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A Comprehensive Review of Intelligent Maximum Power Point Tracking Techniques for Grid-Integrated Tidal Energy Conversion Systems

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ABSTRACT
With the increasing importance of clean and dependable energy production methods, interest in marine renewable energy sources has greatly increased in recent years, particularly tidal energy owing to its predictability and energy density. Maximum Power Point Tracking (MPPT) methods have to be sophisticated in order to extract tidal energy effectively under varying tidal current conditions. This review presents an in-depth study of tidal energy conversion systems along with their MPPT methods and modern optimization techniques. The functioning principles of tidal turbines, Permanent Magnet Synchronous Generators (PMSGs), converters, and grid integration systems are investigated in the work. Comparison of classical MPPT methods (TSR, OTC, and HCS) is provided and their deficiencies under dynamic operating conditions are discussed. In addition, modern advances in intelligent optimization techniques such as Grey Wolf Optimization (GWO), Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Artificial Neural Networks (ANNs), Fuzzy Logic (FL), and Reinforcement Learning (RL) is investigated in terms of accuracy, speed of convergence, harvesting efficiency, and stability of the system.
Keywords: Tidal Energy Conversion System, Maximum Power Point Tracking, Grey Wolf Optimization, Grid Integration, Permanent Magnet Synchronous Generator, Intelligent Optimization Techniques

1. INTRODUCTION

The growing global demand for electricity, rapid industrialization, urbanization, and increasing concerns regarding environmental sustainability have accelerated the transition from conventional fossil fuel-based energy generation to renewable energy resources. Conventional power generation systems are associated with significant greenhouse gas emissions, depletion of natural resources, and adverse environmental impacts, making the development of clean and sustainable energy technologies an international priority [1]. Renewable energy sources, including solar, wind, hydroelectric, biomass, geothermal, and marine energy, have emerged as viable alternatives for meeting future energy requirements while reducing carbon emissions and enhancing energy security. Among these resources, tidal energy has gained considerable attention because of its high predictability, reliability, and energy density compared with many other renewable energy sources.

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Tidal energy utilizes the kinetic and potential energy generated by the periodic movement of seawater due to the gravitational interaction between the Earth, Moon, and Sun. Unlike solar and wind energy, which are highly dependent on weather conditions, tidal currents follow predictable astronomical cycles, enabling stable and continuous electricity generation [2]. This predictable nature makes tidal energy an attractive option for large-scale renewable power generation and contributes significantly to improving the stability of modern power systems. The increasing deployment of offshore renewable energy projects has further encouraged the integration of tidal energy conversion systems into utility grids to diversify energy resources and support global decarbonization goals.

A grid-integrated tidal energy conversion system generally consists of a tidal turbine, a Permanent Magnet Synchronous Generator (PMSG), power electronic converters, control systems, transformers, and grid synchronization units. The tidal turbine converts the kinetic energy of moving seawater into mechanical energy, which is subsequently transformed into electrical energy by the generator. The generated electrical power is conditioned using AC–DC and DC–AC power converters before being delivered to the utility grid. Since tidal current velocity continuously changes throughout tidal cycles, the operating point of the turbine also varies, directly affecting the output power and overall conversion efficiency. Consequently, intelligent control strategies are required to maximize energy extraction while maintaining stable operation under changing environmental conditions [3].

Maximum Power Point Tracking (MPPT) has become one of the most essential control techniques for renewable energy conversion systems. The primary objective of MPPT is to continuously identify and maintain the operating point at which the maximum available power can be extracted from the energy source. In tidal energy applications, MPPT controllers regulate turbine speed, generator torque, or converter duty cycle to ensure efficient energy harvesting despite fluctuations in tidal current velocity [4]. Effective MPPT techniques improve energy conversion efficiency, reduce electrical and mechanical losses, enhance dynamic response, and increase the amount of electrical energy delivered to the utility grid.

Several conventional MPPT methods have been widely employed in renewable energy systems, including Tip Speed Ratio (TSR), Optimal Torque Control (OTC), and Hill Climbing Search (HCS). These methods offer simple implementation and relatively low computational requirements; however, their performance often deteriorates under rapidly changing operating conditions. Conventional algorithms generally experience slow convergence, steady-state oscillations around the maximum power point, sensitivity to parameter variations, and limited adaptability to nonlinear system dynamics. These limitations reduce the overall efficiency and reliability of grid-integrated tidal energy conversion systems, particularly under variable marine environments [5].

To overcome these challenges, researchers have increasingly adopted intelligent optimization algorithms capable of handling nonlinear, uncertain, and dynamic operating conditions. Nature-inspired optimization techniques such as Grey Wolf Optimization (GWO), Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Ant Colony Optimization (ACO), Whale Optimization Algorithm (WOA), and Differential Evolution (DE) have demonstrated

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superior optimization capabilities for MPPT applications. In addition, artificial intelligence-based approaches, including Artificial Neural Networks (ANN), Fuzzy Logic Control (FLC), Adaptive Neuro-Fuzzy Inference Systems (ANFIS), Deep Learning (DL), and Reinforcement Learning (RL), have shown remarkable potential in improving tracking accuracy, convergence speed, robustness, and system stability [6]. These intelligent techniques are capable of adapting to continuously changing tidal conditions while minimizing power oscillations and avoiding local optimum solutions.

Recent advances in computational intelligence, power electronics, embedded control, and digital signal processing have significantly expanded the application of intelligent MPPT techniques in marine renewable energy systems. Modern optimization algorithms can effectively coordinate with advanced converter topologies, real-time monitoring systems, Internet of Things (IoT)-based supervisory platforms, and smart grid technologies to improve operational efficiency and grid reliability. Furthermore, hybrid optimization methods that combine multiple intelligent algorithms have demonstrated enhanced convergence characteristics and superior power extraction performance compared with individual optimization techniques.

Despite substantial research progress, several technical challenges remain before intelligent MPPT techniques can be widely deployed in practical tidal energy installations. Many proposed algorithms are validated only through simulation studies, while real-time experimental validation and large-scale field implementation remain limited. High computational complexity, controller tuning difficulties, parameter sensitivity, communication delays, hardware constraints, and uncertainty associated with harsh marine environments continue to affect practical implementation. In addition, comparative analyses of different intelligent MPPT approaches under identical operating conditions are relatively scarce, making it difficult to identify the most suitable optimization strategy for specific tidal energy applications [7].

This review presents a comprehensive analysis of intelligent Maximum Power Point Tracking techniques for grid-integrated tidal energy conversion systems. It critically examines the operating principles of tidal energy systems, conventional MPPT methods, and recent developments in intelligent optimization algorithms. The review compares various optimization approaches in terms of tracking accuracy, convergence speed, computational complexity, robustness, energy extraction efficiency, and grid integration performance. Furthermore, existing research gaps, implementation challenges, and future research directions are identified to facilitate the development of highly efficient, reliable, and intelligent tidal energy conversion systems capable of supporting the next generation of sustainable power networks.

2. FUNDAMENTALS OF GRID-INTEGRATED TIDAL ENERGY CONVERSION SYSTEMS

Grid-integrated tidal energy conversion systems have emerged as a promising solution for sustainable electricity generation because of the predictable and renewable nature of tidal resources. Unlike solar and wind energy, which are strongly influenced by weather conditions, tidal energy follows regular astronomical cycles determined by the gravitational interaction between the Earth, Moon, and Sun. This high level of predictability enables stable power generation and facilitates effective scheduling of electricity production. As global efforts toward carbon neutrality continue to increase, tidal energy has attracted significant attention as an important component of future renewable energy portfolios and smart grid infrastructures.

A tidal energy conversion system converts the kinetic and potential energy of moving seawater into electrical energy using specially designed marine turbines and electromechanical conversion units. Depending on the site characteristics and available tidal resources, several technologies have been developed, including tidal barrages, tidal lagoons, tidal stream turbines, dynamic tidal power systems, and tidal fences. Among these technologies, tidal stream turbines have gained widespread acceptance because they require relatively lower civil infrastructure, have reduced environmental impacts, and provide higher energy conversion efficiency under suitable tidal current conditions [8]. Their modular design also supports gradual capacity expansion and easier maintenance compared with conventional tidal barrage systems.

The basic operation of a grid-integrated tidal energy conversion system begins with the extraction of kinetic energy from tidal currents through submerged turbine blades. The rotating turbine shaft transfers mechanical power to an electrical generator, commonly a Permanent Magnet Synchronous Generator (PMSG), which converts mechanical energy into electrical power. PMSGs have become the preferred generator technology for modern tidal energy applications because of their high efficiency, compact construction, high power density, excellent dynamic performance, and ability to operate effectively over a wide range of rotational speeds. Unlike conventional synchronous generators, PMSGs eliminate the requirement for external excitation systems, thereby reducing maintenance requirements and improving overall system reliability [9].

Since the rotational speed of the turbine continuously varies with tidal current velocity, the generated electrical power is characterized by variable voltage and frequency. Therefore, power electronic converters are employed to regulate and condition the electrical output before it is supplied to the utility grid. A typical grid-connected tidal energy conversion system consists of an AC–DC rectifier, a DC-link capacitor, a DC–DC converter, and a grid-side inverter. The rectifier converts the variable-frequency alternating current produced by the generator into direct current, while the DC-link stabilizes voltage fluctuations and temporarily stores energy. Subsequently, the inverter converts the regulated DC power into grid-compatible alternating current with the required voltage, frequency, and phase angle. Advanced converter control strategies further ensure low harmonic distortion, improved power quality, and compliance with international grid standards.

Grid integration introduces several technical challenges because renewable energy sources exhibit continuously changing operating conditions. Stable synchronization with the utility grid requires accurate regulation of voltage magnitude, frequency, phase angle, and power flow. Modern tidal energy systems therefore employ intelligent controllers to coordinate generator operation, converter switching, reactive power compensation, and grid synchronization. These controllers contribute to maintaining voltage stability, improving transient response, minimizing harmonic distortion, and ensuring reliable operation during network disturbances. The integration of battery energy storage systems, flexible power electronic interfaces, and smart grid communication technologies has further enhanced the operational flexibility and reliability of tidal power plants [10].

Maximum Power Point Tracking (MPPT) is another essential component of grid-integrated tidal energy conversion systems. Because tidal current velocity changes continuously throughout the tidal cycle, the turbine operating point must be adjusted dynamically to maximize power extraction. MPPT controllers continuously monitor electrical and mechanical system variables such as turbine speed, voltage, current, torque, and output power to identify the operating condition that produces maximum energy. By regulating generator torque or converter duty cycle, MPPT algorithms ensure that the turbine operates near its optimal power coefficient under both steady-state and transient conditions. Effective MPPT not only improves energy harvesting efficiency but also reduces mechanical stress, minimizes converter losses, and extends equipment lifetime.

Recent developments in intelligent control have significantly improved the performance of tidal energy conversion systems. Conventional MPPT techniques such as Tip Speed Ratio (TSR), Optimal Torque Control (OTC), and Hill Climbing Search (HCS) have been widely applied because of their simplicity and ease of implementation. However, these methods often experience slower convergence, oscillations around the optimal operating point, and reduced performance under rapidly changing tidal conditions. Consequently, advanced optimization algorithms, including Grey Wolf Optimization (GWO), Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Artificial Neural Networks (ANN), Adaptive Neuro-Fuzzy Inference Systems (ANFIS), and Reinforcement Learning (RL), have gained increasing attention for improving tracking accuracy, convergence speed, and robustness [11]. These intelligent approaches effectively address the nonlinear characteristics of tidal energy systems and enhance overall energy conversion efficiency.

Another important aspect of grid-integrated tidal energy conversion systems is power quality management. Integration of large-scale marine renewable energy resources can introduce voltage fluctuations, harmonic distortion, frequency deviations, and reactive power imbalance. Advanced converter topologies, active filtering techniques, adaptive controllers, and flexible AC transmission devices are increasingly employed to mitigate these issues and maintain grid stability. Furthermore, digital monitoring systems based on Supervisory Control and Data Acquisition (SCADA), Internet of Things (IoT) technologies, and real-time communication networks enable continuous performance monitoring, fault diagnosis, predictive maintenance, and remote system management.

Although significant progress has been achieved in the design and operation of grid-integrated tidal energy conversion systems, several research challenges remain. Harsh marine environments, corrosion, biofouling, high installation costs, maintenance difficulties, and limited field validation continue to affect commercial deployment. In addition, many intelligent control algorithms are evaluated primarily through simulation, while large-scale experimental demonstrations remain relatively limited. Future research is therefore expected to focus on hybrid intelligent optimization techniques, digital twin technologies, advanced power electronics, offshore energy storage systems, and resilient grid integration strategies to improve the efficiency, reliability, and economic viability of tidal energy conversion systems. These developments will play a crucial role in expanding the contribution of marine renewable energy to sustainable power generation and future smart energy networks [12].

3. CONVENTIONAL MAXIMUM POWER POINT TRACKING (MPPT) TECHNIQUES

Maximum Power Point Tracking (MPPT) is a fundamental control strategy employed in renewable energy conversion systems to maximize the extraction of available energy under varying environmental conditions. In grid-integrated tidal energy conversion systems, tidal current velocity changes continuously due to periodic tidal cycles, resulting in variations in turbine speed, generator output, and electrical power. Without an efficient MPPT mechanism, the operating point of the tidal turbine may deviate from its optimum value, leading to reduced energy conversion efficiency and lower power generation. Consequently, MPPT algorithms have become an essential component of modern tidal energy systems, ensuring that the turbine continuously operates at or near its maximum power point while maintaining stable grid operation.

Conventional MPPT techniques are generally based on mathematical models, predefined control rules, or iterative search methods that regulate generator torque, turbine speed, or converter duty cycle. These approaches have been widely adopted because of their simple implementation, low computational complexity, and ease of integration with power electronic converters. Although conventional algorithms provide satisfactory performance under relatively stable operating conditions, they often encounter difficulties when tidal currents change rapidly or when system parameters become uncertain [13]. As a result, their performance may degrade under dynamic marine environments, motivating the development of more advanced intelligent optimization techniques.

One of the earliest and most widely used conventional MPPT methods is the Tip Speed Ratio (TSR) technique. This method is based on maintaining an optimal ratio between the rotational speed of the turbine blades and the velocity of the tidal current. Every tidal turbine possesses an optimal tip speed ratio at which the power coefficient reaches its maximum value. The TSR controller continuously measures tidal current velocity and turbine rotational speed to calculate the actual tip speed ratio. When deviations from the optimal value occur, the controller adjusts the generator speed or converter control parameters to restore optimum operation. The principal advantage of the TSR method is its ability to achieve high energy extraction efficiency under steady operating conditions. Furthermore, the algorithm is relatively simple and provides fast control action when accurate flow velocity measurements are available [14]. However, its dependence on tidal current sensors increases system cost and introduces measurement errors in harsh underwater environments. Sensor degradation, marine fouling, and communication delays may further reduce tracking accuracy and overall system reliability.

Another widely adopted conventional technique is Optimal Torque Control (OTC). Unlike TSR, OTC does not require direct measurement of tidal current velocity. Instead, it estimates the optimal generator torque using predefined turbine characteristics and mathematical relationships between rotor speed and output power. The controller regulates electromagnetic torque to maintain operation at the maximum power point throughout the tidal cycle. Because tidal current sensors are eliminated, OTC offers lower hardware complexity, improved reliability, and reduced maintenance requirements. The method also exhibits relatively fast dynamic response and stable operation over a broad operating range. Nevertheless, the performance of OTC strongly depends on the accuracy of turbine parameters and mathematical models. Any mismatch between the actual turbine characteristics and the assumed model can significantly reduce energy harvesting efficiency [15]. Furthermore, parameter variations caused by mechanical wear, marine corrosion, or changing environmental conditions may decrease controller effectiveness during long-term operation.

The Hill Climbing Search (HCS) method, also known as the Perturb and Observe (P&O) approach in many renewable energy applications, is another popular conventional MPPT algorithm. The HCS technique operates by introducing small perturbations to the operating point and observing the corresponding variation in output power. If the perturbation results in increased power generation, the controller continues adjusting the operating point in the same direction. Conversely, if output power decreases, the search direction is reversed until the maximum power point is reached. The algorithm requires only measurements of voltage, current, or output power, eliminating the need for complex turbine models or environmental sensors. Its simplicity, low computational burden, and ease of implementation have made HCS one of the most widely applied MPPT techniques in renewable energy systems [16].

Despite these advantages, Hill Climbing Search exhibits several well-recognized limitations. The algorithm continuously perturbs the operating point even after reaching the maximum power point, producing steady-state oscillations that reduce average power extraction efficiency. Under rapidly changing tidal conditions, HCS may incorrectly interpret environmental variations as responses to controller perturbations, resulting in incorrect tracking direction and slower convergence. The selection of perturbation step size also presents a trade-off between convergence speed and tracking accuracy. Larger step sizes improve response time but increase oscillations, whereas smaller step sizes reduce oscillations at the expense of slower adaptation to changing tidal conditions.

Several additional conventional MPPT approaches have also been reported in the literature, including Power Signal Feedback (PSF), Incremental Conductance (INC), and constant parameter control methods. Power Signal Feedback determines the reference operating point using experimentally obtained power-speed characteristics stored within the controller memory. Although this technique provides accurate tracking under known operating conditions, its effectiveness depends on precise turbine characterization and may deteriorate as turbine parameters change over time. Incremental Conductance estimates the slope of the power curve to determine the location of the maximum power point, offering improved tracking performance compared with HCS under moderate environmental variations. However, the method involves more complex calculations and still experiences performance degradation during highly dynamic operating conditions [17]. Constant parameter control methods represent the simplest category of MPPT strategies but generally fail to adapt effectively to continuously changing tidal environments.

A comparative assessment of conventional MPPT techniques indicates that each method possesses distinct strengths and limitations. Tip Speed Ratio provides high efficiency under accurate flow measurements but requires additional sensors. Optimal Torque Control reduces hardware complexity but relies heavily on accurate mathematical modeling. Hill Climbing Search offers simplicity and low computational requirements but suffers from oscillations and slower convergence under dynamic conditions. Similarly, Power Signal Feedback and Incremental Conductance improve certain aspects of tracking performance but remain sensitive to parameter uncertainty and environmental disturbances.

The limitations of conventional MPPT algorithms have become increasingly evident as modern tidal energy systems operate under highly variable marine conditions requiring rapid adaptation, robust control, and maximum energy extraction. These challenges have encouraged researchers to investigate intelligent optimization techniques capable of handling nonlinear system dynamics, parameter uncertainties, and rapidly changing operating environments. Consequently, artificial intelligence and nature-inspired optimization algorithms have emerged as promising alternatives for enhancing MPPT performance in grid-integrated tidal energy conversion systems. These intelligent methods are discussed comprehensively in the following section.

4. INTELLIGENT OPTIMIZATION-BASED MPPT TECHNIQUES

As grid-connected tidal energy conversion systems become more complicated, new intelligent optimal maximum power point tracking methods that can achieve greater energy extraction efficiency in dynamic marine environments have been developed. While conventional maximum power point tracking methodologies are simple and computationally efficient, they show slow convergence, oscillation near the maximum power point, and poor operation under variable tidal conditions [18]. As a result, researchers have increasingly utilized computer intelligence and optimization techniques based on nature in order to solve non-linear optimization problems, deal with uncertain environmental conditions, and continuously find the optimal global operating point.

GWO or Gray Wolf Optimization among the different algorithms for optimization has proven itself to be one of the best methods that can be applied for maximum power point tracking in renewable energy systems. Its commitment to using the leadership structure and the collaborative hunting style of grey wolves makes GWO distinguish solution candidates into four groups: Alpha, Beta, Delta, and Omega. Therefore, during the optimization process, three of the best solutions can lead the rest of the agents during the search for a global solution, the agents benefit from the updates in their positions. In addition, due to its self-adapting features, GWO can avoid early convergence while being able to achieve the maximum power point under the effect of fluctuating tidal currents. Despite the fact that GWO needs very few parameters, being easy in terms of calculations and possessing the ability to converge quickly, it still has its drawbacks.

Another optimization technique in maximum power point tracking (MPPT) control that has received prominence is particle swarm optimization (PSO). This algorithm is inspired by the behavior of birds and fish. In nature, where groups of birds or fish can work together in order to find the optimal solution. When this algorithm is used, each particle continues to update its position and velocity through experience and through the best position found in the swarm. PSO has advantages such as fast convergence, and easy implementation, and is one of the best global optimization methods that allow using it for renewable energy purposes. Many studies reported better extraction efficiency and tracking speed compared to traditional MPPT methods. Moreover, PSO could suffer from premature convergence and lack of diversity in the later stages of optimization when the operation becomes highly nonlinear.

Genetic Algorithm (GA) is another successful optimization technique used in controlling solar panels. This technique is based on the principles of natural selection, crossover, and mutation. As stated, GA operates efficiently even in complex and large search spaces avoiding local optimum solutions. In tidal energy systems, GA has been applied to find the best values for turbine operating parameters, controllers, and switches. Results show effective global search performance and robustness even under varying parameters. Nevertheless, GA involves higher computational time than other nature-based algorithms and that can limit its application in real-time controls.

Learning techniques based on artificial intelligence are emerging essential for intelligent methods in Maximum Power Point Tracking (MPPT). Specifically, Artificial Neural Networks (ANN) can learn the nonlinear relationship linking the input of the system to the power output through the training with historical data. After being trained, the ANN can be utilized to determine the optimal operating point of the turbine under different tidal operating conditions. Its learning capability provides very quick decisions and improved tracking performance, even when dealing with conditions of uncertainty. However, the performance of any ANN is contingent upon certain conditions like the existence of well-prepared training data and proper network structure, along with sufficient computations. Poorly trained networks may fail to generalize in cases of the operation that is different from its training experience.

Fuzzy Logic Control has gained popularity due to simulating human thinking thanks to linguistic variables and rule-based decision making. This allows for the system to be controlled without the requirement of precise mathematical formulation of the tidal energy conversion process. The system is controlled by applying expert knowledge encoded in the form of membership functions and IF-THEN rules, which define the actions for the control. Fuzzy controllers are highly resistant to uncertainties, nonlinearity of the systems, and noise in the measurements.

The combination of Fuzzy Logic with Artificial Neural Networks has resulted in the Adaptive Neuro-Fuzzy Inference System, or ANFIS. ANFIS integrates the superior learning capability of artificial neural networks with the reasoning capability of fuzzy logic-based systems which can then perform adaptive and accurate MPPT controls. By training the network, the parameters and also membership functions of frozen sets are adjusted automatically in order to minimize the prediction error and, as a result, the controller adapts to the changing the working environment. Numerous research findings demonstrate that ANFIS has the potential to significantly outperform pure ANN and FLC systems in terms of the speed of convergence and effectiveness of tracking, as well as overcoming the oscillation problem. However, the complications in constructing complex systems and increased computational aspect should be taken into account when implementing the processes in reality.

Recently, the interest in the application of Reinforcement Learning (RL) and Deep Reinforcement Learning (DRL) in MPPT has increased greatly. Unlike conventional supervised methods used in learning machines, in RL, intelligent systems learn how to construct optimal control policies by interacting with the external environment with the process of reward-based knowledge accumulation. Deep neural networks are used to develop better learning possibilities by establishing complex value functions and control policies that are suitable for complicated nonlinear processes. Reinforcement learning allows an intelligent machine to be independent in its adaptation to changing operational environment based on tide currents without the necessity to have complex mathematical algorithms or sophisticated knowledge. Despite the fact that various RL-based control systems have proven to be very helpful in providing high degree of adaptiveness, which is crucial for energy extraction, the practicality of the technologies still raises some difficulties.

Several researchers have also proposed hybrid intelligent optimization algorithms that combine the complementary strengths of multiple optimization techniques. Examples include GWO-PSO, ANFIS-GWO, ANN-PSO, Fuzzy-GA, and GWO combined with Cuckoo Search or Differential Evolution. Hybrid algorithms typically achieve better exploration and exploitation balance, faster convergence, improved global optimization capability, and higher tracking efficiency than individual algorithms. Despite these advantages, hybrid methods often involve increased algorithmic complexity, higher computational requirements, and more complicated parameter tuning procedures.

Research comparing MPPT techniques based on intelligent optimization shows considerable advantages of intelligent techniques over traditional methods. Unlike traditional techniques, nature-inspired optimization methods are more efficient in achieving global search with resistance to local optima trapping; artificial intelligence methods are developed in terms of adaptive learning, nonlinear modeling, and predictive control. These intelligent controllers improve maximum energy extraction, minimize oscillations in steady-state operation, improve transient performance, as well as the quality of the grid and efficiency of the tidal energy conversion system [22]. However, some difficulties related to practical implementation still exist, such as a complex computational setup, hardware limitations, the necessity for controller parameter tuning, cybersecurity issues, as well as the lack of practical experimentation. Thus, future approaches should focus on the application of lightweight optimization methods, hybrid artificial intelligence strategies, the use of digital twins, edge computing, and real-time embedded control systems providing highly efficient advanced intelligent MPPT systems to be used in future tidal energy conversion systems. Comparison analysis of different existing intelligent MPPT approaches has been provided in Table 1, considering speed of their optimization methods as well as strengths and weaknesses of using these methods.

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TABLE 1: COMPARATIVE ANALYSIS OF EXISTING INTELLIGENT MPPT METHODS

Ref.	Method/Technique Used	Key Results	Limitations	Future Scope / Research Gap
[1]	Wave-to-wire modeling and optimization framework for grid-integrated wave energy conversion.	Improved power conversion efficiency, enhanced dynamic performance, and better grid compatibility.	Validation was limited to simulation without real-world experimental testing.	Future work should focus on real-time implementation and intelligent MPPT techniques for practical marine environments.
[2]	Double Deep Reinforcement Learning Twin-Delayed (TD3) control algorithm.	Increased power extraction, improved system stability, and adaptive control under varying sea conditions.	High computational complexity and extensive training requirements.	Lightweight reinforcement learning algorithms should be developed for real-time deployment.
[3]	Integrated hydrodynamic numerical model for BBDB Oscillating Water Column (OWC) converter.	Accurate prediction of wave energy converter performance under different wave conditions.	Lack of large-scale experimental validation.	Future research should integrate intelligent controllers with experimental validation.
[4]	Battery energy management with coordinated control architecture.	Improved energy utilization and stable power supply in stand-alone wave energy systems.	Grid-connected operation was not considered.	Future studies should investigate grid-connected operation with adaptive

				energy management.
[5]	Coordinated battery energy management and power control strategy.	Enhanced energy storage utilization and operational stability.	Battery degradation and long-term performance were not analyzed.	Future work should include battery health monitoring and lifetime optimization.
[6]	BFO-PI controller with Modified SEPIC converter.	Improved voltage regulation, maximum power extraction, and converter efficiency.	Limited to wind energy applications only.	The controller can be extended to hybrid renewable energy and tidal energy systems.
[7]	SASNPAA intelligent controller for an SPV-fed EV battery charger.	Reduced harmonics, faster charging response, and improved grid stability.	Performance under highly fluctuating renewable sources was not fully investigated.	Future work should consider uncertainty-aware and adaptive control methods.
[8]	MPPT-based hybrid wind–solar energy system using MATLAB/Simulink.	Improved renewable energy harvesting and stable grid integration.	Hardware implementation was not performed.	Experimental prototype validation and advanced MPPT algorithms are needed.
[9]	Review of offshore hybrid renewable energy technologies.	Identified benefits of integrating offshore wind, wave, and tidal energy systems.	Limited quantitative comparison of intelligent optimization techniques.	Comparative studies on AI-based optimization methods are required.
[10]	RF-based SOC estimation with an	Improved charging efficiency, battery management, and	Large-scale EV charging network	Future research should

	optimal control strategy.	seamless mode transition.	integration was not evaluated.	address coordinated control for large-scale smart charging infrastructure.
[11]	Fractional-order backstepping sliding mode control for grid-connected PV systems.	Improved voltage regulation, reduced tracking error, and enhanced disturbance rejection.	High computational complexity limits practical implementation.	Develop simplified intelligent controllers for real-time renewable energy applications.
[12]	Optimized Fractional-Order PID (FOPID) controller for hybrid wind–solar–battery systems.	Improved dynamic response, power sharing, and grid stability.	Performance validated only through simulation.	Hardware implementation and real-time validation are required.
[13]	High-gain Y-source DC–DC converter with switched-inductor-capacitor topology.	Increased voltage gain, improved efficiency, and enhanced converter reliability.	Evaluated only for photovoltaic systems.	Extend the converter for hybrid and marine renewable energy systems.

5. CONCLUSION AND FUTURE RESEARCH

In this paper, the principal features of the grid-tied tidal energy generation systems and analyzed the history of maximum power point tracking (MPPT) technologies. Traditional techniques used for MPPT include Tip Speed Ratio (TSR), Optimal Torque Control (OTC), and Hill Climbing Search (HCS), which are uncomplicated and well implemented to tackle a certain problem, but they have significant drawbacks, including slow system convergence, cyclical nature of operation at steady-state, and low effectiveness in dynamic tidal environments. However, the enhancement of intelligent optimization technologies, including Grey Wolf Optimization (GWO), Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Artificial Neural Networks (ANN), Fuzzy Logic Control (FLC), Adaptive Neuro-Fuzzy Inference Systems (ANFIS), and Reinforcement Learning (RL), has made tracking operations more exact, improved efficiency of energy extraction, and let the overall stability of the system increase. The future research should focus on hybrid lightweight optimization algorithms, real-time hardware tests, the digital twin concept, edge intelligence, cyber security of control structures, and other advanced strategies, which would ensure the efficient and reliable functioning of the grid-tied tidal energy conversion systems on a large scale.

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