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Design of an offshore wave energy power plant based on Wave Energy Converter

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Abstract

Wave energy has emerged as one of the most promising renewable energy resources due to its high power density, predictability, and global availability. This study presents the design and simulation of an offshore wave energy power plant based on an Oscillating Water Column (OWC) Wave Energy Converter (WEC). The proposed model, developed in MATLAB/Simulink, integrates environmental parameters such as wave height, tidal intensity, and wind speed to evaluate the system's performance under variable sea conditions. A linear generator is employed in the design, and the role of an inverter and battery storage system is incorporated to stabilize power fluctuations and ensure grid-compatible output. Simulation results demonstrate that while instantaneous power exhibits variability due to the dynamic nature of ocean waves, the integrated inverter–battery system provides a relatively constant and reliable power supply. Both active and reactive power outputs are analyzed, revealing that the proposed design achieves minimal reactive power contribution, thereby improving overall system efficiency. The findings highlight the feasibility of OWC-based WECs for offshore deployment and provide a framework for further optimization and experimental validation of grid-connected wave energy systems.

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1. Introduction

Over time, as societies grow and industry and technology become more complex, human need for energy sources has intensified. What now threatens humanity as the biggest global problem is the reduction of conventional energy sources and air pollution due to the use of fossil fuels. To solve these two major problems, the use of renewable and clean energies has been proposed as one of the operational solutions [1]. Wave energy is one of the energies of interest today, and its related technologies are developing and progressing rapidly. This unique energy is the most concentrated form of renewable energy on Earth with a power density higher than wind and sun. The origin of this energy is the vertical movements of sea waves. In fact, the purpose of this method is to convert the kinetic energy of sea waves into electrical energy. For this purpose, converters are used that convert wave oscillations and the movement of water particles inside them into electrical energy [2]. Another advantage of ocean wave energy is the predictability of the waves, which makes it easier to forecast supply and demand, which is the biggest advantage of this technology over other renewable energy-based methods.

Wave energy converters (WECs) are so-called marine systems that are capable of generating electricity by utilizing the energy of ocean waves. In recent decades, many countries have invested heavily in the design and construction of various types of these systems. These systems for generating electricity from ocean waves are classified based on their appearance, structure, location (near the coast or in the middle of the sea), how they are arranged against the waves, etc. Meanwhile, offshore devices are usually installed completely submerged. In this case, the facilities can be extended to the water surface. However, the costs of constructing offshore facilities and their power transmission lines are very high. The main element in most designs is an oscillating body that is placed floating or underwater near the surface. This oscillating motion is then converted into mechanical energy. Examples of offshore device technology include the Pelamis system, the Edinburgh duck, and the Seto technology, buoy technology, and the Mighty Whale system [3].

Due to the irregular sea motion, a suitable control method for WECs is the process of optimal energy absorption from waves considering the physical constraints of the device and actuator. In [4], a moment-based optimal control strategy for WECs for a flap device is presented in order to maximize energy. Paper [5] analyzes the reactive power control in wave energy devices and introduces a non-optimal model based on wave surface information in the time domain. This paper shows that sufficient information and data are required to predict the wave behavior. Paper [6] proposes an optimal control strategy for wave energy devices subject to reactive power constraints. Using the Legendre quasi-spectral method, the optimization is performed with energy maximization as the objective. In paper [7], the control of a wave energy converter was investigated using the prediction of the incoming wave based on the measurement of the wave top surface height. The aim of this research is to approach the optimal hydrodynamic speed, which leads to the optimal power absorption. The above wave measurement distance is assumed to be close enough to allow for a deterministic propagation model, and both the wave propagation and the device response are assumed to be linear. Wave energy converters require active control to maximize energy absorption over a wide range of sea conditions, which is usually achieved by placing the device at resonance. Excessive device motion due to resonance can lead to nonlinear effects that are ignored by conventional linear models. A general nonlinear WEC control approach based on quasi-spectral methods is discussed in [8].

Researchers in [9] studied the effect of nonlinear velocity-dependent forces on the optimal path, as well as the effect of physical system constraints. In particular, it was shown that under state constraints (such as position and velocity constraints), the optimal velocity wave is affected by static forces. In [10], the impact of long-term climate change based on climate projections up to the year 2100 on the optimal size and efficiency of wave energy converters along the Mediterranean coastline was evaluated. In [11], a new type of device for generating energy from waves with a horizontal rotor was designed and built. When operating at sea, the device floats in the water, but is held by an anchor, so it does not move much. In [12], four oscillatory devices using floating wave energy of different geometries were proposed, in which a kind of floating dolphin method with an energy harvesting mechanism was developed. The integrated method of wave energy device and floating breakwater was proposed, and the integrated model was tested in a tank, and the power generation performance of the wave energy device under different sea conditions was analyzed.

Current wave power generation technologies have many technical limitations. These limitations arise from the complex and dynamic nature of ocean waves, which require robust and efficient technology to capture energy. Challenges include designing and building wave energy devices that can withstand the corrosive effects of saltwater, harsh weather conditions, and intense wave forces. Optimizing wave energy converters (WECs) like oscillating water columns (OWCs), point absorbers, and covered devices necessitates addressing the inherent challenges posed by the dynamic and unpredictable nature of ocean waves. This involves enhancing their performance and efficiency by overcoming complexities related to the wave's dynamic and variable nature.

The proposed design in this study is based on an Oscillating Water Column (OWC)-based WEC. This choice was made because OWCs combine structural simplicity with proven offshore feasibility and can be effectively simulated using linear wave theory. Also, existing studies typically focus on structural optimization or control strategies alone. Our work addresses the gap by analyzing how fluctuations in environmental factors (wave height, wind speed, tidal intensity) affect both turbine output and grid-level power stability, with energy storage included to smooth variability.

The main contribution is the simulation of a WEC power plant that explicitly evaluates both active and reactive power, while incorporating battery storage for grid stability. This integrated focus distinguishes our work from prior studies that typically address hydrodynamic modeling or control strategies in isolation.

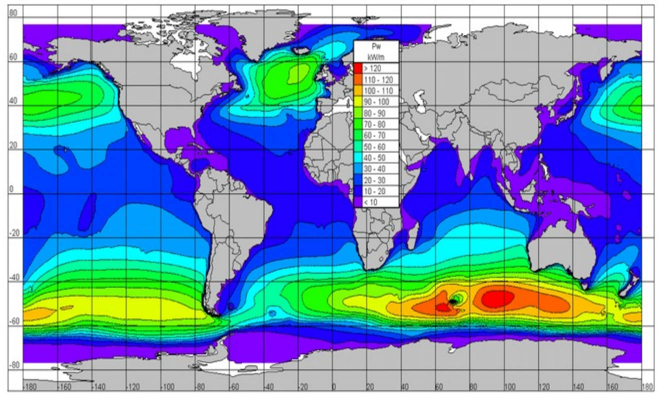

Fig.1: Global distribution of oceans [13]

2. Mathematical model of wave motion

Like many fluid motions, the interaction between ocean waves and energy converters is a high-order nonlinear phenomenon that can be described using the incompressible Navier-Stokes equations [14].

$$\frac{\partial u}{\partial t} + (u.\nabla)u = v\Delta u + \frac{F_{ext} - \nabla p}{p} \quad (1)$$

$$\nabla.u = 0 \quad (2)$$

Where $u(t, x, y, z)$ is the fluid velocity, p is the pressure, ρ is the density, v is the viscosity, and F is the net external force on each fluid particle (usually gravity). However, in typical situations, wave motion is described by airy wave theory, which makes the following assumptions: the fluid motion is approximately irrotational, the pressure is approximately constant at the water surface, and the depth of the seabed is approximately constant. Indeed, in situations related to energy extraction from ocean waves, these assumptions are usually valid.

The first condition implies that the motion can be described by the velocity potential $\phi(t, x, y, z)$.

$$\nabla.u = 0 \quad \Leftrightarrow \quad u = \nabla\phi \quad (3)$$

$$A(z) = \frac{gh}{2w}\frac{\cosh(k(z+h))}{\cosh(kh)} \quad (4)$$

$$w = gk\tanh(kh) \quad (5)$$

where k describes the wavenumber of equation and $A(z)$ and ω are determined by the boundary constraints and the value of k. Specifically, the height h is defined as:

$$h = \frac{H}{2}\cos\left(ks - wt\right) \tag{6}$$

A plane wave propagation in the x-axis direction.

The oscillatory motion is highest at the surface and decreases exponentially with depth. However, for standing waves near a reflective coast, the wave energy is also present in the form of pressure fluctuations at great depths, which cause microseismic effects. The pressure fluctuations at greater depths are too small to be of interest for wave power conversion. The behavior of airy waves presents two interesting regimes: water deeper than half the wavelength, as is typical in the sea and ocean, and shallow water, with wavelengths greater than about twenty times the water depth. Deep waves have frequency dispersion. Waves with long wavelengths propagate faster and tend to overtake waves with shorter wavelengths. Typically, the group velocity of deep water is half the phase velocity, while shallow water waves are dispersionless, with the group velocity equal to the phase velocity, and the wavelets propagate undisturbed.

The proposed design targets in this paper is the deep-water regime (depth > half the wavelength). This allows us to apply linear airy wave theory, simplifying the hydrodynamic modeling. In deep water, the reduction coefficient in the power equations equals one, which makes power estimation more straightforward. This assumption reflects offshore conditions where OWCs are most effective and where wave energy density is higher.

3. Wave power

Below the ocean surface, the wave energy flux is, on average, typically five times denser than the wind energy flux at 20 m above sea level, and 10 to 30 times denser than the solar energy flux [15]. In 2000, the world's first commercial wave power device, Islay LIMPET, was installed off the coast of Islay in Scotland and connected to the UK national grid. In 2008, the first multi-generator wave farm was opened in Portugal at Aguçadoura Wave Farm. Waves propagate at the surface, where the crests move at phase velocity while the energy is transferred horizontally at group velocity. The average rate of wave energy transfer through a vertical plane of unit width, parallel to a wave crest, is the energy flux (or wave power, not to be confused with the output produced by the device).

In general, wave power is the amount of energy transferred by the wave, which in fact indicates the amount of energy available. This quantity is usually expressed in terms of $N.m/\mathrm{Sec}$ and/or kW per meter of wave crest length and its value for sinusoidal waves is obtained from equation (7).

$$P = E.C_g \tag{7}$$

where E is the wave energy and C_g wave group velocity. According to equations (8) and (9), wave power is calculated as equation (10).

$$C_g = nC, \qquad K_S = \left(\frac{C_{g0}}{C_g}\right)^{0.5} \tag{8}$$

$$E = \frac{1}{8}\rho g H^2 \tag{9}$$

$$P = \frac{1}{32\pi}\rho g^2 H^2 \frac{T}{K_S^2} \tag{10}$$

which K_S is the height reduction coefficient. It $C_{g0} = \frac{C_0}{2}$ is also in deep water. In this case, K_S is equal to one and the water power for deep water becomes as follows.

$$P = 0.955 H^2 T \approx H^2 T \qquad \left(\frac{KW}{m}\right) \tag{11}$$

The above equations are for sinusoidal waves, which can be modified for real waves [16].

According to the linear wave theory, in the sea state, the average energy density per unit area of gravity waves on the water surface is proportional to the square of the wave height.

$$E = \frac{1}{16} pgH_{mo}{}^2 \tag{12}$$

Here E is the average wave energy density per unit horizontal area (J/m^2), the sum of the kinetic and potential energy densities per unit horizontal area. The potential energy density is equal to the kinetic energy, both of which constitute half of the wave energy density *E*.

In general, at present, there are various methods for implementing wave energy technology, the three main and important methods being floating cylinders, floating cams and drum islands [17]. On the other hand, wave energy converters can be classified according to their working principle as follows: point absorber buoys, surface attenuators, oscillating water columns and overtopping devices [13].

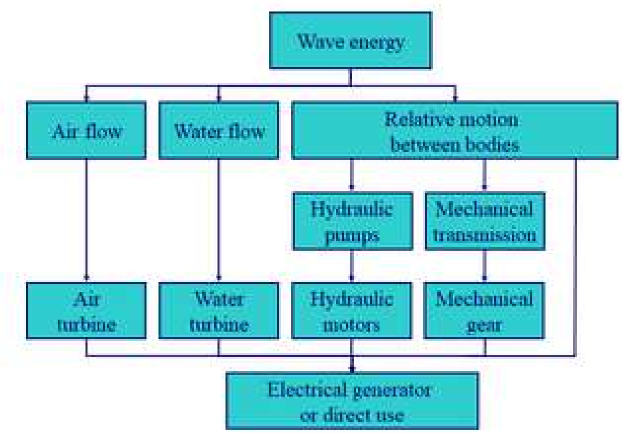

Fig. 2: Different paths of conversion from wave energy to useful energy

4. Proposed model and simulation

The process of determining the wave potential is shown in the block diagram of Fig 3. After collecting the data that affect the wave speed, the results are examined based on the generator performance. The simulations were performed in a linear generator (LEG) and the saturation of the transformers and the hysteresis of its cores were not considered. The proposed model for designing a WEC system is as shown in Fig 4. Also, the parameters considered for the design of the wave energy power plant in this study; Wave height, which is assumed to be equal to one. The wave period is in hours and the waves have a fixed pattern. The speed of the sea tide, which can be defined as a factor between one and four. The number four is defined for the maximum tidal intensity and the number one for the minimum tidal intensity. The wind speed, which has a direct effect on the intensity of the waves.

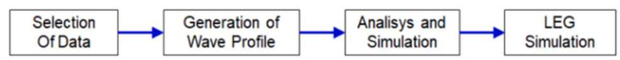

Fig. 3: Block diagram of the proposed system

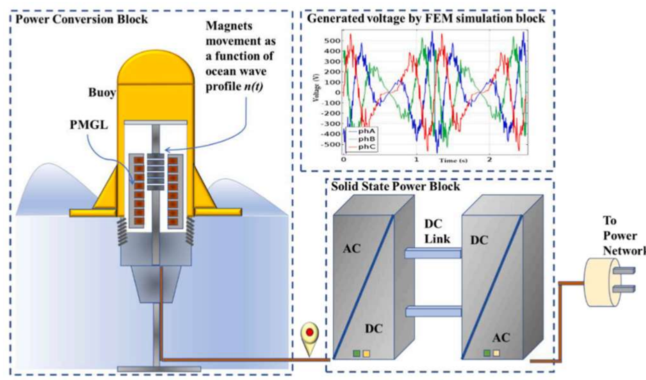

Fig. 4: Proposed system model

Fig. 5 shows the model designed in MATLAB software. As can be seen, the information related to wind speed and other parameters described above is entered into this model. The details of the turbine and gear block are shown in Fig. 6. As can be seen, the figure includes the wave speed and generator speed.

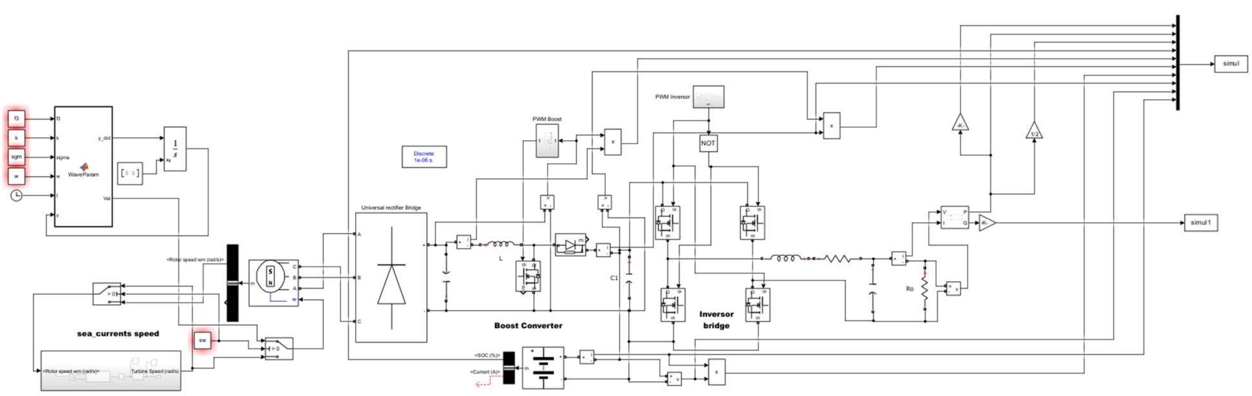

Fig. 5: Simulated model in MATLAB

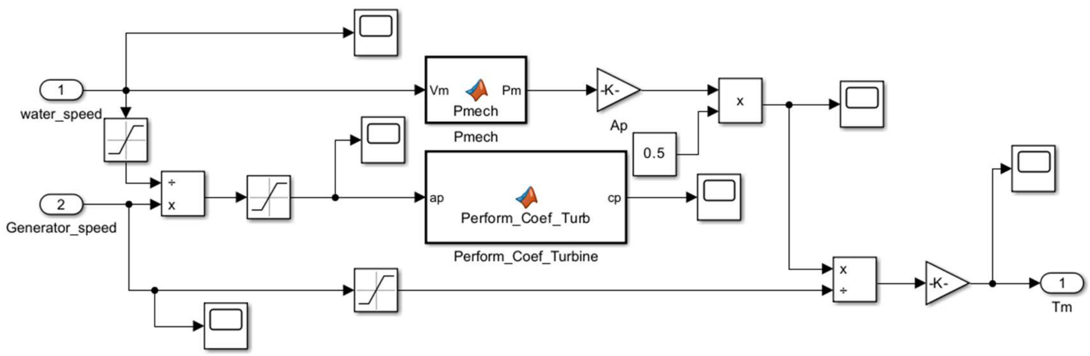

Fig. 6: Calculation of turbine speed using wave speed in the simulated model

4.1. Results and discussion

Fig. 7 shows the output power, which has fluctuations due to changes in the power demand. It can be seen that immediately after the simulation starts, the power has increased suddenly. This sudden increase is due to the start of the movement of the turbine blades and the energy demand. One of the most important equipment in wave energy power plants is the inverter which is used to convert DC to AC power. The input power of the inverter is shown in Fig. 8. It can be seen that the voltage at the input power in the inverter increases logarithmically, although at some times the peak power increase is high and for some moments the inverter experiences large power changes. These power changes are due to power fluctuations in the network. Additional, the peaks are caused by sudden variations in wave characteristics, such as wave height, wind speed, and tidal intensity. These directly affect turbine and generator performance, resulting in input surges.

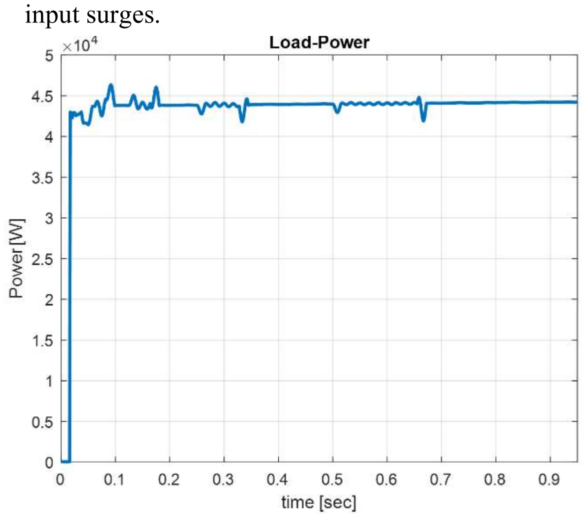

Fig. 7: Power demand in the network

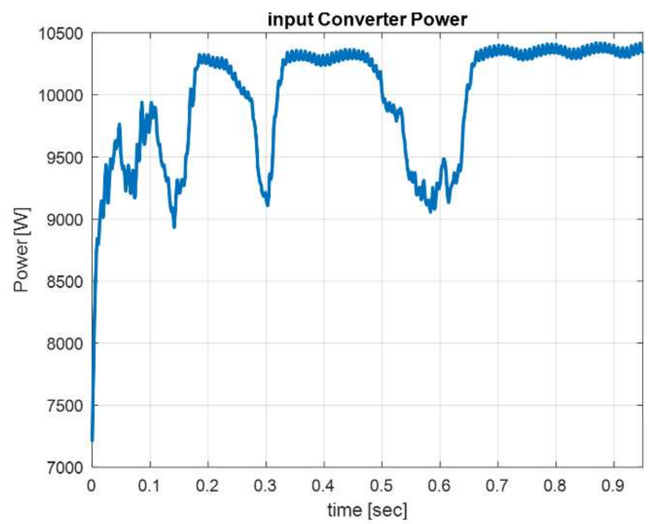

Fig. 8: Inverter Input Power

To mitigate this, our design incorporates (1) a battery system to absorb excess power during surges, and (2) the inverter's control circuitry, which regulates conversion and smooths fluctuations. Together, these measures maintain relatively stable output for grid integration.

The inverter output power is shown in Fig. 9. It can be seen that the output power in the inverter is less than the input power, which indicates that some of the system power is wasted. An important point to note in Fig. 8 and Fig. 9 is that the inverter input fluctuations depend on its input power, which varies since this power is supplied from sea waves. In contrast, the fluctuations in inverter output power are due to the output load, which changes as the consumer load changes, and the delivered power also changes.

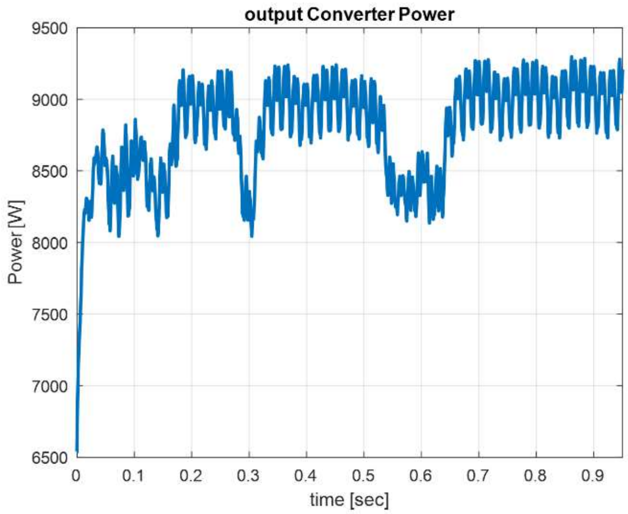

Fig. 9: Inverter Output Power

The reactive power output in this wave energy power plant is shown in Fig. 10. It can be seen that although the reactive power increases over time, its power is small compared to the active power and can be ignored compared to the active power of the network; because this small value will not have an effect on reducing the power factor of the network and reducing the efficiency of the network significantly. It can be seen that the reactive power generated in the power plant is fluctuating and these fluctuations have a limited amplitude, so it can be ignored.

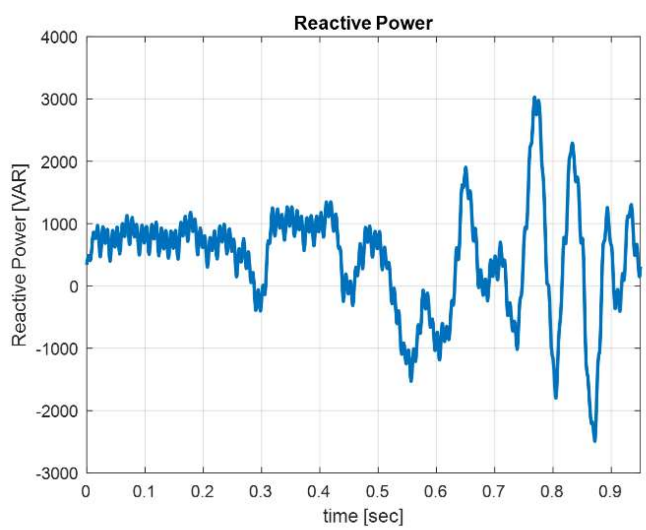

Fig. 10: Reactive power output of the power plant

5. Conclusion

Oceans are a vast source of kinetic energy in the form of waves, tides, salinity gradients, and temperature differences in the ocean. Ocean wave energy is considered a clean and high-density energy source. Wave energy harvesting devices can be located on or off the coast. Submerged pressure differential transducers use flexible membranes to extract wave energy. A submerged transducer may be located on the seabed or in the water. These power plants convert wave energy into electrical energy. In this paper, the design of a wave energy power plant is examined and studied. Because wave energy power plants produce variable energy, equipment is needed to stabilize the output power in the power plant. It should also be noted that the power generated in renewable power plants such as wave energy power plants varies with time and batteries must be used to store energy during hours when the generated power exceeds consumption. It was observed that the power plant was able to produce almost constant power at the output. Although the turbine and inverter input show variability (Figs. 7–9), these fluctuations are moderated by the combined storage and conversion process. The reduced amplitude of fluctuations at the inverter output compared to the input demonstrates that the design achieves practical output stability for grid connection. The obtained active and reactive power diagram shows that the active power of the network is much higher than the reactive power, which causes the power factor of the network to decrease significantly. This shows that the proposed and designed power plant has been able to produce the lowest reactive power.

Although, it can be include to outline future research, as bellow:

1- Experimental validation in a controlled laboratory wave tank.
2- Optimization of inverter control for irregular sea states.
3- Development of predictive energy management strategies under long-term climate change scenarios isolation.

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