (steel, plastics, etc.), but the energy they produce, will have a higher cost. The authors hypothesize that placing turbines not in the air, but in a water flow, will make it possible to bring the LCOE to competitive values, while keeping turbine blades are relatively small (about meters – with some definite turbine construction, which is considered in this paper), which in turn would make it possible

to produce them from more environmentally friendly materials that can be easily recycled. The substantiation of this statement is a complex interdisciplinary task, including issues of hydrodynamics, electrical engineering, economics, system analysis, etc. and which the authors are trying to solve in this paper.

Firstly should be considered existing solutions for harvesting the energy of moving water. One of the promising areas is the harvesting energy from water flows in the open sea, on-the-shelf, as well as in other bodies of water. Examples of such works are included in publications (Park, Mentzelopoulos, & Bernitsas, 2023; Liu, Bao, Chen, Wu, & Wang, 2023), which discuss the harvesting of energy from vibrations caused by sea currents. Similar principles are considered in (Zhu & Gao, 2018; Sun, Zhao, Tan, Yan, Guo, & Luo, 2019). However, the solutions proposed therein are not enough scalable and are also quite difficult to implement technologically. Even more challenging to implement is the proposal in (Zhang, Jing, Wang, Fan, Zhao, Wang, & Cheng, 2022), which offers a triboelectro-electromagnetic generator using a biomimetic fin strategy and a turn-rotate mechanism. However, those works are the striking examples indicating the high interest of the researchers in harvesting the energy of moving masses of water. Hereby we propose other techniques to harvest marine renewable energy.

In the previous paper (Haisha & Haisha, 2021), the concept of a grid of small-sized turbines with vertical axis orientation, operating within the framework of a single system of marine energy generation (i.e., using the energy of water flows), was proposed. The use of the modular approach can have a significant number of advantages that are of serious importance in current world's unstable conditions. The simplicity and high speed of deployment, as well as the ease of dismantling and relocating equipment of the generation plants in the face of military and climate threats, are becoming the most important factors that make it possible not only to ensure the safety of large investments in green energy but also to create a reserve for obtaining constant profit streams from the use of such modular power plants.

Also, an important advantage of the proposed approach is elimination of the known disadvantage of vertical axis installations, which consists in their relatively low efficiency when blown by air flows (LUVSIDE, n.d.). The use of water flows for moving the turbines makes it possible to obtain significantly higher absolute energy values from a single turbine, which reduces the importance of the disadvantage associated with their low efficiency. Even with a lower efficiency factor (compared to horizontally oriented turbines), when using the liquid medium, it is possible to obtain quite acceptable amounts of electrical energy from a single vertically oriented turbine.

The concept of underwater turbines for marine energy harvesting is a relatively new proposition and is described, for example, in materials of the World Economic Forum-2022 (World Economic Forum, 2022). In general, such an influential organization as Advanced Research Projects Agency-Energy (ARPA-E, USA) pays much attention to the research and development of underwater sources of clean energy. For example, in 2023, there is still an active (since 2020) program Submarine Hydrokinetic And Riverine Kilo-megawatt Systems (ARPA-E, 2020) (or SHARKS) which includes 11 projects devoted to the extraction of marine energy which is performed under the water surface. All of these variants have different constructions which are more (like in (AQUANTIS, n.d.)) or less traditional and all of them are called hydrokinetic turbines (or HKT) for tidal and riverine currents. As it is noted by the program organizers, current HKT systems face significant technical and environmental challenges, rendering them economically unviable. The low technical readiness of hydrokinetic energy systems necessitates a comprehensive system-level approach that encompasses

hydrodynamics, structural dynamics, control systems, power electronics, grid connections, and performance optimization. Simultaneously, this approach shall aim to minimize potential adverse environmental impacts while maximizing the system's reliability. The inherently complex and multi-disciplinary nature of this design space has resulted in many systems remaining in the theoretical design phase without progressing to practical implementation. This program seeks to use Constrained Conceptual Design, Conceptual Design, and Design for Operations methodologies to pioneer innovative HKTs tailored for tidal and riverine application, with a primary focus on the substantial reducing the LCOE. The overarching goal of this program is to overcome industry-wide limitations and enable the cost-effective generation of hydrokinetic power, catering to micro-grid and utility-scale application.

One of the most significant researches of the SHARKS program is the Tidal Power Tug project in which AQ Series Turbines (AQUANTIS, n.d.) are designed by Aquantis Inc. The Tidal Power Tug represents a hydrokinetic tidal turbine system, utilizing a vertical yawing spar buoy equipped with a horizontal-axis rotor that facilitates parallel-flow. This turbine system is engineered to ensure reliable and secure operation under varying sea conditions, while achieving remarkable cost-efficiency through the incorporation of innovative materials, a vertical mass-buoyancy distribution mechanism, a high power-to-weight ratio, efficient deployment and retrieval processes, adaptive controls for blade pitch and shear compensation, as well as advanced analytical tools for optimizing operational efficiency and maintenance. Those elements collectively contribute to a significant increase in turbine uptime. The research and development efforts encompass several key areas, including the exploration of structural material innovations, hydrodynamic modeling, the development of adaptive control algorithms, the design of analytical tools for operation and maintenance, and the creation and deployment of a prototype turbine within a tidal stream. The turbine system will be engineered to supply power to both remote and local grids. It will operate autonomously, with a remote supervisory control and data acquisition computer facilitating data analysis and operator input for the onboard controller. The control system will have the capability to prioritize the minimization of energy costs, the extension of component lifespan, and the maximization of available energy output.

BladeRunner (BladeRunner Energy, n.d.), another actual project of the SHARKS program, is implemented like a modular submerged system of turbines (with a horizontally oriented axis and a special form of the blades) which is easy to install and retrieve from the coast. Manta (SRI International, 2021), one more project of the SHARKS program, despite its turbine-less construction, is highly scalable and can form both remote micro-grids and larger scalable systems.

Also, a modular system is proposed by the Michigan University team in its project RAFT - Reconfigurable Array of High-Efficiency Ducted Turbines for Hydrokinetic Energy Harvesting (ARPA-E, 2020). The project team introduces the RAFT concept as a viable solution for the efficient harvesting of hydrokinetic energy. The primary objective of this initiative is to advance the development of multi-physics models, design methodologies, and optimization tools. Additionally, it aims to enhance control systems and algorithms for monitoring the health of the system. The proposed RAFT design comprises multiple micro-turbines and features a modularized architecture with reconfigurable units, rendering it adaptable to a range of applications and marine environments. The innovative turbine designs, coupled with load control distribution and regulator concepts, lead to a substantial reduction in the LCOE. The incorporation of in-situ, real-time optimization-based control and distributed continuous health monitoring system serves to optimize the features of the RAFT, enhancing its performance, resilience, reliability, and cost-efficiency.

In the paper (Ross & Polagye, 2020), the authors investigate the matter of using both underwater horizontally and vertically oriented turbines, but they take into account only spatially limited flows. Also, as one can see from the video presented by the authors of that paper, the vertically oriented turbine is only partially sunken. In addition, the authors of that paper set themselves the goal of studying the efficiency of turbines of different types specifically in limited flows, without considering the possibility of their placement, for example, in conditions of ocean currents or in the beds of wide rivers. So, in one respect, this research proves that vertical orientation of the underwater turbines can be efficient, but in another respect, it raises further questions, that shall be researched in an appropriate study.

So, it should be noted that, in modern literature, there is information only about sunken Horizontal-Axis Turbines or HAWT (where “W” stands for “water”) and no information about real implementations of Vertical-Axis Water Turbine or VAWT. It is obvious, however, that choosing one concrete direction for the turbine axis, limits the potential possibilities of the entire system (as it was shown by the authors in (Haisha & Rusu, 2021)). Thus, the use of underwater VAWTs can be quite effective and provide greater volumes of generated energy from the definite waterflow compared to existing solutions (due to the omnidirectionality of such turbines and the absence of the need to orient them to the direction of the flow). Certainly, qualitatively visible advantages of the proposed approach should be supported by the appropriate calculations, performed in this paper.

### Objectives

The purpose of this work is based on literature review to substantiate, as a first approximation, the effectiveness of such a new solution as a modular system of submerged vertically oriented turbines for collecting energy from water flow. In other words, it should be ensured that there are no obvious factors that make it impossible to effectively implement and/or operate such systems.

### Methods and Techniques

To calculate the parameters of the modular power plant network, it is possible to use the estimated formulas for the parameters of wind turbines. First of all, we should calculate the area, swept by the blades:

$$A = D \cdot H, \quad (1)$$

where  $H$  is the height of a vertically oriented turbine;

$D$  is the diameter of the turbine blades.

Then the theoretical power of the flow entering a given area  $A$  from an external influence (wind or wave) will be equal to the kinetic energy of the volume of the medium that reaches the swept area in a certain time interval, divided by the value of this interval:

$$P_T = \frac{E_K}{t} = \frac{mV^2}{2t} = \frac{\rho AVt \cdot V^2}{2t} = \frac{1}{2} \rho AV^3 \quad (2)$$

From this maximum limit value (2), a real flow energy collection device can take only a certain part (similar to how in Betz's law only part of the air flow energy can be transferred to the system), which is determined by the efficiency of this device (will be described later in the article).

For further estimate calculations, let assume the average power value of one module  $N_1 = 0.5$  kW. Certainly, using of one such module does not solve the problem of energy supply even for one energy-consuming household (at the same time the specified capacity is enough to provide electricity for a small apartment with household appliances, without electric heating). Nevertheless,

when cascading such modules, it is possible to generate tangible capacities of the order of hundreds of kilowatts (or more). The need to consider cascading issues of such modular systems is especially obvious when analyzing the size of modern wind power plants, which are the structures of 200 m in height and above. Each such installation weighs about several thousand tons (for example, for the Enercon E-126 air wind generator, which is well documented in open sources, the total weight is about 7000 tons (Juwi AG, 2011) with a generated capacity of about 6 MW).

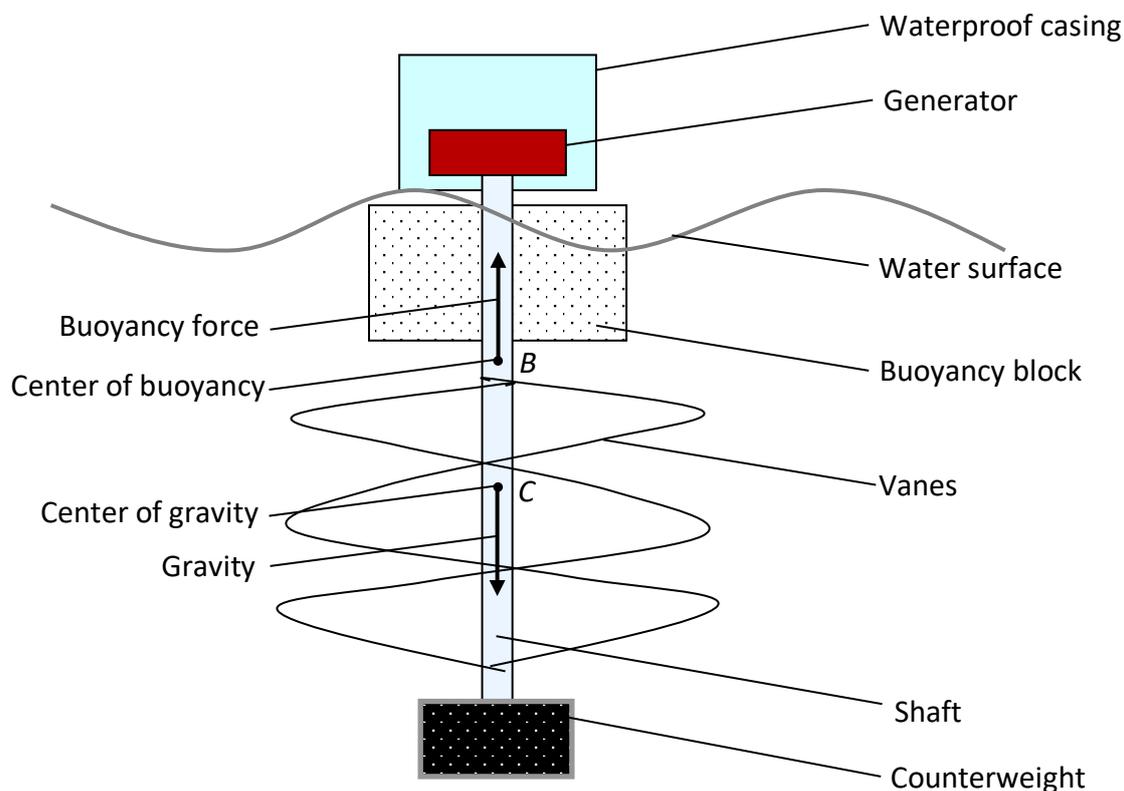
Also it is expedient to estimate the area that the system needs. For further calculations, let's assume that all the modules form a square grid. When numerous modules that harvest energy from a water flow are installed in a single array, their mutual influence is possible, which is especially important for sea currents not limited by the shores. To assess the corresponding effects, a dedicated study on the hydrodynamics of the processes of interaction of the flow with the grid of the proposed modules is necessary, which is planned in future work. It is also possible to consider the placement of the proposed system in a river flow (initially, the idea described in this research arose from observing the powerful flows of the Danube river near the city of Galati, where the width of the channel ranges from 500 to 1000 m with a flow speed of about 2 m/s and a total flow of 6500 m<sup>3</sup>/s). In this case, due to the constant water flow in the river, installing an arbitrary number of modules will not affect the flow rate (therefore, the efficiency of the modules will remain unchanged), but can only lead to a slight increase in the water level upstream in the river.

If we compare the complexity of manufacturing moving parts of turbines, in particular impellers, then for traditional wind power plants it is at a high level, since the blades shall have a verified geometry and, most importantly, have dimensions of the order of tens or even hundreds of meters in length. In the proposed solution, provided that the Savonius rotor is used, the manufacturing technology of a single modular device is extremely simple and is reduced to the creation of curved (and with large radii of rounding, i.e. with a small curvature) cylindrical surfaces. Even when using more efficient Darier or helicoid rotors, due to the small size of each blade, it's possible to manufacture them of almost any material. For example, industrial 3D printers can be used to print parts of 1 m by 2 m in size, some models of which are shown in (ANIWAA, 2024).

It should be noted that in economic terms, the use of 3D printers for production of the blades is advisable only if their geometry is complex (Darrier rotors, helicoid). In this case, materials based on high-strength thermoplastics can be used, which also has a positive effect on reducing the inertia of the moving part and, as a result, an increase in energy production into the external network is obtained, as well as a decrease in the minimum operating wind or water speed. Preliminarily, we can assert that materials suitable for 3D printing with durability include nylon, offering high strength, wear resistance, and excellent impact resistance. Polycarbonate, characterized by strength and impact resistance, is also noteworthy. Variants of reinforced PLA and ABS, which incorporate additives such as fiberglass or carbon fibers, exhibit enhanced strength properties. Polyether ether ketone stands out as a high-strength thermoplastic with exceptional thermal and mechanical characteristics. Additionally, polyetherimide, known as ULTEM, demonstrates high thermal, mechanical, and chemical resistance, further contributing to its suitability for 3D printing applications. In the general case (Savonius rotors), the main material of the blades can be metal (stainless or ship steel), for example, with a thickness of about 5 mm, processed by rolling.

In addition to the profiled blades, each module shall contain an electric generator (stator-rotor system), for which underwater operation is undesirable, since in this case much more stable liquid intrusion protection is required (under hydrostatic pressure, because, as is known, one atmosphere is

added for every 11 m of depth; also, when working not in river water, materials resistant to aggressive seawater should be used). It is advisable to place the generator in the device's upper part, which can be implemented above water surface. In this case, the entire network of the proposed modules will be located on the water surface. At the same time, the modules themselves shall be stabilized in space, which can be achieved by their vertical shape and placing the center of gravity lower than its center of buoyancy (the point where the equivalent of all the buoyant forces acting on the module's volume are applied). The layout of the module elements can be as follows: Figure 1.



**Figure 1. Scheme of the main module elements layout**

This figure shows in detail how the turbine can be stabilized in its working position. In fact such layout of the module's hydrostatic elements is typical for any device which uses stabilizing momentum of a pair of forces - gravity and buoyancy force. The generator is located in the upper (on-surface) part of the module. As it is known, the generator has a fairly high mass and its location in the upper part of the module turns it into an unstable structure that tends to tip over. To avoid this and keep the center of gravity  $C$  as low as possible, we need to place a counterweight at the bottom of the module. To ensure free floating on the water surface, a buoyancy block should be attached to the module, and it should be placed at the top of the module, thereby raising the center of buoyancy  $B$ .

The distance  $BC = z_B - z_C$  is the main characteristic of the stability of the module and the positivity of this value is the condition for static stability of the module (provided that the vertical axis  $Oz$  is directed upwards). During small waves such construction provides not only static, but also and dynamic stability of the module in the vertical position. In such case stable module equilibrium is conditioned by the opposite direction of the moment of a couple of forces (gravity and buoyancy) to the angle of the deviation of the module axis from the vertical.

Modules should be placed on the sea shelf, where it is possible to fix them securely with an anchor device. It should be noted that, firstly, it is necessary to fix the center of mass of the device (so that it does not drift freely in the water space, that is, so that there is no free translational movement of the module). Secondly, it is also necessary to fix the module to counteract its free rotational movements (so that the stator part of each module is fixed), which can be done also by the module-to-module strength joint by strong mechanical connections. So, neighboring modules shall be connected by mechanical connections that keep the modules from free rotation.

When a strong storm approaches, the modules shall be removed by the service vessel or, if the buoyancy units are implemented to be adjustable and the generator is implemented to be watertight, the entire network of modules can be submerged to a safe depth where the storm is not felt, and later, after its end, all modules should be raised to the surface.

Since each module is equipped with an anchor device, this already ensures static location on the sea surface; however, as it was mentioned earlier, it is also necessary to provide for the module-to-module strength joint by, which can be done using strong cables. In the absence of strong waves, the cables will remain in a lightly tensioned state, preventing only rotational movements of the modules. The cables will be fully stressed only during significant rough waters.

Thus, for the satisfaction of real consumers' demand for electric energy, it is necessary to use the groups of proposed modules, i.e. to increase their number. Then, the question about the features of their electrical connection arises. As it is known, when generators are connected in series, the EMF (Electro-Motive Force) generated by them is summed up, and when they are connected in parallel, the current generated in each of them separately is summed up in the nodes. It is obvious that modern power plants are located geographically far from the consumers, so in this case, the transmission of the generated electric energy over considerable distances is also required. Considering the formula for specific heat losses in a conductor according to the Joule-Lenz law in differential form (expressed in terms of the resistivity of the conductor material  $\rho$  and the current density  $j$ ):

$$w = \rho j^2 \quad (3)$$

we can see that the transmission of large electrical power cannot be effected using big currents  $I$  ( $j = I / S$ ), since this will be accompanied by high losses due to heating of the conductors. Therefore, it is certainly more advantageous to transmit high voltage over long distances, rather than current, which means that, electrically, the modules shall be connected in series. This method of connection, in addition to producing a ready-for-transmission high voltage, also contributes to saving the electrical conductors, since parallel connection requires an individual wiring from a distribution hub to each module.

If each turbine is connected directly to the wire, and the converter (rectifier, inverter) is placed in a center, which is remote from the grid of modules (possibly on the sea shore), then the question of the shape of the signal transmitted along the line is relevant. It can be determined by directly summing the voltage values (by simulation using the appropriate software) or by summing the complex amplitudes of the main components of the signals from individual generating units (if the frequencies they generate can be considered the same). Also, this process can be carried out by decomposing the complex signals received from each generator separately into a Fourier series with further discarding those components that have amplitudes below a certain limit value. After calculating the current propagation in the circuit, for each harmonic taken into account, the output form of the generated electric current can be obtained by summation. Non-linear effects can be ignored since a current of an arbitrary shape is transmitted, which is then directed to the rectifier

(therefore, even if the waveform is distorted, these processes are not critical for obtaining a power current).

## Results

The most important parameter in (2) is the speed of the incoming flow  $V$  and, if for wind stations this speed is often assumed in the range of 10-11 m/s, then for water stations, it can take values of the order of 0.3-1.5 m/s. For further calculations, we will choose the flow rate of 1 m/s, which corresponds to the minimum estimates of the flow rate of water in the Danube River in Romania (Dumbrava & Andrei, 2019). Then, for example, for an installation with a height of  $H = 2$  m, with a blade diameter of  $D = 2$  m (square section) at a flow rate of 1 m/s, we will have the theoretical power that can be maximally obtained from the freshwater flow under these conditions (better estimates may be obtained in studying physical models, which is planned to be done in further studies):

$$N_T = \frac{1}{2} \cdot 1000 \cdot 2 \cdot 2 \cdot 1^3 = 2000 \text{ W} = 2 \text{ kW}. \quad (4)$$

When the installation efficiency is in the range from 0.2 to 0.4 (let's assume  $\eta = 0.2 \div 0.3$ , based on the performance of wind turbines with a vertical axis) the power supplied to the power system will be:

$$N_1 = N_T \cdot \eta = 2 \cdot (0.2 \div 0.3) = 0.4 \div 0.6 \text{ kW}. \quad (5)$$

The mass of the proposed modular installation can be estimated as a mass of  $k = 3-5$  metal sheets (representing blades if we consider a geometrically simple structure of the "Savonius rotor" type, and for a helicoid structure, the mass will be far less with a thickness of  $d = 5$  mm with an area of  $D/2 \times H$  (reducing the width of the swept surface due to bending of the sheet) plus the mass of the central part, which doesn't exceed  $m_0 = 100$  kg:

$$m_1 = k \cdot D/2 \cdot H \cdot d \cdot \rho_m + m_0 = 5 \cdot 2/2 \cdot 2 \cdot 0.005 \cdot 7800 + 100 = 490 \text{ kg}. \quad (6)$$

Performing an extremely rough estimate calculation for such a parameter as mass of consumables, we can assume that one E-126 installation can be put in compliance with

$$n_1 = 7000 \text{ tons} / 0,49 \text{ tons} \approx 14\text{k} \quad (7)$$

of suggested installations. An estimate of their total output power gives a value close to the power of a wind generator:

$$N_{11} = n_1 \cdot N_1 = 14\text{k} \cdot 0,5 \text{ kW} = 7000 \text{ kW} = 7 \text{ MW}. \quad (8)$$

If we have 14k modules, which are placed at the square grid nodes, so the number of modules in one side can be evaluated as the square root of this number:

$$n_2 = \sqrt{n_1} = \sqrt{14000} \approx 118. \quad (9)$$

Then let the distance between two nearest modules be equal  $l_2 = 4$  m, so the side of the total square is:

$$l = n_2 \cdot l_2 = 118 \cdot 4 = 472 \text{ m}. \quad (10)$$

And the area, taken to the entire system is equal to:

$$S = l \times l = 472 \times 472 = 222784 \text{ m}^2 = 0,223 \text{ km}^2. \quad (11)$$

This value is several times larger than the area which is rejected under the installation of a big HAWT like E-126 (minimum rejection area may be calculated as  $\pi(r+15)^2 = 3.142 \cdot (63+15)^2 = 19116 \text{ m}^2$ , where 15 m is a safety addition). From the other point of view, the proposed systems should be installed offshore, contrary to HAWTs which are often installed at the much more valuable

ground surface. If we use water surface, as for this moment, there is no need to economize it for the most of localities. So, on the “taken area” criterion, the proposed decision is a little worse than traditional monstrous wind generators.

Thus, according to the estimation of the material consumption required to create an array of the proposed modules and other characteristics, the entire system has the indices similar to those of today’s popular wind farms with a horizontal rotor (having maximum efficiency).

Thus, when forming a grid of generating modules, the connection scheme can be in series. The important question is: what type of the needed electrical equipment is expedient to place onto each module and what devices are to be put at the onshore station? The extreme conditions in which all the modules operate (mechanical overloads, vibration, salt water which forms an aggressive environment etc.) should be taken into account. At first sight, all the electrical equipment may be placed at the shore.

The disadvantage of such a connection type is based on the modeling results. If we use many modules, connected in series and all their voltages are summed, then different results can be realized. First, every module can have its own rotational velocity  $\omega_i$ , voltage amplitude  $U_i$  and, certainly, a start phase  $\varphi_i$ . Then, summing all the harmonics, we get the resulting electrical voltage  $f(t)$  which is not of the regular form: due to various frequencies, the sum is not a harmonic function.

Considering a specific example of the grid functioning from the electrical processes point of view, it may be simulated with using of the next parameters. Let the total number of modules is equal to 14000 and every module produces a voltage from 10 to 20 V of an alternating current with the frequency from 0.5 to 1 Hz and uniformly distributed start phase (from 0 to 359 degree). If all the modules are connected in series we should add all the harmonics to get the final result, also it is more convenient to study a rectified signal, so we apply absolute value operation and get Figure 2 (a, b).

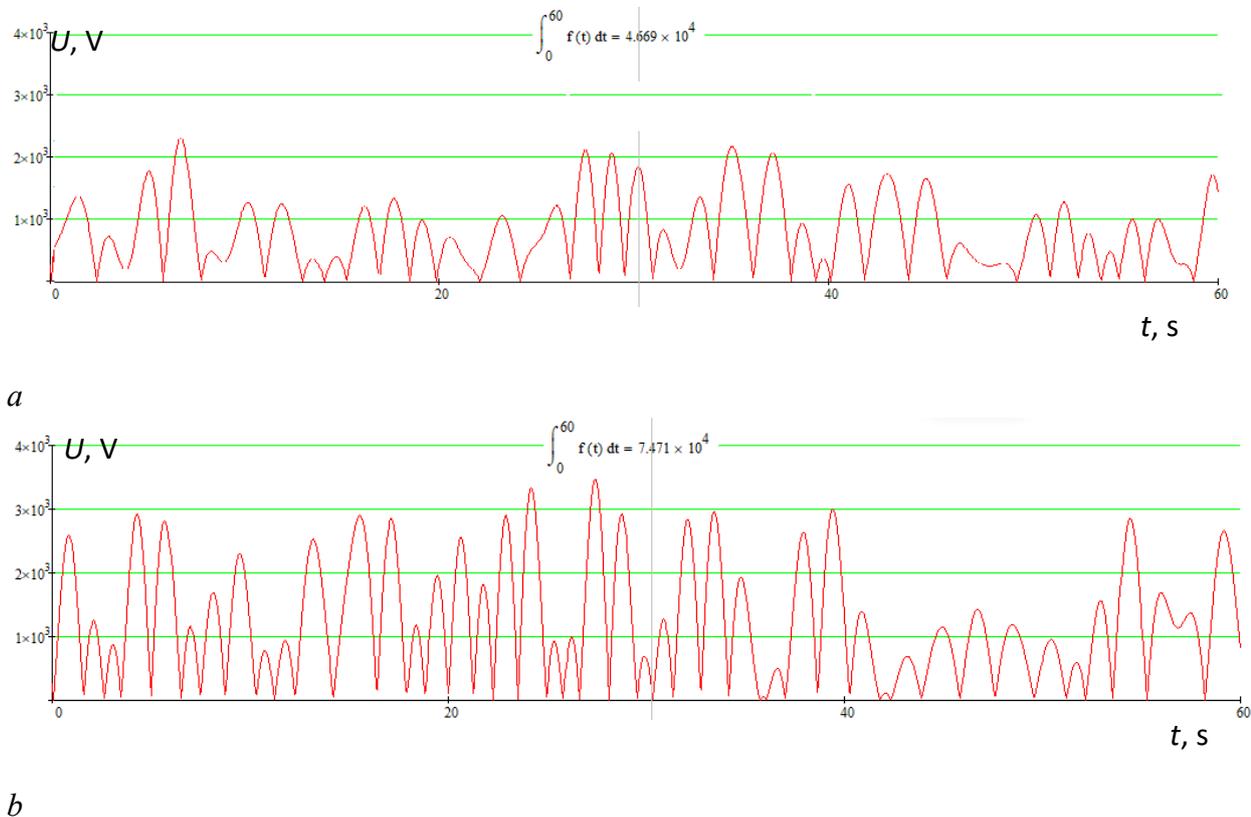
In some periods,  $f(t)$  is very small (Figure 2 (a), about  $t = 13-15$  s) and in others, it is high enough (Figure 2 (b), about  $t = 26-28$  s). Of course, for better energy generation we need as higher value of  $f(t)$  as possible, and it is not appropriate that signals from different modules neutralize each other when they come to the rectifier in the counter phase.

So, if not install any electric units at the modules themselves, so the only way to prevent negative mutual influence of generated voltages in one power wire, is to use many separate wires. So, a more effective electric circuit will be the variant in which separate voltages will not be united and correspondingly they cannot neutralize each other. All the electrical transformations will be provided at the coast at the electric stations, where it is possible to use powerful rectifiers, accumulators and invertors for getting AC (alternating current).

Also, the additional reason to use individual electric part is high voltage excesses, which may be present in a function that is a sum of irregular summed functions. Analyzing Figure 2, one can see that usually, voltage values are inside some mean interval, but sometimes we get very high outlines which are sometimes bigger than typical values. In theory, we are not limited to the value of the sum and it can reach at some particular moments very high values of about some dozen thousand volts (while we have 14000 modules). So, the electric part of the system which is based on the serial connection of modules, earlier or later, will burn out due to electrical breakdown. To prevent this inadmissible process, it is expedient to use an individual wire for each module or at least for some groups of modules, connected in series.

Certainly, if the number of modules is high enough (formula (7)), it is impossible to provide an individual wire for each module. In such a case, we should turn to the variant of installing just

some simple electronic equipment of the “diode bridge” type into each module. Thus, before summing all the harmonics, we should rectify them by adding their absolute values. In this case, we can get a constant voltage characteristic in the wire and we shall use wires at least 150 kV, which are technically accessible and can be introduced into the system of VAWT modules. Besides, when summing many random summands, we get a relatively direct current (we need just filter some high-frequency component) which can be efficiently used for accumulator charging.



**Figure 2. Comparison of two random voltage realizations which in a total result are more than one-and-a-half times different by the amount of the energy generated:**  
**(a) random realization with a low amount of the energy generated;**  
**(b) random realization with a high amount of the energy generated**

Also, when assessing the efficiency of the entire power system, it should be taken into account energy losses not only during transmission, but also during its conversion in the electric rectifier (this value depends on the type and operating conditions of the rectifier and approximately its efficiency can be taken at the level of  $\eta_r = 98\%$ ), accumulator (this value also depends on many conditions and can vary widely; for estimated calculations it is accepted  $\eta_a = 90\%$ ) and inverter (accepted at  $\eta_i = 95\%$  level). The total additional losses during energy conversions will then be up to:

$$\eta_{conv} = \eta_r \cdot \eta_a \cdot \eta_i = 0.98 \cdot 0.9 \cdot 0.95 = 0.84, \text{ 16\% losses} \quad (12)$$

Thus, by applying specific values to the formulas presented in the previous section, were obtained numerical estimates of the parameters of the proposed vertical axis turbine-based marine energy harvesting system. By comparison with similar indicators of existing systems, it was established that the proposed concept is competitive and it's further, more in-depth research is expedient.

So, we have got main parameters of a modular energy station which is based on VAWT rotors for marine (water flows) energy harvesting. The size of a module is about 2 x 2 m while its mass is about 500 kg. Electrical energy generation can be estimated as 500 W and the number of modules necessary to replace one large wind energy station is about 14k (getting power of 7 MW – as some kind of reference point). The total mass of a system is similar to the mass of such a big HAWT. The area taken for deployment and use of the proposed modular system is by several times greater than the area necessary for installing traditional large wind energy station, but as we use it at sea, the problem of the efficient area utilization is not so acute and can be leveled. We should remember that it is quite simple to get the blades of the proposed VAWT, for example with the use of 3D printer (the appropriate model is proposed in this text) – if they have a complex geometry, or by an ordinary technological process of rolling, which is cheap and widely used in modern industry (especially for such small metal sheets with dimensions of 1 m x 2 m).

The mechanical construction of a module that can provide its buoyancy and stability is proposed. The structure of a module is relatively simple and is typical for the construction of floating buoys. A weighting element in the lower part and a buoyancy block on top, which together form the necessary arm of a pair of forces: buoyancy and gravity. Their moment fixes the module in a vertical position and provides both static and dynamic stability.

Thus, the proposed modular design can form flexible (by the number of individual elements) systems with a total number of up to thousands of modules. At the same time, the resulting generated power can be on the order of megawatts, which is comparable to the largest HAWT installations (with a blade diameter of about a hundred meters). And the complexity of production, logistics, installation, deployment and operation of the proposed solution is significantly lower. Also, if necessary, it is possible to simply relocate the array of modules to another geographical location, which is especially important in conditions of increased risks for investors associated with military threats and possible natural disasters (resulting from global warming and catastrophic weather changes).

## **Conclusions**

So it is grounded that VAWT modules (where the letter “W” stands for “Water”) can be as efficient as HAWT mega-turbines. Using modular energy generation can be much more attractive in the new world of active war threats and potentially unfriendly climatic phenomena (such as powerful hurricanes and tropical storms caused by global warming).

An important disadvantage of the proposed solution is the need for active actions to secure it during a heavy storm. These measures must be carried out in advance, based on the weather forecast data, which allows avoiding mechanical damage to the system, up to the loss of its modules. From this perspective, it could be expedient to provide for each module some simple mechanism for sinking (when the storm is coming) and surfacing up (when it’s over). That statement is grounded by the known fact that at the depth storm is not felt. Also, we can pick up all the modules relatively simply using a mother ship, if we need to relocate the system to a new location or to store it temporarily in a safe place.

The possibility and expediency of using modular power generation systems based on small-sized vertical-driven underwater turbines is proved using estimation calculations. Solutions based on wind turbines with a vertical axis are quite common, but underwater turbines of this type are practically not used and the grid of modular vertically oriented underwater turbine for marine energy harvesting is proposed for the first time. Such a technical solution has a significant number of

advantages and is technically feasible, so it is advisable to carry out its subsequent development, which is planned in future work. Therefore, it is required to develop and justify the effective profile of the streamlined surface, which can be done by mathematical modeling with the use of some hydrodynamic simulation packages (CFD software). Then with the use of an optimal geometry got in silico, an experimental sample can be realized and tested in vivo (particularly, low-scaled prototype). So, based on the materials presented in this text, it is possible to investigate in a cheap and accessible way an alternative VAWT construction device for collecting clean marine energy not only from wind flows but from water flows.

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### **Conflict of interest**

The authors state no conflict of interest.

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