

Innovative Wave Energy Conversion Systems for Efficient and Sustainable Power Generation

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Abstract: The increasing need for clean and sustainable global energy encourages the development of renewable energy technologies that are able to reduce dependence on fossil fuels. Marine wave energy is one of the promising sources of marine renewable energy because it has a high energy density and relatively sustainable wave availability in suitable coastal areas. However, the widespread use of wave energy still faces various challenges, including energy conversion efficiency, system reliability, power variability, and extreme marine environmental conditions. This study discusses the development of innovative marine wave energy conversion systems to improve power generation efficiency, operational reliability, and system sustainability. The discussion includes various wave energy converter configurations, hydrodynamic design optimization, power take-off systems, and intelligent control strategies to maximize energy absorption in varying wave conditions. The integration of energy storage technology and intelligent control systems is also studied to improve power stability and compatibility with the power grid. The application of innovations in mechanical, electrical, and control system aspects has the potential to improve energy extraction capabilities while reducing the need for operation and maintenance. The development of efficient and sustainable wave energy conversion systems is expected to support the electrification of coastal areas, diversification of renewable energy sources, and the transition to low-carbon energy systems. Further research and demonstration on a field scale are needed to increase the level of technological maturity, economic feasibility, and application of wave energy systems on a broader scale.

Keywords: Wave Energy Conversion System; Marine Wave Energy; Renewable Energy; Power Generation; Energy Efficiency

1. Introduction

The global demand for electrical energy continues to increase in line with population growth, industrial development, urbanization, and increased economic activity. On the other hand, dependence on fossil energy sources such as coal, petroleum, and natural gas causes various environmental problems, especially greenhouse gas emissions and environmental pollution. These conditions encourage various countries to develop renewable energy sources as part of efforts to create a cleaner, more sustainable, and more energy security energy system. Renewable energy sources such as solar, wind, water, and marine energy have a great opportunity to contribute to meeting energy needs in the future.

Indonesia as an archipelagic country has great marine energy potential due to its large water area and geographical characteristics that support the formation of sea waves. Sea wave energy is a form of renewable energy that comes from the oscillation movement of the sea surface due to the influence of wind. Compared to several other renewable energy sources, sea waves have the characteristics of relatively high energy density and can be available sustainably in certain areas. This potential makes wave energy an attractive alternative to be developed, especially for coastal areas and remote islands that have limited access to conventional power grids.[1].

2. Discussion of the Main Problem

Key issues in development Wave Energy Conversion System (WECS) is how to convert dynamic and unstable ocean wave energy into electrical energy efficiently, reliably, and sustainably. The constantly changing characteristics of ocean waves, such as wave height, period, direction, and speed, cause the amount of energy

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available to be converted to fluctuate as well. These conditions can cause the electrical power produced to be unstable, so a conversion and control system is needed that is able to optimally adjust the performance of the device to changes in wave conditions [2].

In addition to the problem of wave variability, the efficiency of the energy conversion process is also an important challenge. Wave energy must go through several stages before generating electrical energy, namely the process of absorbing energy by devices *Wave Energy Converter* (WEC), the change of wave movement into mechanical energy, and subsequently converted into electrical energy through the system *Power Take-Off* (PTO) and generators. At each of these stages, energy loss can occur so that not all wave energy can be utilized. Therefore, innovations in hydrodynamic design, PTO systems, generators, and control strategies are needed to increase the amount of energy that can be absorbed and converted into electricity [3].

To the existing approach Another significant problem is the extreme conditions of the marine environment. The WECS device must be able to operate in conditions of large waves, ocean currents, wind, corrosion due to seawater, and the growth of marine organisms on the surface of the device or *biofouling*. These conditions can cause damage or decrease in component performance, resulting in an impact on the reliability and operational life of the system. In addition, the location of the device at sea makes the inspection, repair, and maintenance process more difficult and requires relatively high costs. Therefore, WECS design needs to consider structural strength, material resistance, ease of maintenance, and the system's ability to deal with changing environmental conditions [4].

3. Review and Criticism of Existing Approaches

Various approaches have been developed to utilize ocean wave energy as a source of electrical energy, ranging from the use of *Wave Energy Converter* (WEC) devices with different working principles to the application of control systems and *Power Take-Off* (PTO) technology that is increasingly developing. Some of the technologies that are widely studied include *point absorbers*, *oscillating water column* (OWC), *oscillating wave surge converters*, *attenuators*, and *overtopping devices*. Each approach has a different conversion mechanism and operating characteristics so that its performance is highly dependent on wave conditions and application locations. The *point absorber* approach, for example, has the advantage of being able to capture energy from wave movements in a certain area, while OWC technology takes advantage of changes in air pressure due to rising and falling water levels to drive turbines. However, these differences in characteristics also mean that there is no one type of technology that can provide optimal performance for all aquatic conditions.

Approaches that focus on hydrodynamic design optimization have been widely used to improve the device's ability to absorb wave energy. Optimization of the device's shape, size, mass, mooring system, and response characteristics can improve the interaction between WEC and waves. However, designs optimized for specific wave conditions can experience performance degradation when applied to different wave conditions. This issue is important because the characteristics of ocean waves are not constant and can change based on season, weather, and location. Thus, static design approaches have limitations in dealing with dynamic operating conditions [5].

In addition to device design, PTO systems are an important component in determining the overall efficiency of WECS. PTO systems are used to convert the mechanical motion generated by WEC devices into electrical energy. Various PTO technologies, such as hydraulic, mechanical, and linear and rotary generator systems, have been developed to obtain higher conversion efficiency. However, each technology has limitations in terms of mechanical complexity, energy loss, maintenance needs, and ability to cope with changing loads. Complex PTO systems can increase efficiency under certain conditions, but at the same time they can increase the number of components that are potentially failing as well as increase maintenance costs [6].

Control system-based approaches are also increasingly being used to optimize energy absorption. Methods such as *adaptive control*, *predictive control models*, and various optimization algorithms can be used to adjust the WEC's response to wave conditions. This approach has the potential to increase efficiency over conventional control systems because it allows operating parameters to be dynamically adjusted. However, its implementation requires accurate system models, reliable sensors, adequate computing capabilities, and algorithms that can work in real time. Reliance on sensors and electronic systems can also be a challenge in marine environments that have high levels of humidity, corrosion, and environmental disturbances.

Another approach used is the integration of WECS with energy storage systems to address fluctuations in output power. Batteries and other storage technologies can be used to store excess energy and provide energy when production from waves decreases. While it can improve supply stability, the addition of storage systems leads to increased investment costs, space requirements, and system complexity. In addition, the lifespan and performance of storage systems can be affected by operating patterns and environmental conditions. Therefore, the use of energy storage needs to consider the balance between increased power stability and increased cost

and complexity of the system [7].

4. The Author's Perspective or Argument

Based on various problems and limitations in the approach that has been developed, the author is of the view that the development of the Wave Energy Conversion System (WECS) needs to be directed towards a system that is not only oriented towards improving energy conversion efficiency, but also has high adaptability, reliability, and sustainability. High efficiency in certain wave conditions is not enough to show that a technology can be applied effectively in actual marine conditions. The variable characteristics of waves require a system that is able to dynamically adjust its response so that the available energy can be optimally utilized under various operating conditions.

The authors argue that one potential approach is to integrate Optimal hydrodynamic design with adaptive control system and technology *Power Take-Off* (PTO) efficient. Hydrodynamic design plays a role in improving the device's ability to capture wave energy, while adaptive control systems can adjust operating parameters based on changes in wave conditions. The integration is expected to reduce the system's dependence on one specific wave condition and improve device performance under a wider range of operating conditions. Thus, the development of WECS should not only consider the design of the device separately, but also see the entire system as a single integrated unit [8].

According to the author's perspective, the application of intelligent control technology also has a great opportunity in improving WECS performance. The control system can utilize information from sensors to determine the wavelength characteristics and response of the device in real time. The data can then be used to determine the appropriate operating strategy to keep the device in conditions that allow optimal energy absorption. This approach can be an alternative to conventional control systems that use fixed operating parameters. However, the application of an intelligent control system needs to consider the simplicity of the algorithm, the reliability of the sensors, the energy requirements, and the ability of the system to operate in complex marine environments.

The authors also view that efficiency improvements should not be achieved at the expense of reliability and ease of maintenance. Systems that have high efficiency but require frequent maintenance and large operational costs will face difficulties in long-term implementation. Therefore, WECS design needs to consider the principles of reliability, maintainability, and durability from the early stages of development. The use of corrosion-resistant components, modular designs, and condition monitoring systems can help reduce the risk of failure and simplify the maintenance process.

5. Conclusion

The development of Innovative Wave Energy Conversion Systems (WECS) has great potential in supporting the efficient and sustainable use of renewable energy. The main challenges faced include wave fluctuations, conversion efficiency, extreme marine environmental conditions, power stability, and maintenance and operational costs. Approaches such as hydrodynamic design optimization, *Power Take-Off* (PTO) systems, adaptive control, and energy storage can improve system performance.

The integration of these technologies is necessary to produce a more efficient, adaptive, reliable, and sustainable WECS. Further testing in real ocean conditions is needed to ensure its performance and feasibility of application, particularly in coastal and archipelagic areas.

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