A NOVEL OFFSHORE WIND-POWERED SYSTEM FOR SUPPLYING ELECTRICITY TO SHIPS

Ciprian POPA[1], Nicolae-Silviu POPA[1, *], Eduard-Alexandru ANDREI[2], Andrei-Darius DELIU[2], Bianca CĂȘERIU[3], Mihai-Octavian POPESCU[1]

This research article focuses on the development and testing of a wind power system designed for ships anchored in the outer harbor of Constanta Port. The article extensively analyzes the electricity consumption of various types of vessels during anchorage, taking into account significant variations. Emphasis is placed on the importance of designing the system to cover these variations and provide constant and reliable energy. To validate theoretical models and assess the system's efficiency in real conditions, a prototype was constructed and tested near Constanta Port. Tests included measurements of wind speed, voltage, and generated current. Homer Pro software was used to simulate and optimize the performance of the wind power system. A significant alignment between the results of software simulations and field measurements confirmed the validity of theoretical models. The successful validation of the prototype using data from software simulations confirmed that the proposed wind power system can efficiently supply electric power to ships in the outer harbor of ports.

Keywords: conversion systems; current generator; electrical efficiency; electrical energy; floating foundations; horizontal-axis turbine; wind energy system; supplying electricity to ships; power production; prototype testing; renewable energy systems; wind power system.

1. Introduction

In recent times, renewable energy sources have gained significant prominence due to their eco-friendly and sustainable characteristics. Among them, wind energy stands out for being both abundant and cost-free, offering notable advantages in addressing the growing demand for clean energy solutions [1], [2].

Considering the diverse designs of wind power systems and their migration to offshore environments following advanced exploitation in onshore settings, the

* Corresponding author
[1] National University of Science and Technology POLITEHNICA Bucharest, Romania, e-mail: ciprian.popa1@yahoo.com, nicolaesilviu13@gmail.com*, mo.popescu@upb.ro
[2] Naval Academy “Mircea cel Bătrân” Constanța, Romania, aalexandru1406@yahoo.com, e-mail: deliudarius@yahoo.com
[3] George Emil Palade University of Medicine, Pharmacy, Science and Technology, Târgu Mureș, Romania, e-mail: biancacaseriu@yahoo.com

selection of a perfect architectural form takes into account numerous system-specific considerations, possible methods of obtaining electricity [3], [4], [5], [6]. Simultaneously, consumer requirements and environmental factors play a vital role in achieving a reliable system [7].

Analyzing the design variants of wind power systems to ultimately select the best architectural option, which encompasses the characteristics of wind turbines and the overall system, requires consideration of several factors [8]:

• Design variants of wind turbines - concerning the orientation of the main axis of the turbine, a horizontal-axis turbine is chosen due to its higher efficiencies, making it prevalent in modern applications for harnessing wind energy. These turbines are installed at greater heights where the wind is stronger and denser, automatically resulting in higher energy production [8], [9], [10], [11], [12];

• Design variants of foundations and the system's placement - in terms of mobility and installation in expansive areas where higher energy production efficiencies can be achieved, floating foundations anchored to the seabed stand out. The wind turbines could be located approximately 4 nautical miles from the shore in the outer harbour of Constanța. Although fixed foundations were considered suitable and more economical for this distance, we opted for floating foundations to enhance the system's mobility and adaptability to varying environmental conditions, as well as the ability to be deployed in deeper waters where fixed foundations might not be feasible. A wind turbine can also be installed on an offshore platform operating under drilling conditions, contributing to the electrical power supply of the platform's systems [13]. The foundation is a much more delicate element, given that it operates as an autonomous and mobile power supply system. It must primarily be a floating foundation, anchored, and equipped to encompass energy storage and conversion systems, which can be considerably heavy. To fulfill these conditions, an optimal foundation composed of three floaters arranged at the vertices of an equilateral triangle has been chosen, supporting the wind turbine and selecting a semi-submersible structure as per Fig. 1 [14], [15], [16], [17].

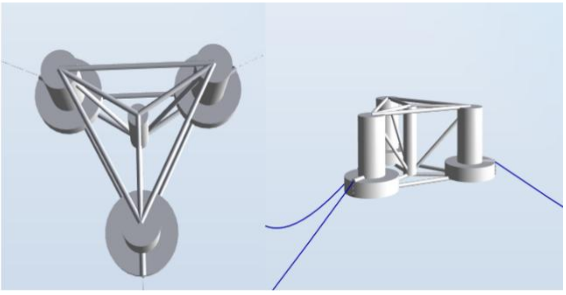

Fig. 1. Optimal system foundation

After previously specifying the necessary criteria for selecting an optimal wind power system for supplying ships in outer harbor, the configuration presented in Fig. 2 will be further examined.

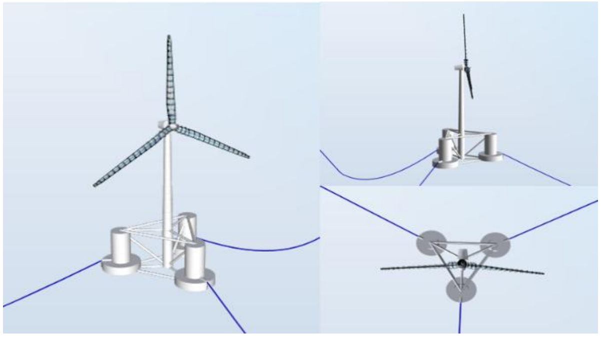
Fig. 2. Optimal wind power system for supplying ships

The research article aims for the wind turbine to be capable of supplying at least medium and large-sized vessels when the wind reaches a speed of 10 m/s. The findings indicate that Romania is characterized by a significant wind energy potential along the Black Sea coast and that is why the experimental part will be carried out in the outer harbour of Constanta. To avoid significantly affecting the system's stability, the turbine must not be excessively tall or heavy [18].

These systems must be designed to provide power to stationary vessels, even though energy consumption varies greatly among different types of ships, as briefly presented in table 1. Furthermore, they must withstand significant voltage fluctuations due to the uneven wind speed, which generates electricity in a sinusoidal form, while maximizing their operational lifespan [19], [20], [21].

Table 1

Electrical energy consumption of different types of stationary ships

Ship types	Electrical consumption (kW/hour) at anchor
Container Ship	50-80
Oil Tanker	30-50
Cruise Ship	100-200
Cargo Ship	20-30
Tugboat	20-30
Fishing Vessel	5-10

To avoid collisions with the wind turbine, it is essential to maintain a safety distance. A buoy allows the ship to anchor at a distance of 100-200 meters, ensuring a safe power supply through cables connected to the system. The buoy adapts to environmental conditions, and the cables must be appropriately sized to support electrical currents and ensure efficient energy transfer between the turbine and the ship.

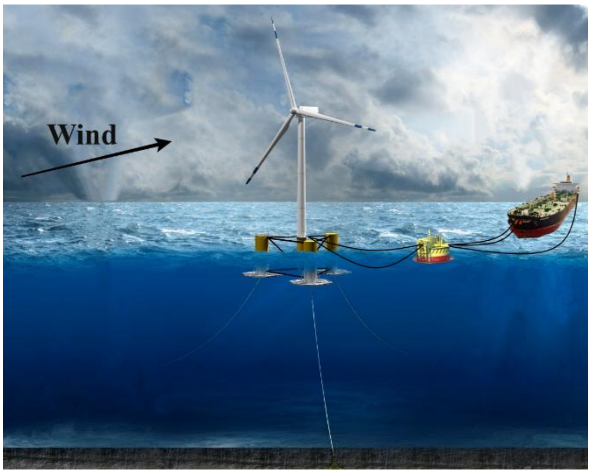

Fig. 3. Interconnected supply buoy between the wind turbine and the ship

It is crucial that the entire system does not obstruct navigation or the connected ships receiving electrical power.

2. Development of the practical model

The steps leading to the practical realization of the miniature wind energy system prototype for data collection from the operating environment were numerous and complex. To design the structural framework, floats, rotor, nacelle, and tower, Fusion 360 software was utilized, resulting in the model shown in Fig. 4. Following the design phase and file conversion, a 3D printer was employed to produce these components, which were subsequently fine-tuned in their electrical configuration [22]. The next step involved assembling all the parts, followed by bonding and reinforcement.

Fig. 4. Sketch of the wind system and its components

The architecture and construction of the system are closely related to factors concerning the stability of the system under various loads and the actions of disturbing forces. Without considering this aspect, the efficiency of the wind system is closely tied to its electrical components.

To convert the mechanical energy of the rotor, a 1:4 gearbox and a direct current generator with a maximum voltage of 5V and a minimum voltage of 0.1V were used, operating at rotational speeds ranging from 20.9-628.3 rad/s. The rotor's rotation speed varies significantly due to the discontinuous wind flow, resulting in variations in the electrical energy produced [19]. To regulate this, a 5V voltage regulator board with an efficiency of 85% was used after the generator. Depending on the number of batteries or their nominal voltage, a voltage step-up/down board model MT3608 was employed, with a minimum input voltage of 2V, maximum output voltage of 28V, and an efficiency of 93%, to meet battery charging requirements. Finally, a TP4056 charging module was used to store energy in the batteries. The final electrical schematic is depicted in Fig. 5.

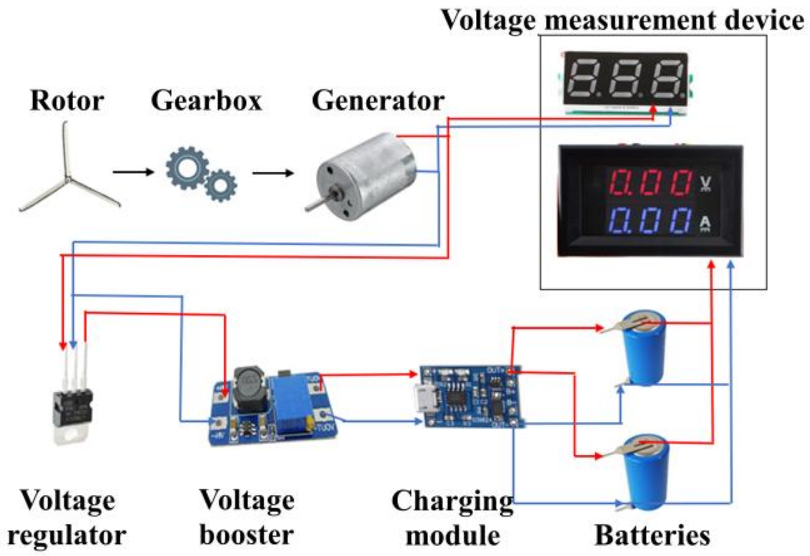

Fig. 5. Main electrical components

The batteries also aim to mimic the weight and characteristics of the actual system; therefore, their nominal voltage is 3V, and their number is evenly distributed among the floats to balance the system. To measure current intensity, a load is required, and it varies depending on each load's specific requirements, so consumers with different power ratings will be used.

3. Prototype testing in Homer Pro software

Homer Pro is advanced software for simulating and optimizing renewable energy systems, used for analyzing and designing renewable energy systems. Homer Pro provides tailored solutions for the efficient integration of renewable energy sources into energy systems [23], [24], [25].

Using Homer Pro software, this wind turbine model will be tested to obtain results regarding its electrical efficiency, with the results later compared to data obtained from the prototype. The software's database does not include a wind turbine with such low power, as it is designed to test large-scale wind turbine models [23], [24], [25]. In this case, the smallest utility wind turbine, Generic 3kW, will be used and all system components are set to have a 99% efficiency.

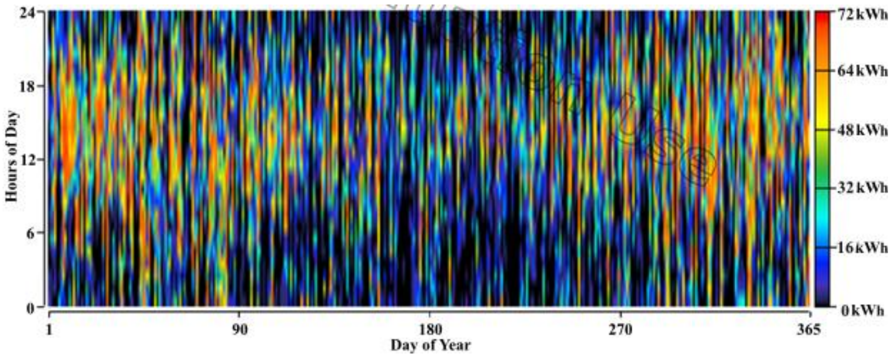

Fig. 6. Daily energy produced by the 3 kW wind turbine generator

In the graphical representation of the daily energy produced for the wind turbine Generic 3kW throughout the year, each hour is meticulously color-coded to illustrate the variations in energy production. Daily energy produced by the 3 kW wind turbine generator, capped at 72 kilowatthour (kWh), serves as a benchmark, symbolizing the pinnacle of achievable energy generation under optimal conditions. Fluctuations in wind speed, atmospheric conditions, and other environmental factors contribute to the dynamic nature of the graph, revealing the intricacies of harnessing wind energy. While the turbine's design aims for efficiency, the graphical representation vividly demonstrates the real-world complexities and highlights the importance of considering diverse factors in evaluating daily energy production over an extended period.

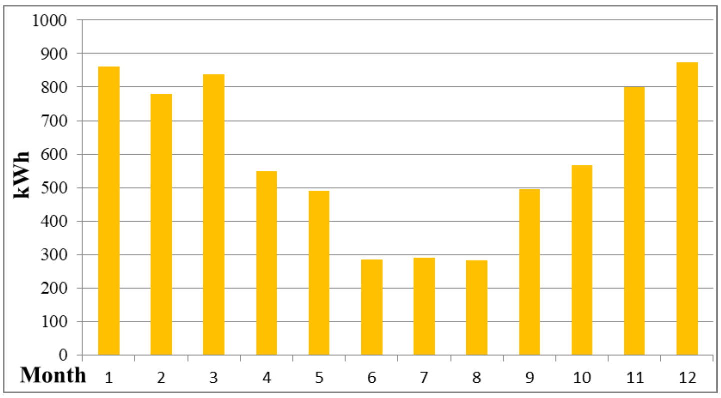

Fig. 7. Monthly electrical energy production from Generic 3kW database from 1993-2013

After processing the results obtained from the Generic 3kW system, the values were calculated and converted to match the prototype's system by dividing them by 857 in order to display the simulated results produced by the 3.5W wind prototype.

Table 2

Converted values from the Generic 3 kW taking into account as the simulated results

Month	Monthly electrical energy production Generic 3kW [kWh]	Monthly electrical energy production prototype turbine 3.5W [Wh]
January	861.13	1004.82
February	778.89	908.86
March	838.90	978.88
April	548.29	639.77
May	489.11	570.73
June	286.36	334.14
July	289.16	337.41
August	282.55	329.69
September	496.07	578.85
October	566.50	661.02
November	800.22	933.74
December	874.25	1020.13

Since the default values provided by Homer Pro are calculated over the course of a year and cannot be modified, they will need to be interpreted based on the duration of data collection from the prototype wind model.

4. Validation of results obtained in Homer Pro with results from the wind prototype

To validate the simulated results, the wind system was installed for a limited period in the coastal area of Constanța. The waves and wind power had a significant impact on the system's stability, but the aerodynamic shape and three-point anchoring flotation mitigated this issue. Fig. 8 shows the stability of the system.

Fig. 8. Placement of the wind model near Constanța harbor

To collect information from this miniature wind system, the following devices were used: an anemometer for wind speed measurement (model UT363), a digital voltage sensor for measuring battery voltage (0-30V), and another for measuring generator output voltage (model DSN-VC288). The measurement accuracy of these devices is as per table 3.

Table 3

Measurement errors of devices

Device	Measurement Accuracy
Anemometer UT363	± 5%
Digital voltmeter 0-30V	±1%
Voltmeter DSN-VC288	±1%

For measurements, a digital display device connected to the wind prototype via a cable that retrieves real-time data from the system was created. Using a Mist Duster 3WF2.6 blowing device, various wind speeds required for measuring intensity and generator voltage were reproduced and simulated to determine the generated power.

The accuracy of the calculations made is displayed in Fig. 9, which contains captures with the results obtained during testing of the miniature wind prototype using measurement devices. The battery monitor display, which is connected to the batteries, displays results starting from a minimum value of 1A. Given the dimensions of the model, the maximum current generated was 0.8A, as the measuring device did not have this precision. Therefore, an external device with much higher precision was used.

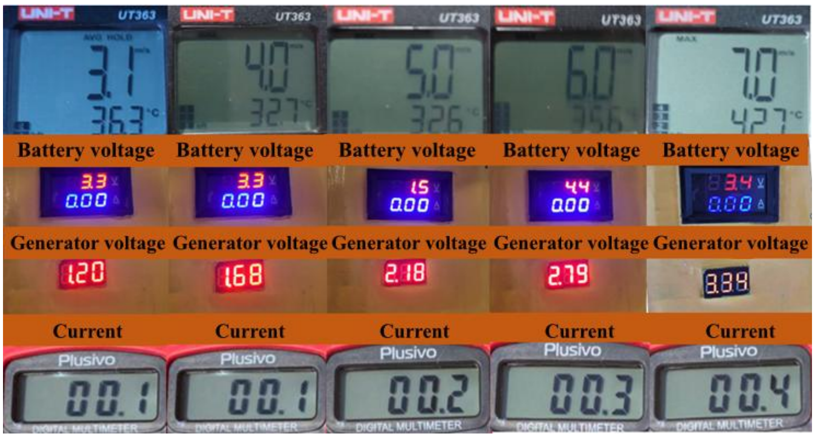

Fig. 9. Wind speed measurements from 3 to 7 m/s

After analyzing the measurements and results obtained, a table was created to present the main sources of errors and the proportion in which they affect the efficiency offered by the miniature wind system.

Table 4

Errors influencing the efficiency of the wind model

Error Source	Proportion
Energy losses due to voltage regulator	≈4%
Energy losses due to voltage amplifier	≈3%
Energy losses due to charging module	≈2%
Measurement device accuracy	≈1%
Human measurement errors	≈1%
Calculation errors	≈0,1%

Table 5

Values obtained from testing using a mist duster 3WF2.6 blowing device

Wind Speed [m/s]	Current Intensity [A]	Voltage [V]	Power [W]
3	0.1	1.20	0.12
4	0.1	1.68	0.16
5	0.2	2.18	0.44
6	0.3	2.79	0.83
7	0.4	3.34	1.33
8	0.5	3.94	1.97
9	0.7	4.01	2.80
10	0.8	4.13	3.30
11	0.8	4.13	3.30
12	0.8	4.13	3.30

In order to validate the simulated results obtained in Homer Pro with the wind prototype’s tested results and to estimate the amount of electrical energy generated monthly by the prototype wind turbine, calculations will be based on average wind speed variation obtain from software.

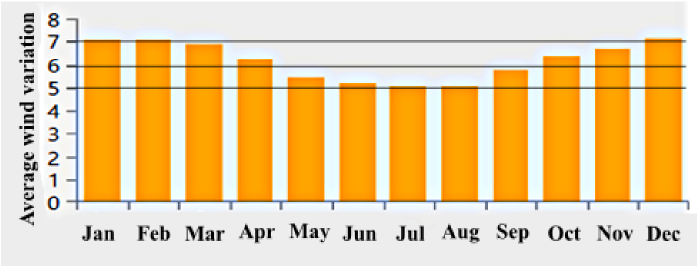

Fig. 10. Average wind speed variation obtain from software

According to table 5, the electrical power will be obtained through interpolation based on these average wind speeds (Fig. 10.), with the result being multiplied by the total number of hours in the respective month in order to determine the total amount of energy experimentally produced over the course of the month.

Table 6

Tested values obtained from the 3.5W prototype wind turbine

Month	Monthly average wind speed [m/s]	Average power [W]	Number of hours per month	Monthly electrical energy production [Wh]
Jan	7.1	1.35	744	1003.66
Feb	7.1	1.35	672	906.53
Mar	6.9	1.31	744	975.38
Apr	6.4	0.89	720	637.44
May	5.5	0.76	744	566.06
Jun	5.2	0.46	720	329.47
Jul	5.1	0.45	744	333.91
Aug	5	0.44	744	327.36
Sep	5.8	0.80	720	577.68
Oct	6.4	0.89	744	658.69
Nov	6.8	1.29	720	930.24
Dec	7.2	1.37	744	1017.79

The simulated values generated by the Homer Pro software were compared with the experimental data obtained from the prototype wind turbine, thereby establishing the validity of these data, with a maximum relative error of 1.42%. This variation can be attributed to electric energy losses in the system, errors associated with measurement devices and their accuracy, as well as reading and calculation errors, in addition to differences between the databases utilized.

6. Conclusions

This article presents the development and testing of a wind energy system for ships anchored in Constanța's outer harbor. Horizontal-axis turbines were preferred to maximize efficiency in offshore settings, with floating foundations anchored in deep water identified as optimal, specifically semi-submersible designs. The system's ability to accommodate variable electricity demands from ships was analyzed, and a prototype was tested near the port. The study highlighted a maximum relative error of 1.42% between simulated and experimental results, attributed to minor system losses and measurement errors. Overall, the research confirms the system's effectiveness for reliably powering ships.

R E F E R E N C E S

[1] S. Suman, D. Chatterjee, M. Anand, R. Mohanty, and A. Bhattacharya, "an Improved Harmonic Reduction Technique for the Pv-Wind Hybrid Generation Scheme Using Modified Whale Optimization Algorithm (Mwoa)," UPB Sci. Bull. Ser. C Electr. Eng. Comput. Sci., vol. 84, no. 1, pp. 231–248, 2022.

[2] M. Q. Duong, F. Grimaccia, S. Leva, M. Mussetta, G. Sava, and S. Costinas, "PERFORMANCE ANALYSIS OF GRID-CONNECTED WIND TURBINES," U.P.B. Sci. Bull., Ser. C, vol. 76, 2014.

[3] Z. Li, X. Guo, X. Shen, and H. Tang, "Summary of Technologies for the Development of Offshore Wind Power Industry in China," Power Gener. Technol., vol. 43, no. 2, pp. 186–197, 2022, doi: 10.12096/j.2096-4528.pgt.22028.

[4] L. Xuezhong et al., "Experimental research on stator insulation system of 5 MW offshore Wind turbine generator under simulated marine environments," Annu. Rep. - Conf. Electr. Insul. Dielectr. Phenomena, CEIDP, pp. 52–55, 2013, doi: 10.1109/CEIDP.2013.6748199.

[5] X. Liu et al., "The effect of the marine environment on the stator insulation system of an offshore wind turbine generator," IEEE Electr. Insul. Mag., vol. 31, no. 3, pp. 10–17, May 2015, doi: 10.1109/MEI.2015.7089117.

[6] F. Deliu, P. Popov, and P. Burlacu, "The Impact of the Wind Speed on the Dynamics of the Wind Energy System," in International conference KNOWLEDGE-BASED ORGANIZATION, 2016, vol. 22, no. 3, pp. 628–633.

[7] E. F. Camacho, T. Samad, M. Garcia-sanz, and I. Hiskens, "Control for Renewable Energy and Smart Grids," 2011.

[8] J. Fadil, Soedibyo, and M. Ashari, "Performance comparison of vertical axis and horizontal axis wind turbines to get optimum power output," QiR 2017 - 2017 15th Int. Conf. Qual. Res. Int. Symp. Electr. Comput. Eng., vol. 2017-December, pp. 429–433, Dec. 2017, doi: 10.1109/QIR.2017.8168524.

[9] M. Gutu, V. Odainai, I. Malcoci, and T. Nicolae, "Aerodynamic Efficiency Numerical Estimation of 1 kW horizontal axis wind turbine rotor," SIELMEN 2021 - Proc. 11th Int. Conf. Electromechanical Energy Syst., pp. 109–114, 2021, doi: 10.1109/SIELMEN53755.2021.9600363.

[10] A. Das, K. B. Chimonyo, T. R. Kumar, S. Gourishankar, and C. Rani, "Vertical axis and horizontal axis wind turbine- A comprehensive review," 2017 Int. Conf. Energy, Commun. Data Anal. Soft Comput. ICECDS 2017, pp. 2660–2669, Jun. 2018, doi: 10.1109/ICECDS.2017.8389937.

[11] J. J. N. Quispe, J. H. Nina, and S. T. Jara, "Study and application of wind rose for vertical and horizontal axis wind turbine installation in Lima," Proc. 2020 IEEE Eng. Int. Res. Conf. EIRCON 2020, Oct. 2020, doi: 10.1109/EIRCON51178.2020.9254076.
[12] K. Cheng, Z. Wang, Y. He, and G. Yang, "The comparison of theoretical potential application of two types of wind turbines in Northern Shaanxi," Asia-Pacific Power Energy Eng. Conf. APPEEC, 2012, doi: 10.1109/APPEEC.2012.6307134.
[13] L. C. Lipan and N. Stoican, "Monitoring the power quality in a Naval Power Systems," UPB Sci. Bull. Ser. C Electr. Eng., vol. 72, no. 4, pp. 261–268, 2010.
[14] L. Dannenberg, "Offshore Wind Energy," Underst. Wind Power Technol. Theory, Deploy. Optim., vol. 9781118647, no. October, pp. 406–454, 2014, doi: 10.1002/9781118701492.ch11.
[15] Z. Yang, "Wind Turbine Controls for Farm and Offshore Operation," no. December, 2013.
[16] K. Khodabux, B. S. Bhujun, P. Dhawankar, and K. Busawon, "A review of offshore wind turbines and their various classifications," 2022 7th Int. Conf. Environ. Friendly Energies Appl. Renew. Sustain. Energy Syst. Hybrid Transp. Syst. Energy Transition, Energy Secur. EFEA 2022 - Proc., 2022, doi: 10.1109/EFEA56675.2022.10063842.
[17] L. Li and J. Ren, "Offshore wind turbines and their installation," CICC-ITOE 2010 - 2010 Int. Conf. Innov. Comput. Commun. 2010 Asia-Pacific Conf. Inf. Technol. Ocean Eng., pp. 248–251, 2010, doi: 10.1109/CICC-ITOE.2010.69.
[18] J. Wang, M. Qin, A. Cai, and D. Zhang, "Analysis of bearing capacity behavior of single bucket foundation for offshore wind turbines under eccentric horizontal loading in soft clay," Proc. 2010 World Non-Grid-Connected Wind Power Energy Conf. WNWEC 2010, pp. 159–164, 2010, doi: 10.1109/WNWEC.2010.5673131.
[19] O. Cristea, M.-O. Popescu, F. Deliu, and A. S. Calinciuc, "Dynamic performances of a wind power system," in 2014 International Symposium on Fundamentals of Electrical Engineering (ISFEE), Nov. 2014, pp. 1–5, doi: 10.1109/ISFEE.2014.7050635.
[20] L. Hong and D. Jiang, "The influence of wind characteristic on aeroelastic stability for wind turbine blades," 2009 Int. Conf. Energy Environ. Technol. ICEET 2009, vol. 1, pp. 888–892, 2009, doi: 10.1109/ICEET.2009.220.
[21] M. Xu, L. Wu, H. Liu, Y. Yang, and Y. Li, "Research on the mechanism and control methods of repeated voltage fluctuations in large-scale wind power integrartion system," Proc. - 2021 Int. Conf. Power Syst. Technol. Carbon Neutrality New Type Power Syst. POWERCON 2021, pp. 1214–1219, 2021, doi: 10.1109/POWERCON53785.2021.9697533.
[22] M. G. Manea, C.-P. Clinci, and O. Cristea, "Comments on the Use of 3D Printing Technology in the Design of an AUV Destined for the Identification and Destruction of Underwater Mines," J. ETA Marit. Sci., vol. 11, no. 2, pp. 66–78, 2023, doi: 10.4274/JEMS.2023.44712.
[23] L. Khalil, K. Liaquat Bhatti, M. Arslan Iqbal Awan, M. Riaz, K. Khalil, and N. Alwaz, "Optimization and designing of hybrid power system using HOMER pro," Mater. Today Proc., vol. 47, pp. S110–S115, Jan. 2021, doi: 10.1016/J.MATPR.2020.06.054.
[24] B. Belgacem et al., "Citation: Photovoltaic Power Prediction Using Analytical Models and Homer-Pro: Investigation of Results Reliability," 2023, doi: 10.3390/su15118904.
[25] I. Panhwar, A. R. Sahito, and S. Dursun, "Designing Off-Grid and On-Grid Renewable Energy Systems Using HOMER Pro Software #," J. Int. Environ. Appl. Sci., vol. 12, no. 4, p. 270, 2017.