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Design and evaluation of a hybrid offshore wave energy converter and floating photovoltaic system for the region of Oran, Algeria

Introduction. *This paper presents* ***the novel*** *design and analysis of a hybrid renewable energy system that combines a wave energy converter (WEC) with a floating photovoltaic (FPV) system for offshore installation, with a specific focus on Oran as a case study. The purpose of integrating these two technologies is to harness both wave and solar energy, thereby maximizing energy output and enhancing the reliability of renewable energy sources in offshore environments.* ***The goal*** *of this study is to develop a hybrid system that leverages the complementary nature of WEC and FPV technologies to maximize energy output and improve reliability. By integrating these technologies, the system aims to overcome the limitations of standalone energy systems.* ***The methodology*** *includes selecting suitable WEC and FPV technologies, optimizing their configurations, and analyzing their combined performance under various environmental conditions. To assess the energy production potential, structural stability, and economic feasibility of the hybrid system, computational simulations and data analysis are employed. This comprehensive approach ensures rigorous testing and optimization for real-world applications.* ***The results*** *demonstrate substantial improvements in energy yield and system resilience compared to standalone WEC or FPV systems. The hybrid system shows enhanced performance, particularly in consistent energy output and structural robustness. These findings indicate that combining WEC and FPV technologies can lead to more reliable and efficient offshore renewable energy solutions.* ***The practical values*** *are significant, providing insights into efficient and sustainable offshore renewable energy solutions. By focusing on Oran, it offers a localized perspective that can be adapted to similar coastal areas globally, contributing to the advancement of renewable energy technologies. The hybrid system's enhanced reliability and efficiency support the broader goal of sustainable energy development in marine environments, highlighting its potential for widespread application and impact.* References 23, tables 4, figures 17.

Key words: **wave energy converter, maximum power point tracking, hybrid system, floating photovoltaic system.**

Вступ*. У статті представлено нову конструкцію та аналіз гібридної системи відновлюваної енергії, яка поєднує в собі перетворювач хвильової енергії (WEC) з плавучою фотоелектричною (FPV) системою для морської установки, з особливим акцентом на регіоні Оран як тематичному дослідженні. Призначенням інтеграції цих двох технологій є використання хвильової та сонячної енергії, таким чином максимізуючи вихід енергії та підвищуючи надійність відновлюваних джерел енергії в морському середовищі.* ***Метою*** *цього дослідження є розробка гібридної системи, яка використовує взаємодоповнюючий характер технологій WEC і FPV для максимізації виходу енергії та підвищення надійності. Інтегруючи ці технології, система має на меті подолати обмеження автономних енергетичних систем.* ***Методологія*** *включає в себе вибір відповідних технологій WEC і FPV, оптимізацію їх конфігурацій і аналіз їх спільної продуктивності в різних умовах навколишнього середовища. Для оцінки потенціалу виробництва енергії, структурної стабільності та економічної доцільності гібридної системи використовується обчислювальне моделювання та аналіз даних. Цей комплексний підхід забезпечує ретельне тестування та оптимізацію для реальних застосувань.* ***Результати*** *демонструють суттєві покращення у виході енергії та стійкості системи порівняно з автономними системами WEC або FPV. Гібридна система демонструє покращену продуктивність, зокрема стабільну вихідну енергію та міцність конструкції. Ці висновки вказують на те, що поєднання технологій WEC і FPV може призвести до більш надійних і ефективних рішень для морських відновлюваних джерел енергії.* ***Практичні значення*** *є значними, що дають змогу зрозуміти ефективні та стійкі рішення для відновлюваних джерел енергії в морських умовах. Зосереджуючись на Орані, пропонується локальна перспектива, яку можна адаптувати до подібних прибережних районів у всьому світі, сприяючи розвитку технологій відновлюваної енергії. Підвищена надійність і ефективність гібридної системи підтримує більш широку мету сталого енергетичного розвитку в морському середовищі, підкреслюючи її потенціал для широкого застосування та впливу.* Бібл. 23, табл. 4, рис. 17.

Ключові слова: **перетворювач енергії хвиль, відстеження точки максимальної потужності, гібридна система, плавуча фотоелектрична система.**

Introduction. This paper presents the design and analysis of a hybrid renewable energy system combining a wave energy converter (WEC) and a floating photovoltaic (FPV) system for offshore installation, specifically focusing on Oran, Algeria as a case study. The integration of these two technologies aims to harness both wave and solar energy, maximizing the energy output and improving the reliability of renewable energy sources in offshore environments [1]. The design process involves the selection of suitable WEC and FPV technologies, optimization of their configurations, and analysis of their combined performance under varying environmental conditions [2]. Computational simulations and experimental data are utilized to assess the energy production potential, structural stability, and economic feasibility of the hybrid system. Results indicate significant improvements in energy yield and system resilience compared to standalone WEC or FPV systems. The findings provide valuable insights into the development of efficient and sustainable offshore renewable energy solutions, contributing to the advancement of hybrid energy systems for coastal regions [3].

The control and the power management of hybrid power generation systems involves sophisticated strategies to ensure seamless integration of diverse energy sources such as solar, wind, and energy storage with the electric grid. Centralized, decentralized, and hierarchical control methods are deployed to balance efficiency, reliability, and scalability. Advanced energy management systems, leveraging artificial intelligence and machine learning, optimize power flows and storage utilization, enhancing overall system performance [4]. Load forecasting and demand response techniques play a pivotal role in maintaining grid stability by adjusting loads based on generation availability. Additionally, peak shaving and load leveling techniques help in managing demand and reducing grid strain.

Compliance with interconnection standards is essential to ensure safety, reliability, and interoperability of hybrid systems with the grid. These systems can also provide ancillary services like voltage regulation, frequency control, and reactive power support, contributing to grid resilience. Case studies demonstrate successful applications of hybrid systems in various settings, from island communities to industrial plants, highlighting their versatility and benefits. Current research is focused on improving control algorithms, power electronics, and integrating emerging technologies such as block chain and advanced data analytics to enhance system reliability and transparency.

The goal of the paper is to develop a comprehensive hybrid renewable energy system combining wave energy and floating solar panels. The study aims to optimize the design for effective offshore deployment, considering the unique environmental and oceanographic conditions of Oran. By analyzing the performance and integration of these technologies, the paper seeks to enhance energy efficiency and sustainability. The ultimate objective is to provide a viable solution for clean energy generation in coastal regions, contributing to the reduction of carbon emissions. The case study of Oran serves as a practical example to validate the system's feasibility and potential benefits.

Subject of investigations. This paper involves a comprehensive exploration of integrating WECs with FPV systems for offshore energy production. The research delves into the design and engineering aspects, assessing the structural and functional synergy between these renewable energy technologies. Key investigations include analyzing the performance, efficiency, and durability of the hybrid system under the specific marine conditions of Oran. Additionally, the study examines the economic viability and environmental impact of deploying such a system offshore. The goal is to identify the potential benefits and challenges, providing insights for future applications in similar coastal regions.

Designs of hybrid FPV-WEC technologies. Hybrid projects combining floating solar panels and WECs have the technological capacity to produce a large portion of the world's annual electricity [5, 6]. This hybrid solution is particularly suitable for countries with abundant wave energy resources. Developers can utilize existing infrastructure, such as transmission lines, if the floating solar farm is built near WECs. An innovative technology using floating solar with battery storage and wave energy was proposed for coastal regions. The intermittent floating solar resource is integrated with a battery energy storage system to meet peak demands. Colocation with WECs will help to boost the generation of such assets and smooth out the generation curve. The addition of a floating solar system near a WEC compensates for the unstable generation of these systems by adjusting wave energy production, while PV systems can compensate for the wave energy shortfall in the medium to long term [7]. This hybrid FPV-wave energy system is flexible and complementary. A schematic of a hybrid FPV-WEC system is shown in Fig. 1.

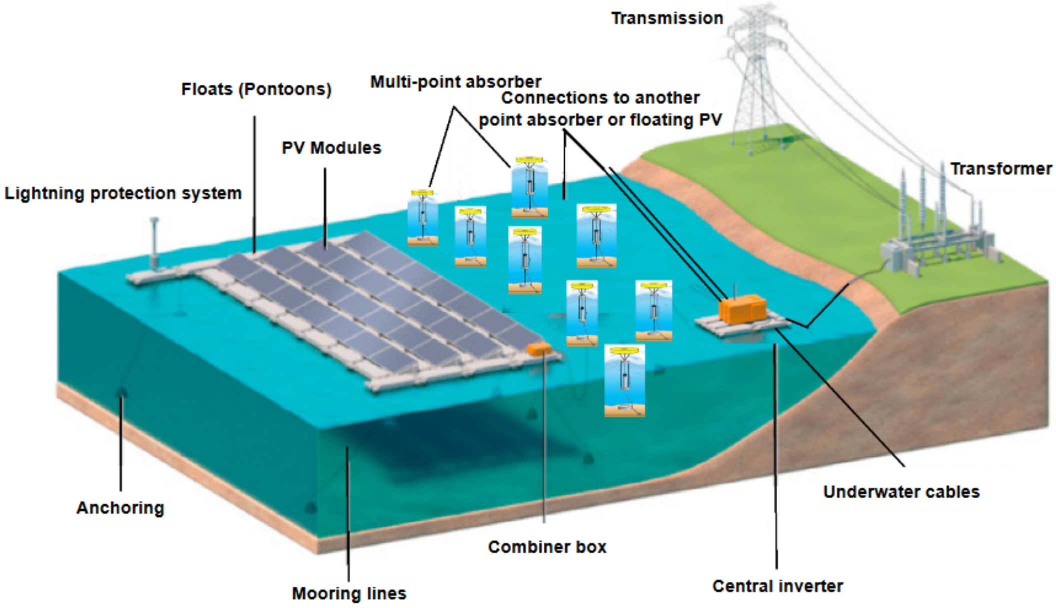

Fig. 1. Illustration of a hybrid FPV and WEC system

Study region, data and wave models. The study concentrated on the area with the highest wave energy potential in Algeria, specifically the northwest coast in the Oran region. Figure 2 of the map highlights the Oran region in Algeria, identified for its high wave energy potential and favorable solar conditions. This strategic location is ideal for installing a hybrid station combining FPV panels and WEC. The hybrid system aims to harness both solar and wave energy to provide a reliable and sustainable power supply to the Oran region. The map illustrates the targeted area for exploitation, showcasing the geographical advantages that make Oran a prime candidate for this innovative energy solution.

Table 1 provides comprehensive information about the Mediterranean coasts of Oran, detailing the potential for installing FPV systems and utilizing wave energy in this region. It includes key metrics such as average solar irradiance and wave energy density, highlighting the dual renewable energy resources available. The table also outlines suitable coastal areas for FPV installation, considering factors like water depth and proximity to the shore. Seasonal data on wave heights and periods further emphasize the region's capacity for wave energy exploitation.

This combination of solar and wave energy data underscores the feasibility of developing a hybrid renewable energy system in Oran to ensure a sustainable and efficient power supply.

Fig. 2. Map of potential deployment sites in the region of Oran

Table 1

Potential for wave energy utilization in the region of Oran

Parameters	Values
Average wave height, m	1.5-2.5
Wave period, s	5-7
Peak sun hours, h/day	5
Distance from shore (FPV), m	500
Distance from shore (WEC), km	1-5
Surface area available, km^2	≈20
Wave energy flux, kW/m	10-20
Water depth, m	20-50
Seabed conditions	Sandy to rocky
Environmental impact	Low to moderate
Proximity to grid, km	5-10
Accessibility	Good
Number of WEC units	10
Grid connection proximity, km	5
CO_2 emissions avoided, tons/year	80000

Hydrodynamics modelling of multi-point absorber. One kind of WEC that uses energy from ocean waves is a point absorber. A point absorber is modeled from both an electrical and hydrodynamic perspective. The following are the essential formulas for point absorber modeling. To illustrate the idea and layout of a WEC, a simple sketch might be utilized. The primary purpose of a WEC is to convert the kinetic and potential energy of waves in the ocean into electrical power that can be used [8, 9]. In the sketch, you might illustrate how a buoyant building rises and falls in response to the passing waves. Figure 3 serves as a typical illustration of a self-reacting point absorber, showcasing how the device efficiently harnesses ocean wave energy for power generation.

Fig. 3. OPT © power buoy device serves as a typical illustration of a self-reacting point absorber [10]

This buoy is connected to a mechanical linkage that, as shown in Fig. 4, transforms the vertical motion into mechanical motion. This mechanical linkage is often in the form of a piston or hydraulic system. Since WEC hydrodynamic modeling is the subject of numerous research, this paper only offers a general review of point absorber hydrodynamic modeling [11].

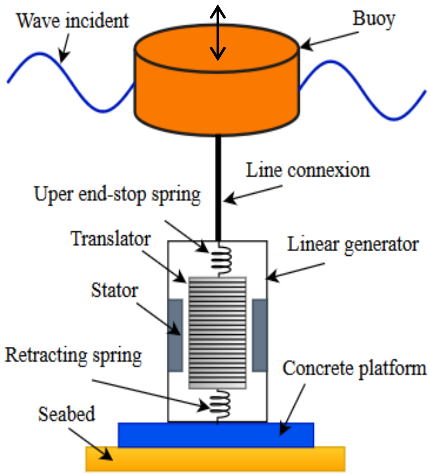

Fig. 4. Concept and layout of the WEC in a sketch

Wave equation. The incoming wave motion affects the point absorber's motion. Equation (1) from linear wave theory can be used to characterize the wave elevation [12]. Figure 5 depicts a smooth, periodic oscillation pattern representing a sinusoidal wave, characterized by its consistent amplitude and wavelength:

$$\eta(x,t) = A\cos(kx - \omega t), \quad (1)$$

where η is the free surface elevation with respect to $z = 0$ (m); A is the amplitude of the wave (m); k is the number of wave (rad/m); ω is the frequency of angular motion (rad/s); x is the horizontal position (m); t is time (s).

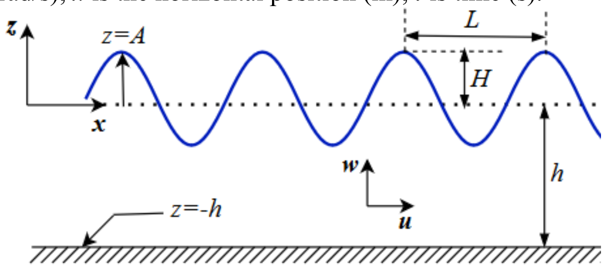

Fig. 5. Sinusoidal incidence wave form

Particle velocity. The particle velocity of the water particles beneath the absorber is given by:

$$u(x,t) = \frac{A\omega}{k}\sin(kx - \omega t). \quad (2)$$

This velocity is important for estimating the kinetic energy of the incident waves.

Buoyancy force. The buoyancy force acting on the point absorber can be calculated using Archimedes' principle [13]:

$$F_b = \rho_\omega g V, \quad (3)$$

where F_b is the force of buoyancy (N); ρ_ω is the water's density (kg/m^3); g is the acceleration brought on by gravity (m/s^2); V is the volume that the point absorber has displaced (m^3).

Power capture. The electrical power captured by the point absorber can be calculated as [14]:

$$P_e = \frac{1}{2}\rho_{\omega} g V H_s C_d v^3 P_g\,, \quad (4)$$

where P_e is the output of electrical power (W); H_s is the noteworthy wave height (m); C_d is the coefficient of power capture; v is the difference in velocity between the waves and the absorber (m/s); P_g is the effectiveness of the generator.

To investigate the nonlinear effects of the device, time domain models are required. All the forces acting on a wave energy device are captured by (5), without going into detail about how they interact.

Then, considering a floating body that is just limited in heave motion, Newton's second law is considered. It says that the total force of the body, or F_{net}, is equal to the mass times the translational acceleration (the same laws apply to moments, which are not discussed here):

$$F_{net} = m\frac{\mathrm{d}^2 z(t)}{\mathrm{d}t^2} = F_g(t) + F_{FK}(t) + F_{rad}(t) + F_{res}(t) + F_{PTO}(t) + F_{spring}(t) + F_{add}(t), \quad (5)$$

where F_{net} is the total force exerted on the buoy (N); m is the point absorber's mass (kg); $z(t)$ relates to the point absorber's vertical movement over time (m); $F_g(t)$ is the force of gravity (N); $F_{FK}(t)$ is the force of Froude-Krylov (N); $F_{rad}(t)$ is the force of radiation (N); $F_{res}(t)$ is the force of viscosity (N); $F_{PTO}(t)$ is the power take-off (PTO) force (N); $F_{spring}(t)$ is the force of mooring (N); $F_{add}(t)$ is the additional force (N); F_{add} is another force operating on the structure, such as drift, wind, tidal, or other body-water interactions.

Gravity force. The gravitational force exerted on the point absorber:

$$F_g(t) = -mg\,. \quad (6)$$

Froude-Krylov force. The hydrodynamic force due to the motion of the point absorber. It depends on the acceleration of the point absorber:

$$F_{FK} = -m\frac{\mathrm{d}^2 z(t)}{\mathrm{d}t^2}\,. \quad (7)$$

Radiation force. The force brought on by the waves that the point absorber's motion radiated. It is also dependent on the velocity of the absorber. The radiation force F_{rad} depletes the system's energy, as was previously stated. Since of this, F_{rad} is proportional to the floater's velocity in the following manner since it is functioning as a damper [15]:

$$F_{rad}(t) = -b\frac{\mathrm{d}z(t)}{\mathrm{d}t}\,, \quad (8)$$

where b is the radiation damping coefficient (kg/s); $\mathrm{d}z(t)/\mathrm{d}t$ is the first time derivative of the vertical displacement of the buoy, i.e. the velocity (m/s).

The restoring force F_{res} according to Archimedes' law of buoyancy, is taken proportional to the vertical displacement of the buoy according to:

$$F_{res}(t) = -cz(t)\,, \quad (9)$$

where c is the coefficient of restoration (kg/s^2); z is the buoy's vertical displacement (m).

Power take-off (PTO) force. The force produced by the PTO system, which uses the point absorber's motion to extract energy. These forces, like the PTO damping force F_{PTO}, radiation force F_{rad}, mechanical spring force F_{spring} and restorative force F_{res} are produced by:

$$F_{spring}(t) = -k_{SP} z(t)\,; \quad (10)$$

$$F_{PTO}(t) = -\beta\frac{\mathrm{d}z(t)}{\mathrm{d}t}\,, \quad (11)$$

where k_{sp} is the spring coefficient in mechanical terms (kg/s^2); β is the damping coefficient of the PTO (kg/s).

Additional force. Any other forces – like drift, wind, tidal forces, or other body-water interactions – that can have an impact on the point absorber. As implied by its name, the additional mass force F_{add} acts in addition to the buoy's absolute mass. As a result, it is assumed to be proportionate to the floater's acceleration as:

$$F_{add}(t) = -a\frac{\mathrm{d}^2 z(t)}{\mathrm{d}t^2}\,, \quad (12)$$

where a is the mass coefficient added (kg); $\mathrm{d}^2 z(t)/\mathrm{d}t^2$ is the acceleration (m/s^2), or the second time derivative of the buoy's vertical displacement $z(t)$.

Gaining insight into the behavior and energy conversion efficiency of the point absorber can be achieved by solving (5) of motion using suitable numerical techniques while taking into account the unique features and design of the device.

Modeling of the PV array. Many similar circuits have been devised thus far to simulate solar cells. Generally speaking, they can be divided into two main categories: single- and two-diode. The single diode model (Fig. 6) is one of the most widely used equivalent circuits for PV cells [16].

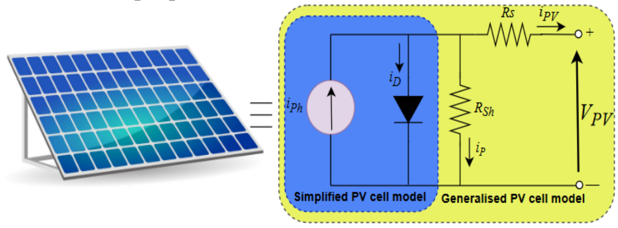

Fig. 6. The equivalent circuit of a PV cell

The PV current i_{Ph}, diode current i_D, series resistance R_S, parallel resistance R_{Sh} and net cell current i_{PV} are shown in Fig. 6. When the equivalent circuit of the PV panel is considered, equation (13) produces the net cell current i_{PV}:

$$i_{PV} = i_{Ph} - i_D - i_P\,. \quad (13)$$

Using the established linkages in [17], the final mathematical Eq. (14) of this model, which characterizes the I–V properties of the solar panel, can be found as:

$$i_D = i_0\left(\exp\left(\frac{V_{PV} + R_s i_{PV}}{nv}\right)\right); \quad (14)$$

$$i_P = i_0\left(\frac{V_{PV} + R_s i_{PV}}{R_P}\right); \quad (15)$$

$$i_{PV} = i_{Ph} - i_0\left(\exp\left(\frac{V_{PV} + R_s i_{PV}}{nv}\right) - 1\right) - \frac{V_{PV} + R_s i_{PV}}{R_P}\,, \quad (16)$$

where i_{PV} is the PV output current that flows through the series resistance R_S; V_{PV} is the PV output voltage; i_{Ph} is the photo generated current; i_D is the diode saturation current; i_0 is the reverse saturation current; i_P is the current passing via shunt resistance R_{Sh}; n is the number of series connected solar PV cells; v is the junction thermal voltage.

The open circuit voltage of the PV panel is given by:

$$V_{OC} = \frac{a \cdot k \cdot T}{q} \log\left(\frac{i_{Ph}}{i_D} + 1\right), \qquad (17)$$

where a is the ideality constant of a diode; q is the charge of an electron (1,602·10^{-19} C); k is the Boltzmann constant (1,381.10^{-23} J/K); T is the p-n junction's temperature.

As demonstrated by the equations above, the PV cell current is a complex function of temperature and photon intensity. Since the power produced by PV cells is the result of the product of cell current and voltage, the power of a PV cell is a complex function of temperature and radiation intensity [18, 19].

Figure 7 illustrates the varying electrical output of a PV cell as it responds to changes in light intensity, highlighting the relationship between irradiation and power generation efficiency [20, 21].

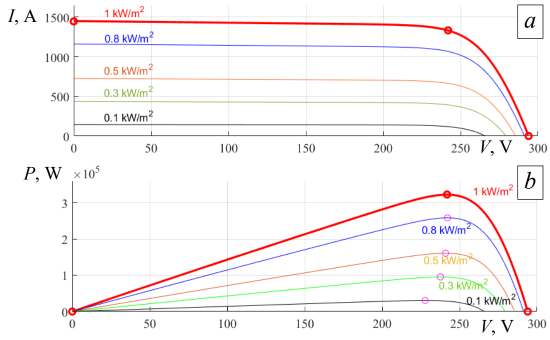

Fig. 7. Characteristics of the PV cell at different irradiation levels: a – $I = f(V)$; b – $P = f(V)$

Control strategy applied to the PFV-WEC. The control strategy for the PFV-WEC hybrid system (Fig. 8), designed to supply the Oran region in Algeria, involves several advanced algorithms.

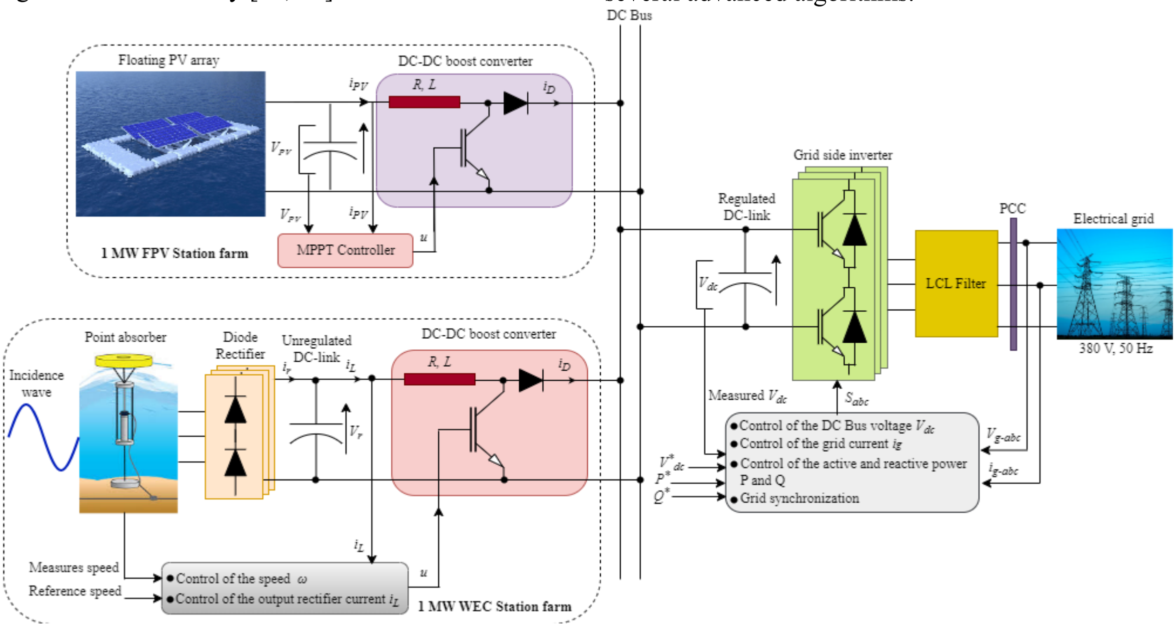

Fig. 8. Different control strategies applied to the hybrid conversion chain

Maximum power point tracking optimizes the energy harvested from the FPV panels. The DC bus voltage regulation ensures stable operation and efficient energy conversion [22, 23]. Additionally, the control of active and reactive power balances the power supply and maintains grid stability. These algorithms work in tandem to maximize energy output and ensure a reliable power supply to the Oran region from the hybrid FPV and WEC system.

Simulation results and discussion. The hybrid FPV and multi-point absorber model with grid connection simulation aims to accomplish three things: first, it will investigate the behavior of important system variables over time; second, it will verify that power produced by the FPV-PTO is successfully injected into the grid; and third, it will verify that current is injected into the grid with unity power factor. It was determined that a 25-second simulation period was sufficient to achieve these objectives. Figure 9 displays a number of variables as trends over time, including the applied wave form with an amplitude of 1 m, the rod speed, the buoy's position, the force produced (250 kN), and the point absorber's response. The parameters used in this simulation are shown in Tables 2–4.

Table 2

Detailed specifications of solar PV station

Parameters	Values
Maximum power, W	255.74
Parallel strings	180
Series connected modules per string	7
Open circuit voltage V_{oc}, V	42
Short circuit current i_{sc}, A	8.03
Cell per module N_{cell}	60
Voltage at maximum power point V_{mp}, V	34.56
Current at maximum power point i_{mp}, A	7.4
Temperature coefficient of V_{oc}	0.361
Temperature coefficient of i_{oc}	0.007

Table 3

Detailed specifications of WEC station

Parameters	Values
Wave amplitude, m	0.8 – 1.2
Number of the PTO	4
Stator resistance R_s, Ω	0.01
Armature inductance, μH	80
Flux linkage, Wb	0.8
Moment of inertia, kg·m^2	0.002008
Viscous friction coefficient, kg·s^{-1}	0.0028
Pole pairs	18

Table 4

Electric filter and grid parameters

Parameters	Values
Resistance of the filter, Ω	10
Inductance of the filter, H	0.5
Grid voltage, V	380
Frequency, Hz	50
DC capacitor, mF	10
DC link voltage, V	1200

The simulation results evaluating the transient and steady-state performance of the controllers under sudden changes in wave speed are illustrated in Fig. 9. Both controllers perform effectively in steady-state conditions, as evidenced by Fig. 10,*a*, which shows the linear permanent magnet synchronous generator (LPMSG) rotational velocity response to wave speed using the model controllers. The electromagnetic torque generated by the LPMSG is illustrated in Fig. 10,*b*. Figure 10,*c* presents the active and reactive power components of the LPMSG. The employed control strategy demonstrates a satisfactory decoupling between these components. This approach ensures a high active power yield and a highly stable direct bus voltage by maintaining the reactive power at zero throughout the simulation period.

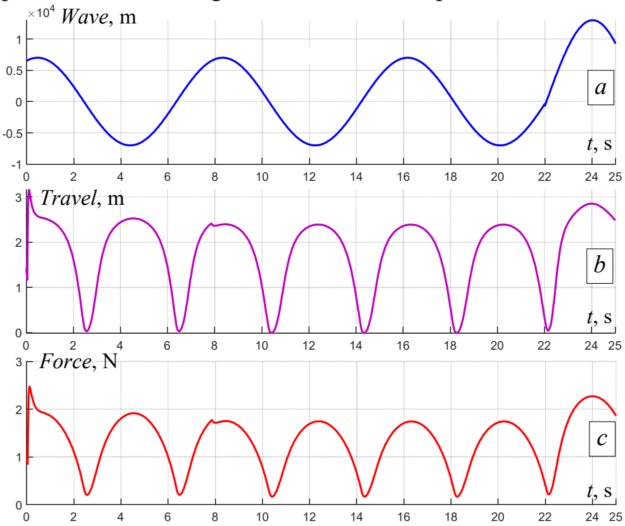

Fig. 9. Time evolution of important parameters in the multi-point absorber based on WEC: *a* – sinusoidal wave signal; *b* – travel curve; *c* – force curve

Figure 11 displays the voltage and current outputs of the LPMSG along with detailed zoomed-in views of these waveforms. The main plots show the overall behavior, while the zooms highlight finer details such as amplitude and frequency. This provides insight into the LPMSG's performance and stability under various conditions.

The DC bus voltage varies with amplitude of approximately 1200 V, showing fluctuations of about 1.5 % of the nominal value, which corresponds to changes in the applied wave's waveform. As illustrated in Fig. 12, the performance of the PV station is analyzed under different levels of solar irradiation. The surface temperature of the PV array is maintained at a constant 25 °C during the simulation. As depicted in Fig. 12, the performance of the PV system is primarily influenced by the cell's temperature and the level of irradiation received. Higher temperatures reduce efficiency. Figure 12,*a* illustrates the variation in solar irradiation, showing how sunlight changes throughout the day and the effect of a cloud casting a shadow, for example. Figures 13,*a*,*b* depict the grid voltage and current, illustrating that the signals are purely sinusoidal. The voltage amplitude remains constant at 380 V, and the current amplitude is 20 A.

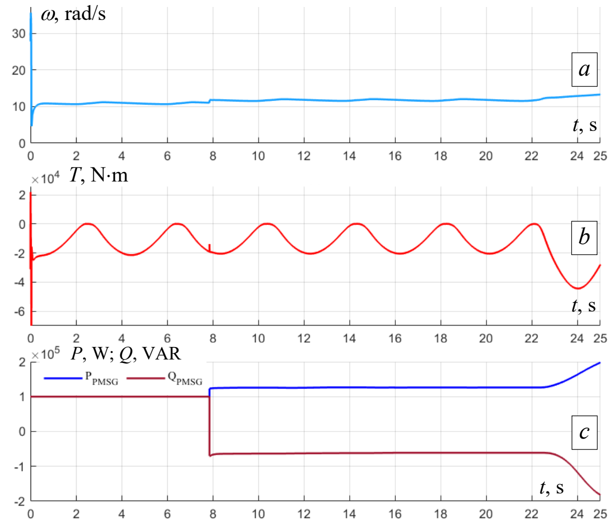

Fig. 10. LPMSG electrical variables during the maritime substation test: *a* – speed; *b* – electromagnetic torque; *c* – active and reactive power

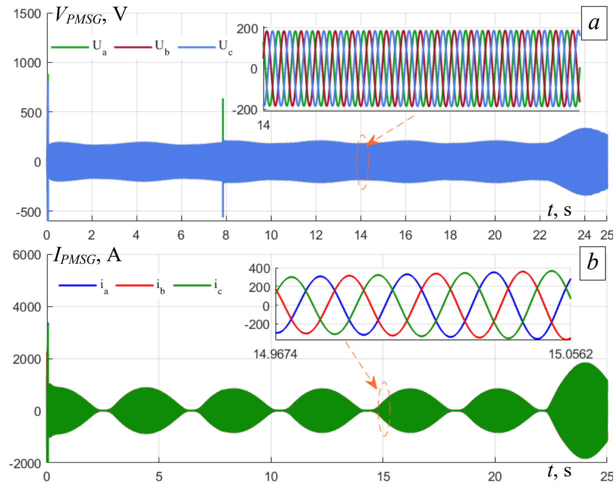

Fig. 11. In a normal maritime operation, the LPMSG's output of three phases of voltage (*a*) and current (*b*)

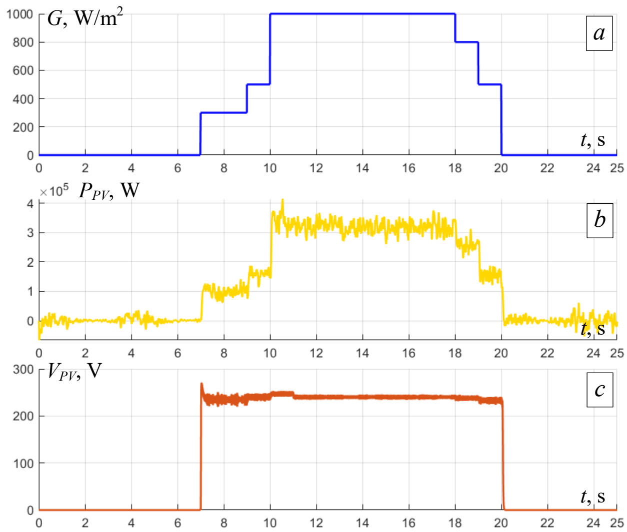

Fig. 12. Performance of FPV farm: *a* – solar irradiance profile; *b* – generated power; *c* – PV voltage

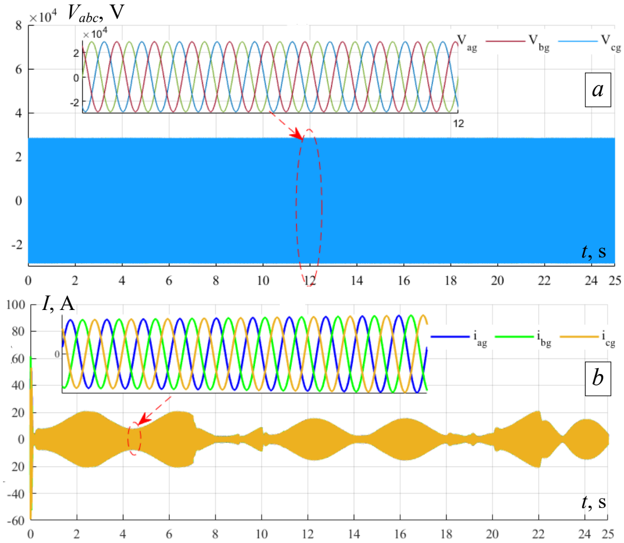

Fig. 13. FPV-WEC hybrid system performance at point of common coupling bus: *a* – grid voltages; *b* – grid current

Figure 14 shows the three-phase voltage and current outputs of the inverter, including detailed zoomed-in views of the waveforms. The main plots illustrate the overall behavior of the voltage and current, revealing their consistent and balanced nature across all phases. The zoomed-in views highlight finer details, such as waveform amplitude and frequency, providing a closer look at the inverter's performance. This comprehensive depiction emphasizes the inverter's ability to deliver stable and efficient power output under various operating conditions.

When the applied wave oscillates, Fig. 15,*a* and Fig. 16 show the waveforms of the active power grid and DC link voltage, respectively. Figures 15,*a*,*b* indicate the apparent active power and reactive power as 1 MW and 0 VAR, respectively.

Energy management is maintained throughout this study (Fig. 17). The power demanded by the load equals the sum of the power generated by the combined FPC-WEC system and the power supplied by the public grid.

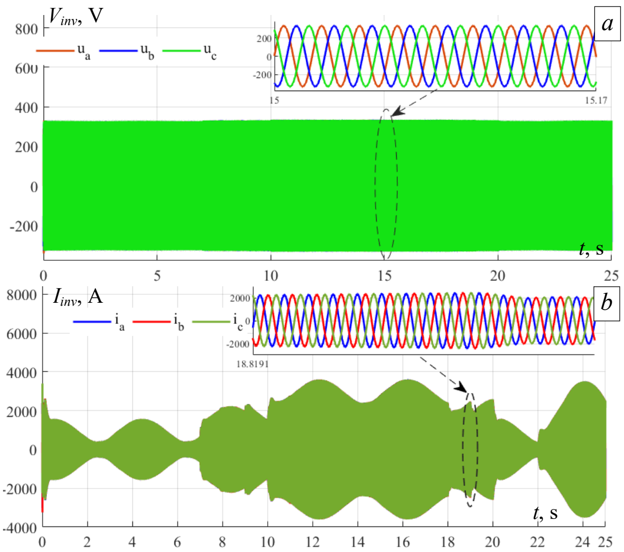

Fig. 14. Three phase voltage (*a*) and current (*b*) of the output of inverter

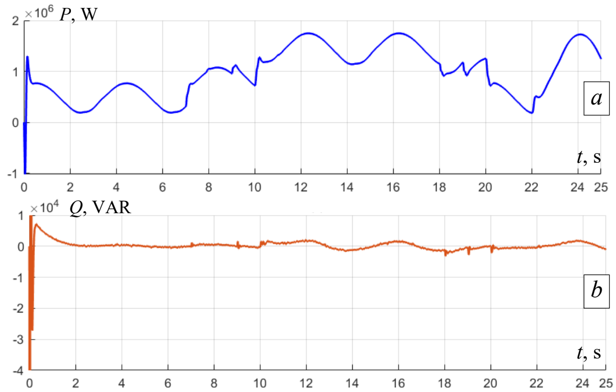

Fig. 15. Delivered active (*a*) and reactive (*b*) power

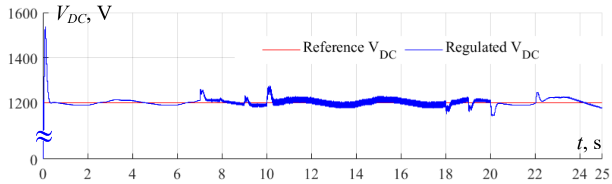

Fig. 16. DC link voltage

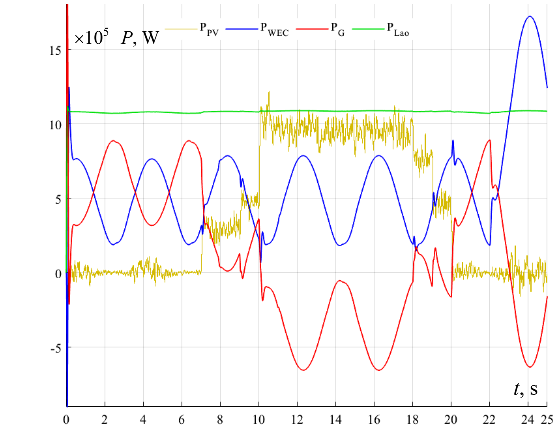

Fig. 17. Actual active power flow between the load, grid, and hybrid system

Conclusions. This paper presents the design and analysis of a hybrid wave energy converter (WEC) and floating photovoltaic (FPV) system specifically designed for offshore deployment in the Oran region. By integrating WEC and FPV technologies, a synergistic approach is achieved, harnessing both wave and solar energy to enhance energy output and improve system reliability. The comprehensive design process involved identifying suitable WEC and FPV components and optimizing their configurations to meet the unique environmental and operational conditions of the Oran site. Computational simulations and numerical data were utilized to assess the performance, structural stability, and economic feasibility of the hybrid system. The findings of this study show substantial enhancements in energy yield and system resilience compared to standalone WEC or FPV installations. The hybrid system leverages the complementary nature of wave and solar energy, offering a more consistent and reliable energy supply, thereby addressing the intermittency challenges common to renewable energy sources. Additionally, the economic analysis suggests that the hybrid system is a viable investment, offering potential cost savings and enhanced energy production efficiency in the long term. These findings highlight the potential of hybrid renewable energy systems as a sustainable solution for offshore energy generation.

This research provides valuable insights into the design and implementation of hybrid WEC and FPV systems for offshore use. The Oran case study exemplifies how such integrated renewable energy solutions can be effectively applied to similar coastal regions, highlighting their feasibility and benefits. Future research should focus on further optimization, scaling, and real-world deployment of these hybrid systems to maximize their potential in achieving a sustainable and low-carbon energy future.

Conflict of interest. The authors of the article declare that there is no conflict of interest.

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