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Artificial Intelligence and Machine Learning Applications in Wave Energy

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ABSTRACT

This study delves into the optimization of wave energy conversion through the integration of artificial intelligence techniques, specifically deep machine learning. Wave energy, recognized for its high power density and availability, stands as a promising source for sustainable power generation. However, challenges persist in achieving satisfactory energy harvesting efficiency in Wave Energy Converters (WECs), particularly in off-resonance states. To enhance energy capture, two main strategies are explored: the utilization of a non-linear Power Take-Off (PTO) system known to increase energy absorption in random waves and the implementation of a controller, such as latching control, to regulate WEC dynamics and improve overall efficiency. Practical implementation of control in WECs introduces the necessity of predicting future wave forces. Leveraging the capabilities of artificial neural networks trained with deep machine learning algorithms, this study aims to develop a real-time controller for WECs by forecasting short-term wave forces. Simulation results showcase a significant increase in average energy absorption when the developed controller is applied, suggesting its potential applicability to full-scale wave energy converters. However, the study underscores the critical consideration of prediction errors, as inaccuracies in forecasting can lead to a reduction in energy absorption. In essence, this research contributes to the evolving field of wave energy conversion by proposing innovative solutions, driven by artificial intelligence techniques, to address efficiency challenges and pave the way for more effective and reliable utilization of wave energy for sustainable power generation.

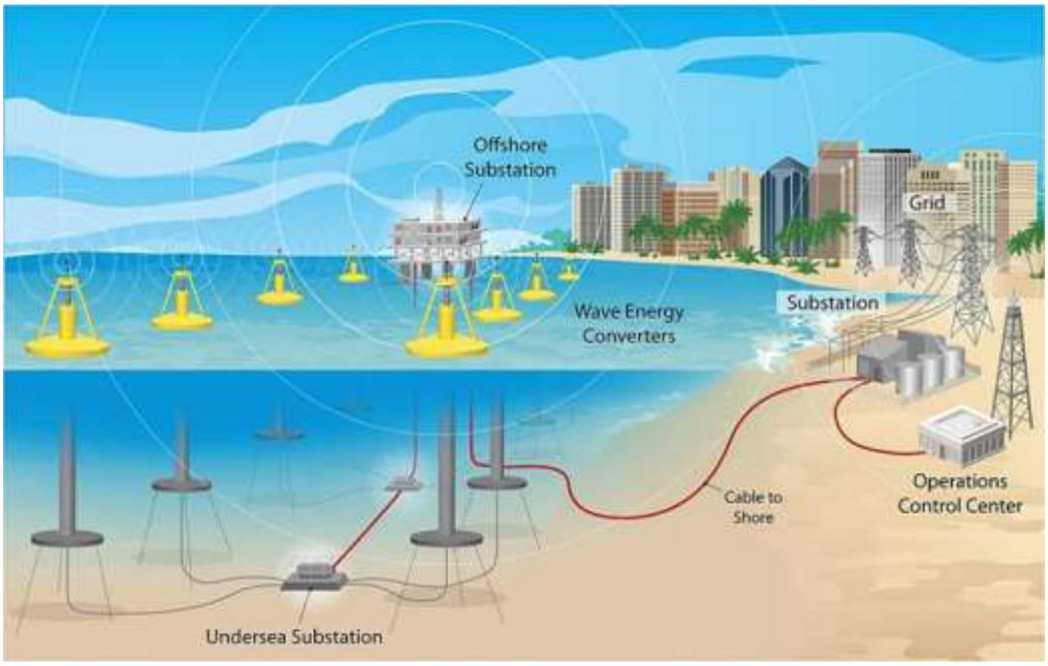
Keywords: Wave Energy Converters

1. Introduction

Energy is the important driving force of world economy. Most of the developing countries and industries are still totally relying on the conventional energy resources that are coal, oil and gas. Conventional energy resources will vanish within few decades because of its limited availability. Excessive uses of conventional energy resources are harmful for health of living things, environment and ozone layer. Clean renewable energy is the best alternative to avoid further deterioration of the earth’s environment. This can be possible only when there is solution of many technical problems. All countries are individually or collectively taking efforts to solve technical problems and developing new technologies in the field of renewable energy. Ocean possess many forms of energy namely Thermal energy, tidal energy, and energy from waves and circulating currents. And the study on the integration of ocean energy into smart and sustainable energy systems.

The application of artificial intelligence (AI) in sustainable and smart ocean energy systems is a forward-looking aspect of the study. AI can play a crucial role in optimizing operations, enhancing energy management and controls, and facilitating collaboration within multi-carrier energy networks.

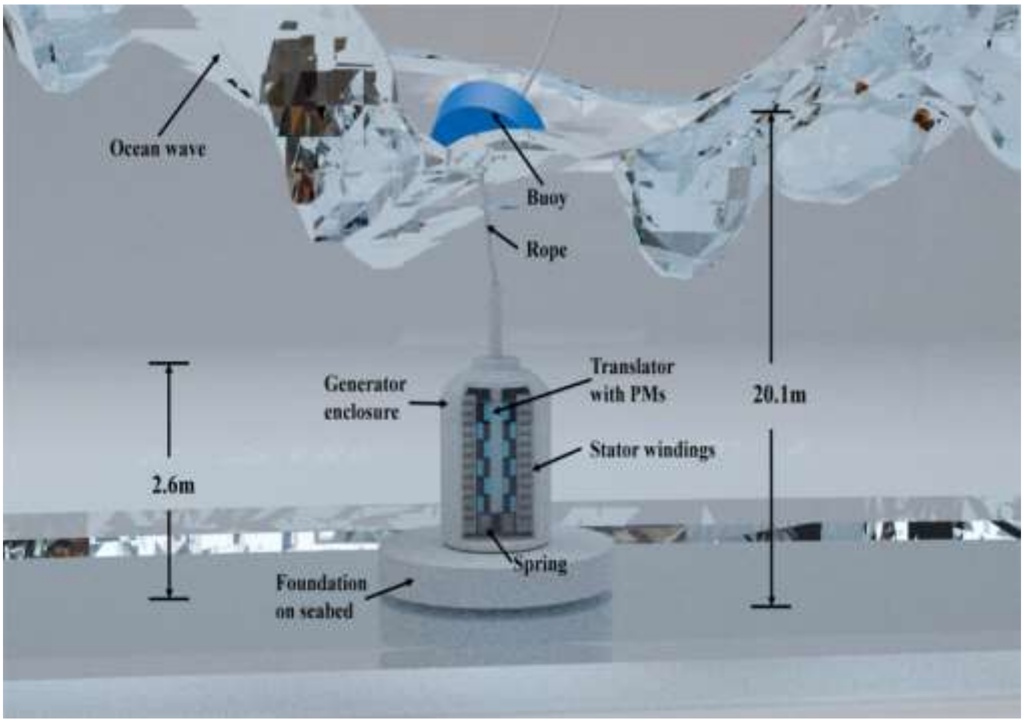
It covers various aspects, including the challenges posed by the spatiotemporal (relates to space and time) power supply characteristics of vertical cascade ocean energy systems and the potential solutions to ensure stable and grid-friendly operation. The incorporation of hybrid renewable energy dispatch, demand-side management, and energy storage technologies reflects a holistic approach to address the intermittency and fluctuations associated with ocean energy.



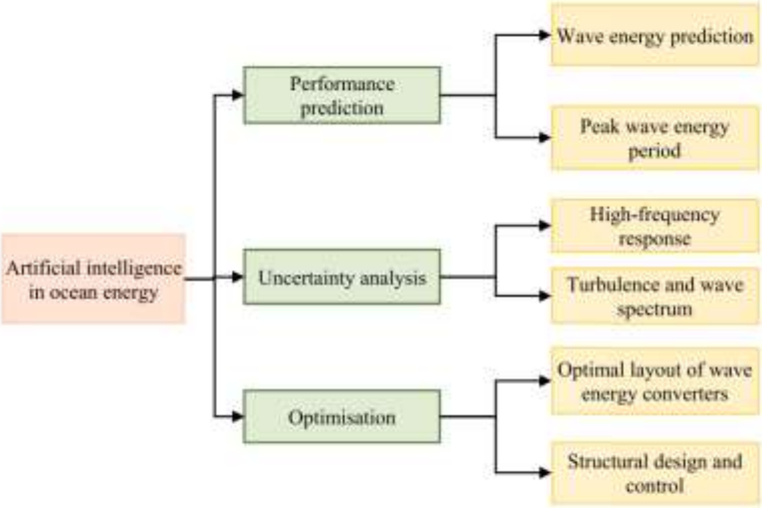
2. WAVE ENERGY CONVERTER

The device used to harvest energy from ocean waves is called a wave energy converter (WEC).The design of efficient Wave Energy Converters is a cornerstone of this evolving landscape. Models based on hydrodynamic and aerodynamic principles, as illustrated by the typical design. highlight the multi-dimensional considerations required to harness the various motions of wave energy. Systematic reviews, such as that conducted by Boerner and Alam, emphasize the ongoing need for model redevelopment, especially when integrating experimental subdomain models. This promising landscape has led to heightened global interest in the development of Wave Energy Converters, with leading nations, including Europe, the United States, China, and India, actively incorporating wave energy into their energy portfolios. Research efforts have been diverse, involving government research centers, private organizations, universities, and individual innovators, resulting in a surge of patent applications worldwide. However, the journey towards harnessing wave energy is not without its challenges. Researchers, exemplified by Uihlein et al, delve into the complexities of wave and tidal current energy utilization, highlighting research gaps and technical barriers. Life cycle assessments, power output fluctuations, storage solutions, and grid interactions emerge as crucial areas demanding further exploration.

The pursuit of sustainable and renewable energy sources has become a paramount global concern, driven by the depletion of traditional fossil fuels and the urgent need to mitigate environmental impacts. In this context, the ocean emerges as a vast and promising reservoir of energy, offering various potential sources, including marine currents, osmotic energy, ocean thermal energy, tidal energy, and particularly, wave energy. Compared to other established renewable energy forms, such as solar and wind, wave energy exhibits compelling characteristics that make it an increasingly attractive prospect. The energy density of wave farms is notably higher, ranging from 2 to 3 kW/m2, surpassing the energy densities of solar parks (0.1–0.2 kW/m2) and wind farms (0.4–0.6 kW/m2). Equally significant is the temporal aspect—wave energy is available approximately 90% of the time, providing a consistent and reliable power source in contrast to the intermittency associated with solar and wind power.Recent advancements in wave energy harvesting technologies exemplify the innovative spirit driving this field forward. Designs such as the smart ocean wave energy pitching harvester based on the piezoelectric effect and hybrid devices utilizing both triboelectric and piezoelectric effects showcase the potential for optimizing power generation from ocean waves. In the midst of these advancements, Shahriar et al. present a dynamic model for a Searaser wave energy converter, demonstrating its potential in hydroelectric power generation. The decentralized Mini Hydroelectric Power Plant (MHPP) model showcases the adaptability and capacity of wave energy systems. This introduction sets the stage for a comprehensive exploration of the current state, challenges, and innovations in wave energy utilization. As nations strive for a sustainable energy future, understanding the intricacies of harnessing the power of ocean waves is crucial for shaping effective policies, advancing technology, and contributing to a cleaner and more sustainable global energy landscape.



3. ARTIFICIAL INTELLIGENCE IN OCEAN ENETGY



The study on the integration of ocean energy into smart and sustainable energy systems. It covers various aspects, including the challenges posed by the spatiotemporal (relates to space and time) power supply characteristics of vertical cascade ocean energy systems and the potential solutions to ensure stable and grid-friendly operation. The incorporation of hybrid renewable energy dispatch, demand-side management, and energy storage technologies reflects a holistic approach to address the intermittency and fluctuations associated with ocean energy.

The review of advanced ocean energy converters based on thermodynamic, hydrodynamic, aerodynamic, and mechanical principles indicates a thorough examination of the technologies involved. Analyzing power supply characteristics from diversified ocean energy resources, considering factors like intermittency and spatiotemporal uneven distribution, adds depth to the study.

The focus on hybrid ocean energy storage solutions, such as pumped hydroelectric energy storage, ocean compressed air energy storage, and ocean hydrogen-based storage, with different response time durations, demonstrates a nuanced understanding of the need for varied storage options to address the unique challenges of ocean energy integration.

The application of artificial intelligence (AI) in sustainable and smart ocean energy systems is a forward-looking aspect of the study. AI can play a crucial role in optimizing operations, enhancing energy management and controls, and facilitating collaboration within multi-carrier energy networks.

The emphasis on effective strategies for stable and grid-friendly operations, including complementary hybrid renewable system integrations and synergies on hybrid thermal/electrical storages, aligns with the goal of achieving a reliable and resilient ocean energy infrastructure.

Additionally, the consideration of geographical factors and the proposal for flexible on-shore and off-shore installation of transformers for large-scale ocean energy system integrations indicate a practical approach to overcome transmission challenges and optimize energy transmission efficiency.

In conclusion, your study provides a comprehensive and forward-thinking exploration of the integration of ocean energy into smart energy systems. The identified strategies and technologies have the potential to contribute significantly to the transition towards carbon neutrality, offering alternatives to traditional solar and wind energy resources. The research outcomes can indeed serve as a valuable resource for policymakers, researchers, and industry stakeholders involved in the development of sustainable energy solutions.

2. POWER PREDICTION

Power prediction in the context of renewable energy, especially for sources like wave energy, involves forecasting the amount of power that can be generated over a specific period. Accurate power prediction is crucial for efficient grid integration, resource management, and overall system optimization. Several approaches can be employed for power prediction, and machine learning techniques are increasingly being used for their ability to handle complex and dynamic data.

Here is a general outline of the process involved in power prediction:

1. Data Collection: Gathering relevant data is the first step. For wave energy, this may include historical wave data, meteorological information, and other relevant parameters such as sea surface temperature, wind speed, and wave height.

2. Feature Selection: Identifying and selecting the most relevant features or variables that influence wave energy generation. This could involve data preprocessing and cleaning to ensure data quality.

3. Model Selection:Choosing an appropriate model for power prediction. Traditional statistical methods, physical models, and machine learning algorithms are common choices. In recent times, machine learning, particularly regression and time-series forecasting models, has gained popularity due to its ability to capture complex patterns in the data.

4. Training the Model:Using historical data to train the selected model. This involves feeding the algorithm with input features (such as wave characteristics) and corresponding power output data to learn the relationships and patterns.

5. Validation and Testing: Assessing the trained model's performance using a separate dataset not used during training. This helps evaluate how well the model generalizes to new, unseen data.

6. Fine-Tuning:Adjusting model parameters or features to improve performance, if necessary. This step may involve iterative processes to optimize the model.

7. Deployment: Implementing the trained and validated model for real-time or future power predictions. This can be integrated into the control system of the wave energy converter.

8. Continuous Monitoring and Updating Regularly monitoring the model's performance and updating it with new data to ensure accurate and up-to-date predictions. This is especially important in dynamic environments where conditions may change.

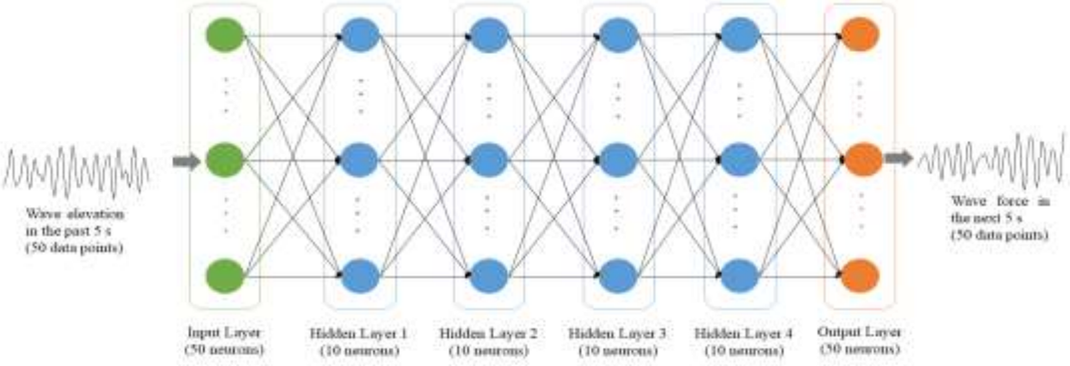
Popular machine learning algorithms for time-series forecasting, such as Long Short-Term Memory (LSTM) networks, Support Vector Machines (SVM), and Random Forests, can be applied to predict wave energy generation. Automated machine learning techniques can also be employed to streamline the model selection and tuning process.

It's important to note that the effectiveness of a power prediction model depends on the quality and quantity of available data, the chosen features, and the appropriateness of the selected algorithm for the specific characteristics of the system.

2.3 FORECASTING

The significance of this forecasting method lies in its use of real-time wave surface elevation, an easily measurable parameter, to predict future wave force. This practical application eliminates the need for measuring the challenging-to-assess wave force, making it cost-effective. The trained neural network, represented by parameters w and b, offers a convenient and robust solution for practical implementation without additional costs. The method is particularly advantageous as it is adaptable to varying wave states, employing wave surface elevation for forecasting, which allows real-time implementation across a diverse range of ocean sites.

The forecasting approach in this study utilizes a feedforward backpropagation neural network with six layers (one input layer, four hidden layers, and one output layer) to predict future wave force based on the established link between past free surface elevation and wave force. The neural network architecture comprises 10 neurons in each layer, as illustrated in Figure.



3. Literature Review

I. Yuekuan Zhou,Ocean energy applications for coastal communities with artificial intelligence–a state-of-the-art review.The paper discusses the design of smart ocean wave energy harvesters based on the piezoelectric and triboelectric effects, which can improve energy conversion efficiency. It also mentions the design of wave energy converters based on hydrodynamic and aerodynamic models, as well as the development of a dynamic model for a Searaser wave energy converter.

II. Chenhua Ni , Xiandong Ma, Prediction of Wave Power Generation Using a Convolutional Neural Network with Multiple Inputs. predicting power generation results.The power output of the double-buoy oscillating body WEC has a positive correlation with wave height, particularly when the wave height is higher than 0.2 m and becomes even stronger when the wave height is higher than 0.6 m. The proposed approach using the CNN algorithm can potentially detect changes and anomalies in the WEC system, making it suitable for condition monitoring and fault diagnosis of marine energy converters.

III. Alireza Shadmani, Mohammad Nikoo , Amir Gandomi, Ruo-Qian Wang, Behzad Golparvar, A review of machine learning and deep learning applications in wave energy forecasting and WEC optimization. Novel algorithms incorporating machine learning and deep learning have been presented to forecast wave energy resources and optimize WEC design. These algorithms can improve the configuration and forecasting of wave characteristics and optimize the design of WECs.

IV. Hengyi Yang, Hao Wang, Yong Ma, Minyi Xu, Prediction of Wave Energy Flux in the Bohai Sea through Automated Machine Learning. The significant wave height (SWH), mean wave period (MWP), and WEF in the Bohai Sea were concentrated in the center of the sea and dispersed in the nearshore areas. The maximum annual average WEF at each research coordinate in the Bohai Sea was around 1.5 kW/m in the years 2000, 2010, 2020, and 2030, with a higher flux in autumn and winter.

V. Peng Hao, Shuang Li, Yu Gao, Lichuan Wu, Carlos Pe ́rez-Collazo V, Significant wave height prediction based on deep learning in the South China Sea. The input length of the models was found to impact the prediction results of SWH. However, it was observed that longer input lengths did not necessarily lead to better prediction performance. The best prediction performance was achieved when the input length was set to 24 hours.

VI. Liang Li, Zhiming Yuan, Yan Gao, Maximization of energy absorption for a wave energy converter using deep machine learning. The use of artificial intelligence techniques, specifically a multi-layer artificial neural network trained by deep machine learning algorithms, has been shown to improve the energy absorption of wave energy converters. The prediction of future wave forces using the developed neural network allows for the implementation of real-time latching control action, resulting in a substantial increase in average energy absorption. However, it is important to note that prediction errors can negatively affect the control performance and lead to a reduction in energy absorption.

VII. D Ning, Z Yuan, Development of a non-causal wave energy control algorithm based on artificial intelligence. The present research developed a non-causal wave energy control algorithm based on artificial intelligence, which uses online forecasting of future wave force to optimize the control command. A feedforward artificial neural network is developed for the forecasting, establishing the link between past free surface elevation and future wave force through machine learning algorithm. The implementation of the developed algorithm enhances power capture substantially while minimizing system motion. The effect of prediction error on power extraction is investigated, with phase error having a greater impact than amplitude error. The research also identifies a link between power capture efficiency and the constraint on control. A real-time declutching wave energy control based on model predictive control strategy is developed, using artificial intelligence to tackle non-causality and investigating the effects of forecasting error and constraint on control efficiency.

VIII. Rui Li, Jincheng Zhang, Xiaowei Zhao, Daming Wang, Martyn Hann, Deborah Greaves, Phase-resolved real-time forecasting of three-dimensional ocean waves via machine learning and wave tank experiments. The study focuses on phase-resolved real-time prediction of three-dimensional ocean waves using machine learning methods. It investigates the mapping relationships between historical wave data and future wave elevations. Four machine learning methods are employed, and a Dual-Branch Network (DBNet) is proposed for performance improvement. Wave basin experiments are conducted to collect data on three-dimensional waves. The results show that upstream wave data measured by the gauge array can be used for control-oriented wave forecasting with a forecasting horizon of more than 20s. The directional information provided by the upstream gauge array is vital for accurately predicting downstream wave elevations. By using only local wave data, very short-term phase-resolved prediction (less than 5s) can be achieved. However, this is not sufficient for control-oriented wave forecasting.

IX. Ismail Elkhrachy, Ali Alhamami, Saleh Alyami, Aníbal Alviz-Meza, Novel Ocean Wave Height and Energy Spectrum Forecasting Approaches: An Application of Semi-Analytical and Machine Learning Models. The study compares the performance of different models for wave height and energy spectrum forecasting in the Gulf of Mexico and Aleutian Basin. The Sverdrup Munk Bretschneider (SMB) semi-analytical approach, Emotional Artificial Neural Network (EANN) approach, and Wavelet Artificial Neural Network (WANN) approach are evaluated.

X. Yi Shen, Yihang Wu, Weimei Zhi, Wave Energy Output Power Design Based on Machine Learning. The paper focuses on the design of the maximum wave energy output power and establishes motion and optimization models for wave energy devices. It provides theoretical support for designing a new generation of wave energy equipment. The motion model of the float and oscillator in the wave energy device is solved using Newton's theorem and Lagrange's equation, and the displacement and velocity of the float and oscillator are determined using the fourth-order Runge-Kutta method. The optimization model of the maximum average output power in the wave energy device is solved using a genetic algorithm and the traversal method. The genetic algorithm is compared with the traversal method to help choose the algorithm for studying this problem.

Conclusion

Accurate wave force prediction is crucial for optimizing control strategies and maximizing energy absorption in wave energy converters (WECs) .Artificial neural networks trained with deep machine learning algorithms have been proven effective in predicting short-term wave forces. The use of deep machine learning-based wave force prediction enables the implementation of real-time latching control actions in WECs. With accurate wave force prediction, the control efficiency of WECs can be significantly improved, leading to increased energy absorption.The reduction of prediction deviation is essential to maintain optimal control performance and maximize energy absorption in WECs. The development of reliable wave force prediction methods contributes to the practical application of control strategies in full-scale wave energy converters .

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