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Review

Advancement of Tidal Current Generation Technology in Recent Years: A Review

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Abstract: Renewable energy provides an effective solution to the problem existing between energy and environmental protection. Tidal energy has great potential as a form of renewable energy. Tidal current generation (TCG) technology is the earliest renewable energy power generation technology. The advancement of science and technology has led to TCG rapidly developing since its emergence in the last century. This paper investigates the development of TCG in recent years based on the key components of TCG systems, both in terms of tidal energy harvesting research and power generation unit research. A summary of tidal energy harvesting is presented, investigating the main tidal energy harvesting units currently available. In addition, research on generators and generator control is summarized. Lastly, a comparison between horizontal and vertical axis turbines is carried out, and predictions are made about the future trends in TCG development. The purpose of this review is to summarize the research status and research methods of key components in tidal energy power generation technology and to provide insight into the research of tidal energy-related technologies.

Keywords: tidal current generation; renewable energy; tidal energy collection; power generation

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1. Introduction

Energy production that can meet society's energy demand is a key concern for mankind. With the rapid development of technology, energy demand has also increased significantly. However, fossil fuels have continued to be the most used energy source [1]. Renewable energy is being studied around the world in order to reduce carbon dioxide emissions and other environmental pollution caused by traditional energy sources [2–8].

As shown in Figure 1, the proportion of renewable energy sources will gradually increase in the future. The optimal use of renewable energy sources is a key factor in achieving environmental protection and sustainability in future energy systems [9,10]. As a renewable energy source, tidal energy has considerable potential as a form of ocean energy [3]. There are two main types of tidal energy, the potential energy of the water level generated by high and low tides and the kinetic energy carried by ocean currents. Substantial research has been conducted in this field by scholars around the world and many developments have been achieved in various countries [11–17].

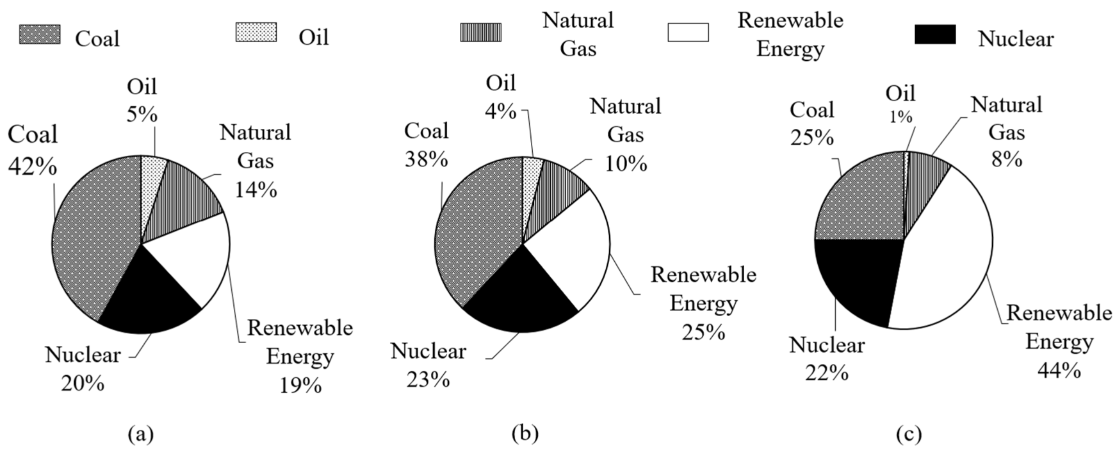


Figure 1. World primary electricity generation statistics chart (**a**) World primary energy for electricity generation 2010 (**b**) World primary energy for electricity generation 2017 (**c**) IEA Policy Statement 2040 [18].

In particular, there are two parts that have been extensively studied in the field of tidal energy. The first part is tidal energy collection, which covers how to collect tidal energy through mechanical equipment such as turbines. For tidal energy collection, research has been carried out on the mechanical structure, optimization of blades, and other tidal energy collection devices. The other part is power generation unit design, where the conversion of mechanical energy into electrical energy through the generator has been studied. The efficiency of power generation is variable so the design of the generator and the control of the power generation have become the focus of research [19–23].

The purpose of this paper is to investigate the current state of the TCG field, to understand the progress of research in various aspects of the TCG field and to identify which issues have been the subject of more in-depth research. There are two parts to the paper. The first part describes the classification of tidal energy collection devices. The recent research results are summarized from the perspective of different types of devices. The second part summarizes the research results of power generation units, summarizes the types of generators currently used, and analyzes the control technology of the power generation system. Finally, the development status of the TCG field and its prospects are analyzed. This paper provides a valuable reference for the design and use of TCG systems in the future.

2. Tidal Energy Harvesting

Tidal energy is converted into mechanical energy for power generation through a collection device, which is the first stage of TCG. Tidal energy collection devices can be divided into vertical-axis tidal current turbines (VATCT), horizontal-axis tidal current turbines (HATCT), and other collection devices. The mechanical structure of the collecting device affects the efficiency of tidal energy collection. Therefore, much research has been conducted on the structures of these collecting devices in order to maximize their efficiency.

2.1. Study of HATCT

Compared with VATCT, HATCT has longer development history and more established technology. As a result, HATCT is widely used in TCG systems [24]. An example of a HATCT is the 1.5 MW tidal stream turbine named Atlantis AR1500 shown in Figure 2. Turbine performance and turbine arrays are currently hot topics in the HATCT field.

Figure 2. Atlantis AR1500 turbine [25].

2.1.1. HATCT Performance Study

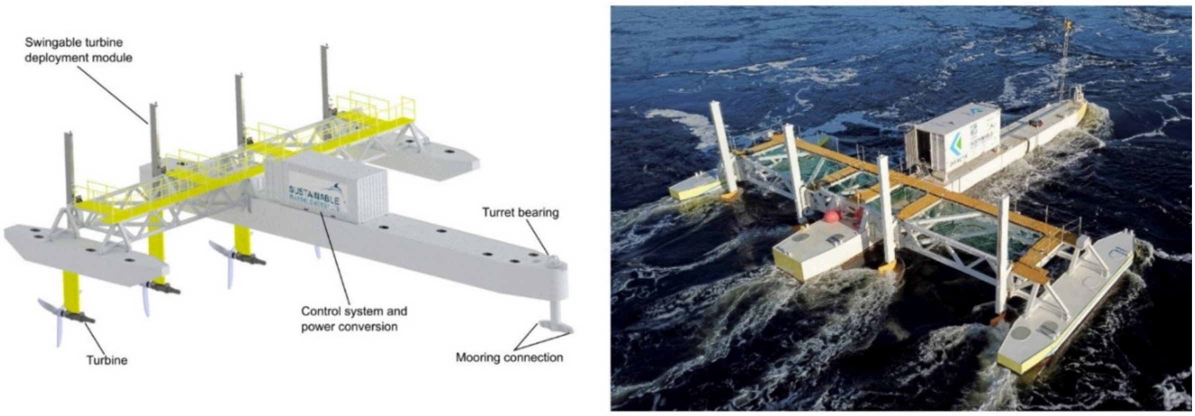
The blades are a particularly critical part of the turbine. The hydrodynamic performance of the blades directly affects the hydrodynamic performance of the turbine and therefore turbine research is focused on the blades [26–29]. For the dynamic analysis of the blades, blade element momentum theory (BEMT) is currently used [30–32]. The blade is divided into infinitely thin blade elements along the radius direction, known as the blade element, when the flows through the blade element, the pressure difference on the surface of the blade element forms the momentum change in the airflow in and out of the blade element, thus the whole blade analyzes dynamic performance. In this regard, Yeo et al. proposed and verified a higher accuracy version of BEMT, where the power coefficient and thrust coefficient of the algorithm were 0.99828 and 0.99488, respectively [32]. CFD/BEMT is the addition of computational fluid dynamics (CFD) to BEMT for more accurate modeling of blade and seawater interactions. Ortega et al. made a study for the CFD/BEMT blade calculation model and compared it with BEMT. The results provided a CFD/BEMT simulation that shows the effects of turbulence, which is particularly important for assessing additional stress sources in the overall mechatronic system [30]. A BEMT-based neural network model was devised by Zhu et al. The neural network model was developed to apply a multi-objective optimization algorithm to the hydraulic performance of a tidal turbine to improve the energy harvest efficiency of the blades in a variable flow range, resulting in a 2% increase in the turbine power factor at maximum [28]. An improved method for blade design based on a multi-objective genetic algorithm has been proposed by Liu et al. An equivalent S-N curve model and a simplified load spectrum have also been presented. With this improved blade design method, the relationship between blade life and output power can be determined more easily and quickly [33].

In addition to the blade performance algorithm studies, there are also studies on other turbine parameters [34–37]. Alipour et al. studied the effects of curvature, thickness, and pitch angle on turbine performance and determined the conditions for maximum blade performance considering the probability of the presence of fatigue loads. There have also been studies to determine the blade number for optimal turbine performance, and studies to determine the optimal design for turbine blades using blade element momentum theory. The results show that the optimum leaf tip speed ratio is five and that a larger number of blades should be used when it is less than the optimum leaf tip speed ratio while a smaller number of blades should be used when it is greater than the optimum leaf tip speed ratio [38,39]. Ha et al. investigated the effects of starting flow turbulence characteristics, and wave and blade pitch angles, which in turn determined the distribution of chord length and pitch angle. In addition, there are many studies on the performance patterns of turbines in terms of different parameters, which guide the design of the turbine blades [40–46].

For the current turbine designs, the high capital and maintenance costs required to operate them in the harsh subsea environment limit their commercial viability. The reliability and durability of HATCTs are critical issues, as once the equipment is deployed the cost of recovery and maintenance is high [47,48]. Because the blades are a critical component with high failure rates, improving the robustness of the blades through material selection and appropriate geometric design is very much in focus. A design methodology was established by Gonabadi et al. for the preliminary evaluation of tidal turbine structures using low-cost composite materials [49]. These composite blades have undergone many experimental studies, comparing them with traditional materials, verifying the advantages and shortcomings of composite materials, and predicting the development prospects of composite blades [27,49,50].

2.1.2. HATCT Array Research

Energy harvesting efficiency is an important factor in power generation efficiency and for this reason, many scholars have conducted research into improving power generation efficiency [51]. The amount of energy that can be collected by a single turbine is very limited, but multiple turbines can increase the efficiency of tidal energy collection so multiple turbine arrays may be an efficient option [52,53]. As a result, studies have been conducted on turbine arrays [54–60]. Figure 3 shows an experiment on a power generation platform using a turbine array technology, named PLAT-I, which is an example of a HATCT array. Many companies producing tidal generators are now introducing multi-rotor power generation platforms. A multi-rotor power generation system is a use of turbine array technology, where multiple horizontal axis turbines are combined to obtain a larger amount of power. In addition, a large combination of turbine arrays can be used for large-scale power generation. As research into renewable energy sources intensifies, more tidal power stations using turbine array technology will be built as larger-scale power generation platforms [16].



(a) (b)

Figure 3. Example of a turbine array (**a**) CAD-model of the tidal energy converter system PLAT-I (**b**) Full-scale tests in Western Scotland, UK [56].

In a HATCT array arrangement where turbines are not only arrayed side by side but also front to back, the wake from turbines located upstream will have a non-negligible effect on the tidal flow downstream [61]. Therefore, turbine wakes have become a hot topic in recent years. Hill et al. conducted experiments on wake flow based on a two-rotor turbine system and showed that the turbine wake would increase the turbulence level in the downstream tidal flow and reduce the available efficiency of the tidal flow [62]. The relationship between the parameters of the wake and the turbine system has been studied to determine how the effects of the wake can be modified [63]. In recent years, HATCT arrays have been extensively studied as an effective way of increasing power generation. The turbine wake is a key factor in this, and research has focused on the factors that affect the variability of the wake.

HATCTs are currently the most commonly used tidal energy harvesting device in the world. With the spread of CAE technology, the optimal design of HATCTs has been extensively investigated in a number of ways. The hydrodynamic performance of the turbines has been studied through calculation methods, geometrical parameters and material usage. Furthermore, turbine arrays have become a promising research area that is currently focusing on mainly turbine wake variations. In the future, turbine arrays will become increasingly more sophisticated and will be important for the establishment of large-scale power stations.

2.2. Study of VATCT

A VATCT is a type of tidal turbine that harvests tidal energy by rotating its blades around a vertical axis, which allows it to harvest tidal energy in multiple directions [57,64]. A HATCT has horizontal rotational movement, which is subject to high fatigue losses caused by gravity, whereas a VATCT is able to avoid blade fatigue losses caused by gravity [58]. However, due to the complexity of its blade motion, BEMT does not apply to the blade calculation analysis of vertical axis turbines. As a result, VATCT is less studied and less developed. Almost no commercial TCT systems using VATCT have emerged. The research focus for VATCTs is similar to that of HATCTs, mainly in blade performance studies and turbine array studies.

The hydrodynamic performance of the blades is key to the energy harvesting efficiency of the VATCT and therefore the optimal design of the blades has been studied by many scholars [59,65,66]. The hydrodynamic performance of a vertical axis twin rotor turbine in surge motion is discussed in depth by Wang et al. A two-rotor turbine operating at different surge frequencies, surge amplitudes, and tip speed ratios have been simulated and the variation characteristics of the thrust, lateral forces, and flow fields have been analyzed [59]. In addition, there are various factors such as rotor height to diameter ratio, chord length, blade design, number of blades, and free flow tidal velocity for spiral blade performance have been studied. These studies provide a reference value for the optimal design of turbines [67–71].

Due to the special motion of VATCT, the wake effect generated by the turbine array becomes an important issue to be addressed. The wake effect can lead to reduced power production and increased structural fatigue in downstream turbines. Based on field measurements, the power of the TCG system can be reduced by 10 to 25% due to the wake effect. Close prediction and assessment of wake effects are therefore imperative to improve the efficiency of tidal power generation and to mitigate the risk of fatigue in the VATCT [72,73]. In recent years, computational fluid dynamics (CFD) has been widely used for wake prediction by simulating turbine outflow field and wake flow [74,75]. Ma et al. established a numerical simulation method based on CFD to systematically analyze the turbine load conditions and the power output efficiency of a turbine under the action of wave-induced motion. They then went on to discuss in depth the hydrodynamic performance of vertical axis twin rotor turbines during surge motion, analyzing twin rotor turbines operating at different surge frequencies, surge amplitudes, and tip speed ratios. The results show that the average power output of the twin-rotor turbine can be increased by 15.3% compared to a single turbine. The oscillation caused by the surge increases the turbine load and power output fluctuations but does not change the average turbine load and power output [76–78]. A visit array-based non-constant boundary element model was studied by Li, G.N. et al. Hydrodynamic interference phenomena in tidal turbine arrays were investigated via a hydrodynamic performance prediction procedure. As a result, the turbines are arranged at an angle, as shown in Figure 4. In the interval ψ = 90°~30°, the turbine power coefficient decreases slowly from the maximum value, and in the interval ψ = 30°~0°, the turbine array power coefficient decreases rapidly to the minimum value. Therefore, in the arrangement of the turbine array, the angle between the axis of the twin turbines and the direction of air intake should be avoided as much as possible, ψ = −30°~30° [79]. Two equations for predicting turbine wake flow have been proposed by Ma et al. The first equation for predicting efflux velocity (Efflux velocity is the minimum velocity closest to the turbine downstream) was derived based on axial momentum theory and dimensional analysis. The second equation used to predict the lateral velocity distribution is derived based on a Gaussian probability distribution [80]. Muller et al. used acoustic Doppler velocimetry to characterize the three-dimensional wake developed downstream of independent and dual vertical axis turbines with different combinations of inter-axis distance and rotation directions based on mean velocity and turbulence statistics and quantified their effect on momentum recovery [81]. Some scholars have introduced new algorithms based on CFD to simulate and analyze the flow field of turbine arrays. The Kutta algorithm has been introduced by some scholars for the analysis of turbine wake flows to make the results more accurate [82,83]. Studies made on turbine arrays have deepened the understanding of multi-turbine interactions and have provided a reference value for vertical axis turbine arrays [62,83–86].

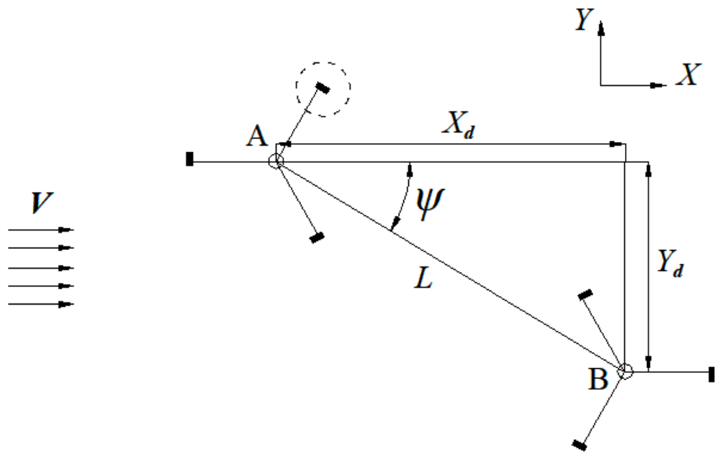


Figure 4. Turbine layout diagram [79].

VATCTs have many advantages over HATCTs. Because of its vertical axis rotation, it can collect tidal flow in multiple directions, and its energy harvesting efficiency is higher than that of a HATCT. However, due to their difficult design, VATCTs are less developed and far less popular than HATCTs. As a result, most companies launch tidal power platforms with HATCTs instead of VATCTs. In the future, as the degree of VATCT development increases and the design costs decrease, VATCTs will increasingly appear in TCG systems.

2.3. Special Tidal Energy Harvesting Device

Turbines are widely used in TCG, but there are also devices with different designs. These special collection devices can be divided into new turbines based on traditional turbine designs and collection devices with different working principles.

For new turbines based on traditional turbine designs, blade rotation is the main way to collect tidal energy. Counter-rotating horizontal-axis tidal turbines (CRHATT) have been investigated by Cao et al. The principle of the CRHATT is to add a set of counter-rotating blades to a conventional turbine to increase energy harvesting efficiency [87]. Cao et al. investigated in detail the effect of key parameters on the energy harvesting efficiency of the CRHATT and verified the reliability of the CRHATT design [88]. Tidal currents are roughly bi-directional at low and high tides. A horizontal axial tidal turbine (HATT) with a unidirectional foil must be able to face the current direction in order to maximize the collection of current energy. A bi-directional blade turbine that can harvest tidal energy in both directions was designed by Guo et al. Its hydrodynamics were analyzed and compared with that of a conventional turbine [89]. Some scholars have studied tethered undersea kites (TUSK). As shown in Figure 5, a TUSK is similar to a kite. It is connected to a submarine foundation and has wings and a rudder and is equipped with axial turbines that can be directionally controlled to increase the efficiency of power generation [88,90]. Ducted turbines (DC) and shaftless ducted turbines (SDT) are also new tidal turbines that have recently emerged and have an additional duct compared to conventional paddle turbines. The duct makes use of the Venturi effect, where a restricted flow appears to increase in velocity as it passes through a reduced cross-section, the velocity of which is inversely proportional to the cross-section. The efficiency of tidal energy harvesting can be increased by controlling the tide. The SDT is similar to the DT but has no shaft, which reduces the effect on the flow field and improves the performance of the turbine by avoiding fatigue damage caused by the shaft. The 500 kW rated SDT at the Paimpol Bréhal site in Northern France is shown in Figure 6. The detailed hydrodynamic-energy losses of DT and SDT were compared by Song et al. using CFD methods and the results showed that SDT has higher power levels at low tip-to-velocity ratios (TSR) with reduced potential flow resistance and disturbance relative to DT [91]. Additionally, DT and SDT have been studied by many scholars [92–98]. These new turbines, based on conventional turbine designs, have many advantages but are currently less researched and less developed. In the future, as the technology of these new turbines develops further, they will replace conventional turbines for TCG.

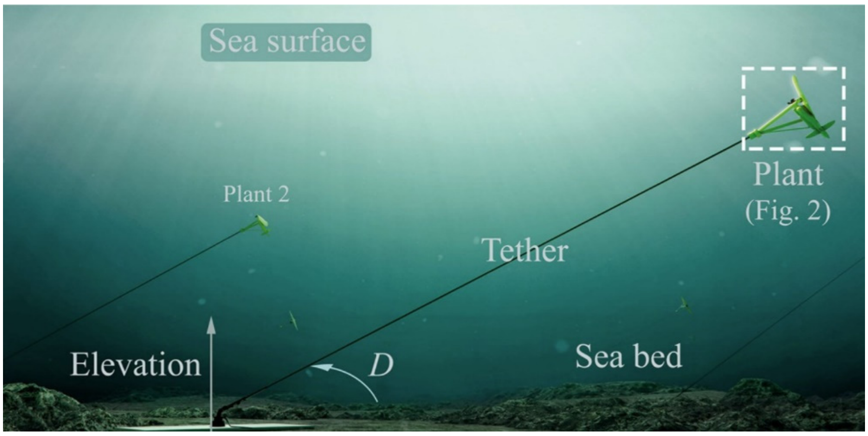


Figure 5. Diagram of the TUSK [90].

Figure 6. The use of SDT in reality [99].

In addition, there are many other collection devices that have different working principles from turbines. Ma et al. used fluttering wings to extract tidal energy and proposed a biplane coupled hydraulic system to achieve self-sustained oscillatory motion of the airfoil. It has obvious advantages in shallow waters [100,101]. Under current conditions, almost all commercial TCG systems use turbines to harvest tidal energy. Although some other types of TCG exist, they cannot be used on a large scale due to a variety of problems. For example, the fluttering wings unit is suitable for areas with shallow water depths but is less powerful than the turbine in conventional waters.

3. Power Generation unit Study

The power generation unit is the core of the TCG system. Its main role is to convert mechanical energy into electrical energy and store it. The main parts of a power generation unit are the generator, controller, and transformer. The turbine collects tidal energy and converts it into mechanical energy, and the generator converts the mechanical energy into electrical energy. The energy is then converted into a current by a converter, the transformer changes the voltage, and finally, it flows into the grid to collect electricity. This process is accompanied by a controller to control the efficiency of the generated electricity. Generator optimization design and power control are the focus of this field.

3.1. Design of Power Generator

The choice of generator is a factor to be considered when designing a tidal power system. Currently, there are two types. One is an asynchronous generator and the other is a synchronous generator.

Asynchronous generators are simple, robust, and particularly suitable for high circumferential speed motors. They have high reliability due to the absence of collector rings and carbon brushes, regardless of the place of use. The absence of a rotor excitation field eliminates the need for synchronization and voltage regulation devices and simplifies the required power station equipment. The two main types of asynchronous generators currently used are the squirrel cage induction generator (SCIG) and the wound rotor induction generator (WRIG). Figure 7 shows a TCG system based on SCIG [101,102] consisting of a turbine, gearbox, SCIG, and transformer.

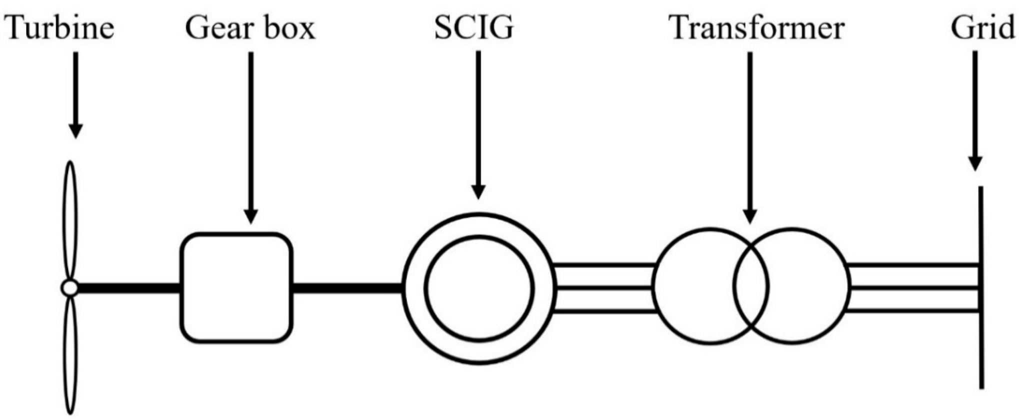


Figure 7. SCIG-based TCG system.

Figure 8 shows a WRIG-based TCG system consisting of a turbine, gearbox, WRIG, back-to-back bi-directional converter, control system, and transformer [103]. The generator used in this system has a variable speed and a constant frequency. When the rotor speed is less than the synchronous speed, the rotor absorbs power from the grid to provide rotor excitation [104]. A comparative study of the different modes of operation of doubly fed induction generators and permanent magnet synchronous generators on tidal turbines was carried out by Sur et al. [105].

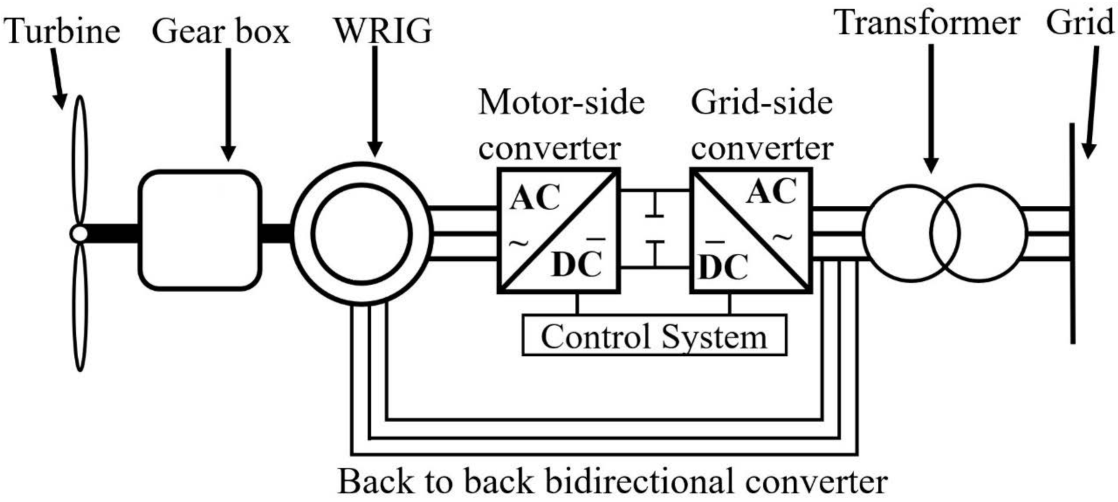


Figure 8. WRIG-based TCG system.

Synchronous generators, which require an external excitation current, have the same stator speed and the same magnetic field speed. Among the available synchronous generators, permanent magnet synchronous generators (PMSG) are the most widely used [106]. Figure 9 shows a TCG system based on a PMSG. The PMSG replaces excitation by excitation winding with permanent magnet excitation, (excitation: the device that provides the generator with an operating magnetic field) resulting in a simpler motor structure, lower machining and assembly costs, and the elimination of problematic collector rings and brushes, increasing the reliability of motor operation. As no excitation current is required, there are no excitation losses, which improves the efficiency of the motor. Not requiring an excitation current also increases the efficiency and power density of the motor. PMSG has been studied by many scholars during the period of 2018 to 2022. A linear rotating motion permanent magnet generator capable of meeting the requirements of wave and tidal energy generation has been designed by Guo et al. [107] A permanent magnet generator design has been proposed by Touimi et al. and an analysis of the cost-effectiveness of the system has been made [22]. Zhang et al. proposed an optimized design method for double-stator PMSG [108].

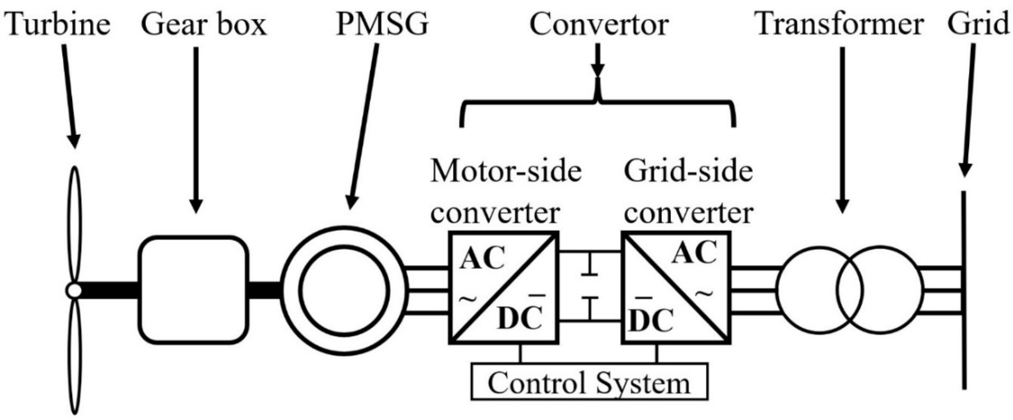


Figure 9. PMSG-based tidal TCG system.

With the development of science and technology, some new technologies have also been applied to power generation. Nanogenerators are one of the emerging technologies that have been applied in energy harvesting and new sensors due to their high sensitivity and flexible structure. The principle of friction nanogenerators uses nylon and PTFE, which gather electrons when they come into contact and generate electricity through relative friction. Shen et al. provided an overview of the current environment of friction nanogenerators from various perspectives and provide an outlook for the future. They have greater advantages in low-frequency (<5 Hz) environments and have greater potential for remote sea deployment and large-scale nanogenerator network construction [109]. Yang et al. designed a fully packaged water wheel-like rolling friction-electrical-electromagnetic hybrid nanogenerator. A fully packaged rolling frictional electro-electromagnetic hybrid nanogenerator of the waterwheel type can be utilized in harsh environments (e.g., underwater) to convert mechanical energy into electrical energy to power electrical equipment [110]. In addition, a disc generator for ocean wave energy harvesting, coaxial to the magnetic gear, was designed by Dobzhansky. et al., who investigated its performance characteristics. The permanent magnets of both the generator and the MG are arranged in a special way to improve the overall performance of the system [111]. Zhao, H. designed a new double modulator magneto-gear machine for TCG, which has the advantage of high torque output at low speeds [112]. A novel magnetically geared tubular linear motor for tidal and wave energy conversion has been designed by Ho et al. Compared to existing products of this type, this machine has a higher force density due to its transmission effect, resulting in a simpler mechanical structure [113].

Comparing the different generators, synchronous generators and asynchronous generators are now the mainstay. Synchronous generators are more efficient but complex, expensive and relatively difficult to maintain, while asynchronous generators are less efficient, but easier to install and use, and are cheaper. Asynchronous generators are advantageous for small installations or where tidal currents are constant and stable, but real tidal currents are highly unstable, and the scale of generation is generally large in order to increase the capacity of the power platform. Therefore, synchronous generators are the better choice.

3.2. Power Generation Control

Due to the random nature of the tides, their speed is variable. The power of the generator varies dynamically on a curve. This requires control of the variables associated with energy handling. In recent years, maximum power point tracking (MPPT) of TCG systems has become a popular research topic [114–117]. There are three types of MPPT methods, the first being the tip speed ratio (TSR), another being the perturbation and observation (PO) and the last being the power signal feedback (PSF)/optimum torque (OT) method [118].

The proportional–integral (PI) controller is widely used in TCG systems [119]. As a linear controller, the PI regulator controls an object by linearly combining the proportional and integral deviations of the given value with the actual output value to form a control deviation [120–124]. (Figure 10 shows the working principle of the PI controller).

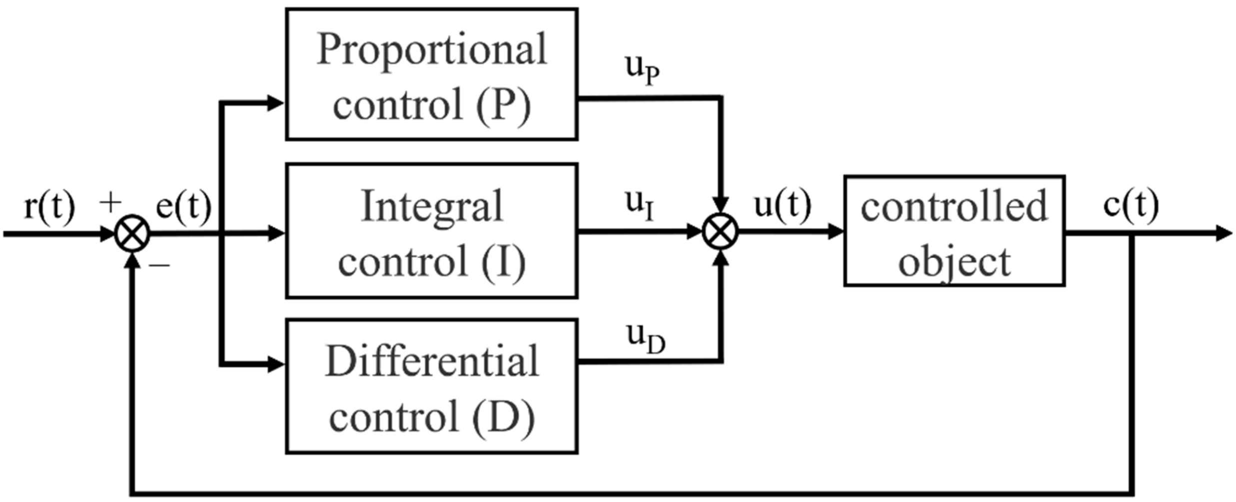


Figure 10. PI controller working diagram.

A reactive voltage control strategy for wind farms that takes into account reactive power adequacy and end voltage balance was proposed by Dai et al. The reduction in terminal voltage difference is approximately 2.8% and the reduction in active power losses in wind farms under disturbing conditions such as load is approximately 7.8% [125]. Toumi et al. proposed a robust variable step size perturbation observation algorithm. It improves the quality of the extracted power by 0.88%, 1.78% and 3.82% over SS-P&O, LS-P&O and VS-P&O, respectively [126]. Dong et al. studied the simple power controller of a horizontal axis-independent power flow generation system. The MPPT controller provides a simple and practical method for maximum power control of independent tidal flow energy conversion systems [127]. Zhu et al. proposed a power smoothing control strategy based on kinetic energy for permanent magnet synchronous generators in wind power conversion systems. The output power efficiency of the power smoothing method is lower than that of the maximum power control. The effectiveness of rotor kinetic energy control was verified [128]. Nguyen et al. proposed a robust control method for permanent magnet synchronous generators based on error symbols. When we use the proposed controller, the power coefficient value is almost kept at its maximum value, which is better than the PID controller [129].

Current research on controlling power generation systems has seen scholars investigate control systems from various perspectives, with some making optimized designs based on MPPT and analyzing the impact of new algorithms on power. Some scholars have made studies from the perspective of controllers, analyzing the impact of different controllers on the efficiency of power generation. Others have designed control methods for power generation systems based on other parameters. Nowadays, CAE technology is very popular and power studies of power generation systems are widely carried out. In the future, the power of power generation systems will be studied more intensively and the algorithms for power will be more accurate.

4. Summary and Analysis of Future Trend

Due to the effects of climate change, people have started to think about how to save energy and reduce emissions, and in order to reduce dependence on fossil fuels, researchers and energy companies in various countries are focusing on renewable and clean energy [130]. As one of the renewable clean energy sources, tidal energy is a predictable energy source that depends on the gravitational force of the Moon and the Sun and the centrifugal force generated by the rotation of the Earth-Moon system. The oceans cover 70% of the Earth's surface area, so the total amount of tidal energy is enormous. As a result, the potential for tidal energy is huge, and in the future, tidal energy will become one of the world's major forms of power generation. Over the years, the field of tidal energy has gained considerable ground, with many large tidal power stations having been built around the world, and many companies involved in TCG having emerged around the world.

Turbine and PMSG are widely used in the field of TCG and are the focal points of research in recent years. As the most ideal energy harvesting device at present, the high capital and maintenance costs required to operate turbines in harsh seabed environments currently limit their commercial feasibility [131]. Efficient power generation and low maintenance are the design goals of turbines. The durability, robustness, and energy collection efficiency of turbines are the main performance indicators. A comparison between HATCT and VATCT is shown in Figure 11. HATCT has been in development for a long time and the technology is more complete. VATCT has many advantages over the horizontal axis turbine, but due to the lower amount of research and shorter time in development, few VATCTs are currently in commercial use. The HATCT has a simple structure, and the pouches are analyzed using the BEMT, making it less difficult to design, while the VATCT has more complex movements and is more difficult to design. Therefore, the HATCT has developed for longer and faster than VATCT, which is the main reason why the VATCT is used less frequently. The HATCT is subject to gravity, its load profile is variable, and its fatigue strength is poor, while the VATCT has a constant load and good fatigue strength, and the power unit can be installed on the surface, so it costs less money to install and maintain. As tidal power is similar to wind power, this paper makes reference to wind turbines for the comparison of the two types of turbines [29]. Unlike wind power, the load from gravity is reduced in the ocean due to buoyancy and the movement direction of the tide is not as variable as wind. These advantages are combined with the low design difficulty and established development of horizontal axis turbines, which makes the advantages of VATCT over HATCT not as obvious. Although VATCTs have many advantages, they are still not widely used.

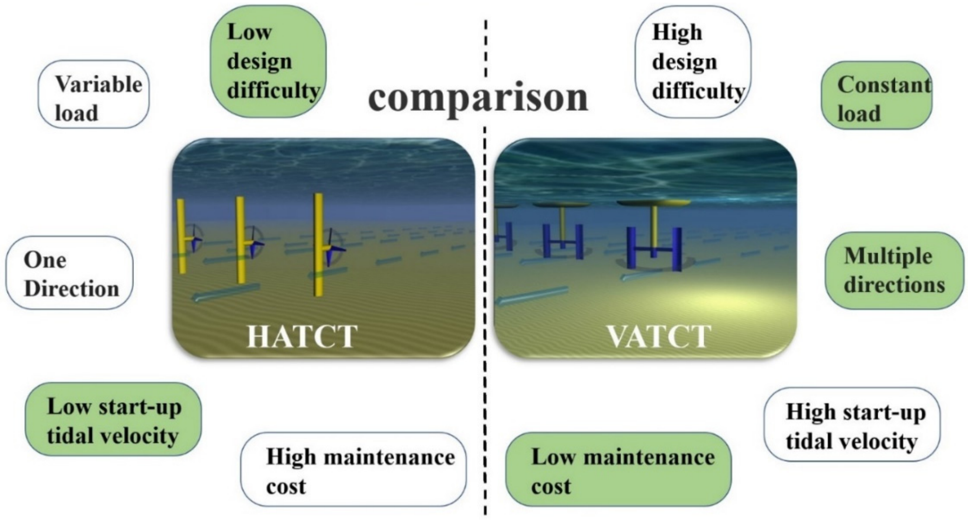


Figure 11. The comparison of HATCT and VATCT.

Turbine arrays are a hot topic for both VATCT and HATCT. Multiple turbine arrays can greatly increase the efficiency of tidal power generation, but the impact of the turbines on each other cannot be ignored. The wake generated by the turbines affects the state of the flow field around them and therefore the efficiency of the entire array, so the layout to maximize the efficiency of the power generation has become a focal point. Many of the current commercial tidal power platforms use a two-rotor design. Large-scale turbine arrays are also required for larger power stations. The use of tidal energy is increasing, and more large-scale power stations are being built, so the study of turbine arrays is necessary. Ouro et al. experimented with arrays of two types of turbines. Three sites were selected, in which the HATCT array and VATCT array were set up, respectively, and the arrays were tested for power generation. The results showed that the HATCT achieved an average power of 49.3 W m^{-2} and the VATCT array averaged 34.7 W m^{-2} across the three sites. The HATCT array had higher power density when the tidal flow velocity was high, and the VATCT had higher power density when the flow velocity was low. This is mainly because HATCT has higher energy harvesting efficiency than VATCT when the tidal flow velocity is high. Although the energy collected by the VATCT is not limited to one direction, in a real site, the peak of tidal energy is at high tide and low tide, and there is less energy at normal times [132].

In the future, as research into VATCT intensifies, the performance of VATCT will be further improved, design costs will be reduced, and the use of VATCT in tidal power turbines will rise. However, HATCT technology is also advancing with the emergence of new horizontal axis turbines such as the DT and SDT, which are also improving in performance. Therefore, this paper infers that vertical-axis turbines will not completely replace horizontal-axis turbines.

As the core of a power generation system, PMSG is widely used in TCG due to its high efficiency and high torque. The efficiency of permanent magnet synchronous generators can be improved by optimizing the design of the generator itself by starting with the components of the generator, such as by optimizing the permanent magnet material, designing new rotor structures, or researching more efficient mechanical structures such as gearboxes. Control techniques that combine power converters to optimize the power generation system, such as MPPT, can also improve MPSG efficiency. There are two main types of MPPT. The first is the optimal characteristic curve method, which includes the blade tip speed ratio method and the optimal torque (OT) method. The other method is the hill climbing algorithm, which may not give the best results because it is not a comprehensive search. Researchers generally propose a new fuzzy control MPPT algorithm, use data analysis and simulation software, and compare the results with conventional MPPT methods to conclude.

The future trends in TCG are focused on several areas. The first is in tidal energy harvesting, focusing mainly on the hydrodynamic performance of turbines and array research. HATCT and VATCT are the two research directions. In addition to the traditional turbines, new turbines, such as DT and SDT turbines, have emerged for horizontal axis tidal turbines, while VATCT has also been gaining ground in recent years. Secondly, in the area of power generation, the use of permanent magnet synchronous generators in tidal power systems will become more widespread in the future. Future research will focus on optimizing the design of generators and the control technology innovation of the power generation system, thus driving the efficiency of power generation. Thirdly, tidal power stations will become more popular around the world. Today's renewable energy generation technologies are developing rapidly, but the current total amount of tidal energy generation is relatively small. The small number and scale of power stations are one of the key reasons why. However, as the number of tidal power stations rises around the world, tidal power generation is also set for a huge breakthrough.

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