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Review

Cutting-edge progress in offshore wind and tidal stream power technology—State-of-the-Art

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Abstract: The growing global demand for clean and sustainable energy has underscored the critical importance of offshore wind and tidal stream power technologies in addressing energy and environmental challenges. While these technologies hold significant potential to harness marine energy resources, gaps remain in understanding their readiness levels, integration potential, and pathways to overcome existing barriers. This study aims to bridge these gaps by providing a comprehensive review of the latest advancements in offshore wind and tidal stream power systems, focusing on innovations in turbine design, materials, and hybrid systems that combine wind and tidal energy. The methodology involves an extensive review and synthesis of recent research, project reports, and industry developments to evaluate the current technological state, challenges, and opportunities. Key findings include notable progress in turbine efficiency and hybrid system integration, which collectively improve energy conversion efficiency, scalability, and reliability. However, the study identifies persistent barriers such as high costs, environmental impact, and competition with more established renewable energy sources like solar and onshore wind. This paper emphasizes the importance of hybrid systems as a transformative approach to maximizing marine resource utilization and enhancing energy supply stability. The findings have significant implications for guiding future research, fostering innovation, and informing investment strategies in the marine renewable energy sector.

Keywords: hybrid wind-tidal energy systems; marine renewable energy; voltage source converter (VSC); tidal power integration

1. Introduction

The growing demand for electricity and the urgent need to reduce carbon emissions have intensified global efforts to develop renewable energy sources. Offshore energy systems, including wind, ocean currents, and wave energy, are key contributors to these efforts [1]. Offshore wind energy, for example, demonstrates 48% greater sustainability than onshore wind, according to life cycle analysis (LCA) [2]. However, the high cost of electricity from offshore wind remains a major obstacle to widespread adoption [3]. Ocean renewable energy (ORE) technologies, such as wave energy, tidal stream energy, and ocean flow energy, are gaining attention as viable additions to the renewable energy mix [4]. Emerging technologies such as salinity gradient engines and ocean thermal energy conversion (OTEC) also show promise [5]. Tidal energy stands out for its predictability and significant potential, with an estimated global capacity of 3000 GW, including 1000 GW in shallow waters. By 2021, Europe had installed 30.2 MW of tidal stream systems, indicating growing feasibility and scalability [6].

Although less advanced than offshore wind or wave energy, tidal stream systems have the potential to produce around 20 TWh per year [7]. Nevertheless, tidal stream and offshore wind systems have not yet reached full economic viability. At £140/MWh for offshore wind and £305/MWh for tidal stream energy, electricity strike costs are still expensive [8]. The UK, with its vast tidal energy resources, could generate over 4 TWh annually using current technology, with future projections reaching 94 TWh per year and an installed capacity of 36 GW [9,10].

Ocean energy (OE), or “Blue Energy”, encompasses power derived from waves, currents, thermal gradients, and salinity gradients [11]. Among these, offshore wind energy is the most advanced and commercially viable. It is considered the most promising marine renewable energy (MRE) category for large-scale maritime applications. Tidal current energy converters (TCECs), including horizontal-axis turbines, vertical-axis turbines, and oscillating hydrofoils, have seen advancements in blade design, control strategies, array configurations, and environmental impact studies [7,12].

The technology readiness level (TRL) of tidal energy has progressed from laboratory-scale development to the pre-commercial stage [13]. Offshore energy systems include current turbines, wave energy converters, tidal stream generators, and offshore wind turbines, with tidal stream energy being more predictable due to less variability over extended periods. These systems are crucial for maritime electrification and military operations, though research has often focused on specific applications rather than holistic integration [14].

Combining multiple renewable energy sources with storage creates a reliable, eco-friendly, cost-effective energy solution. The integration of wind and tidal energy, in particular, presents a significant opportunity, but this requires collaborative research efforts to develop efficient and reliable systems [15,16]. This paper reviews recent advancements in offshore wind and tidal stream technologies, focusing on innovations that improve energy efficiency, scalability, and reliability. It also highlights ongoing challenges, such as cost competitiveness, and discusses future trends that could drive a wider adoption of these renewable energy solutions.

Section 2 provides an overview of energy policies and underscores the importance of electrical generators as key components of ocean energy converters. Section 3 examines four configurations of low-voltage (LV) converters commonly used in marine energy systems. Section 4 focuses on using synchronous generators in tidal current energy converters (TCECs) and classifies marine current turbines based on their interaction with water motion, noting areas where categories overlap.

Section 5 concludes by exploring hybrid configurations that combine offshore wind and tidal stream technologies. These configurations have the potential to maximize resource utilization and address energy supply challenges. This review aims to help researchers, policymakers, and industry stakeholders better understand the current state and future potential of offshore renewable energy systems. Unlike previous studies that focus on offshore wind or tidal energy individually, this review highlights the integration of hybrid systems that combine these technologies. It examines how the synergy between wind and tidal power can optimize resource use, enhance energy stability, and tackle cost and environmental challenges. By focusing on these hybrid solutions, the study provides practical insights to drive the transition to more sustainable offshore energy systems.

2. Electrical generators are crucial components in ocean energy converters

2.1. Introduction

The European Green Deal prioritizes energy transition to achieve climate neutrality by 2050, while also addressing biodiversity loss and pollution. To meet energy and climate goals, the EU has set 2030 targets to boost renewable energy use [11].

The vast potential of oceanic energy resources has long been overlooked. However, a significant shift is occurring. There is now a growing focus on harnessing eco-friendly energy from the ocean, marking an important development in the energy sector [15,16]. This shift is driven by the belief that wind and tidal energy could significantly contribute to meeting global electricity demands [17]. Astonishingly, the combined energy from wind and tides exceeds current global energy consumption by a factor of 300. However, despite this immense capacity, these resources have remained largely unused, as shown in Figure 1 [18]. This work explores tidal stream energy fundamentals and turbine classifications [19]. However, the current state of marine energy has not yet met the criteria outlined in the Sustainable Development Scenario (SDS), which mandates an annual growth rate of 23% until 2030. On the other hand, countries such as Canada, the UK, China, and Australia have advanced marine energy projects from 10 kW to 1 MW (IEA 2020b) [19].

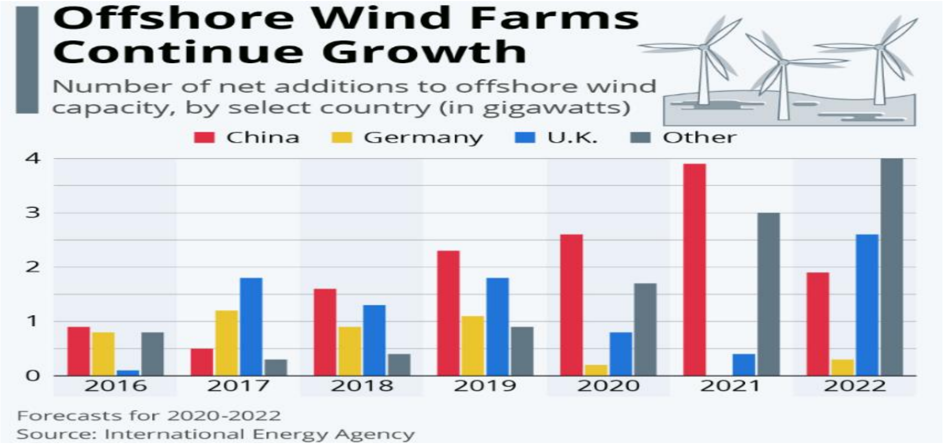


Figure 1. Cumulative global capacity of offshore energy from 2016 to 2022 [20].

Renewable marine energies include wind, wave, tidal, and ocean currents and innovative approaches like ocean thermal energy conversion (OTEC) and osmotic power, which harness energy from temperature variations and salinity gradients, respectively [18]. Evidence of wind energy's expansion manifests in installed capacity statistics. China leads the pack, boasting a substantial 237 GW of wind power, closely trailed by the US with approximately 105 GW [21]. Europe remarkable progress, with installed capacity soaring from 1.48 GW in 2008 to a formidable 25 GW in 2020. Offshore renewable energy (ORE) is a type of renewable energy that can be harnessed from various sources, including wind (both bottom-fixed and floating), ocean energy (tidal and wave), and floating solar technologies. These technologies are currently at different stages of development (see Figure 2) [21].

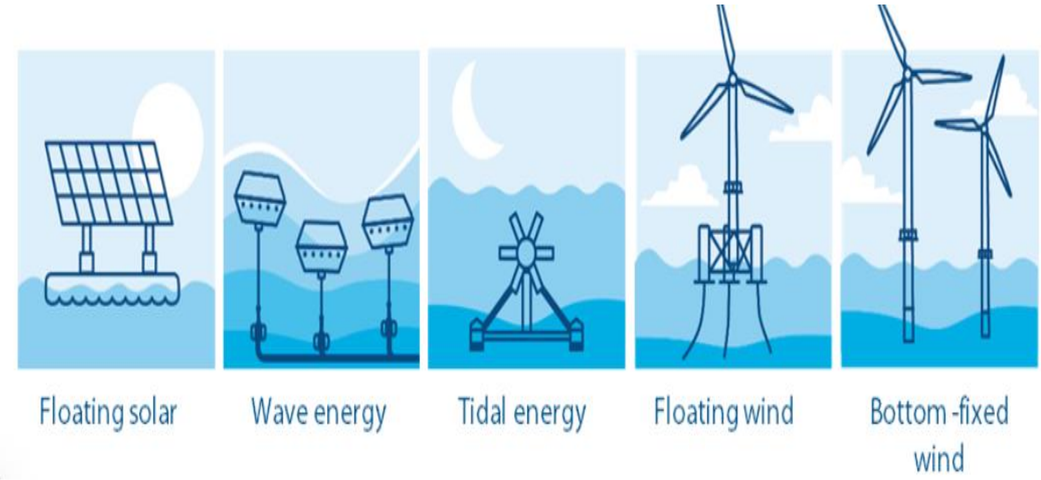


Figure 2. Overview of ORE technologies [18].

2.2. Comparisons between onshore and offshore power systems

The term *offshore*, particularly in the context of tidal stream power, has multiple interpretations that need clarification in this review [22].

As defined by the International Convention for the Safety of Life at Sea, offshore includes internal waters, territorial seas, contiguous zones, exclusive economic zones, and international waters. For this review, offshore power systems (OffPS) are defined as systems located in water, submerged beneath saline layers, or positioned deep within the subsea. While some principles might apply to freshwater environments like rivers and lakes, the focus remains on marine, subsea, deep-sea, offshore islands, and maritime environments [23].

Although OffPS shares some similarities with land-based power systems, they encounter unique technical challenges and risks. Figure 3 illustrates the key factors that shape the distinct resilience and reliability of offshore power system components. Offshore systems, especially those on floating platforms, must withstand oscillations from waves, exposure to moisture, and the corrosive effects of saline water [24]. Onshore high-voltage transmission towers are unsuitable for these conditions due to the harshness of the deep-sea environment. Additionally, subsea cable installation differs significantly from that of overhead land-based cables, with the added benefit that subsea lines are immune to lightning strikes. Consequently, the interaction between the subsea ecosystem and offshore power systems differs substantially from onshore systems [25].

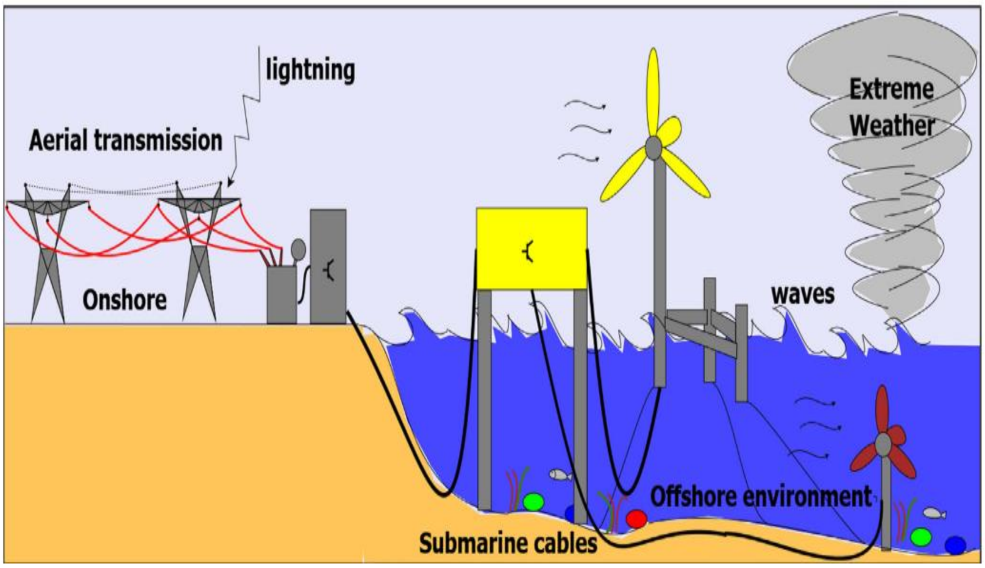


Figure 3. Contrasts between onshore and offshore power systems in terms of transmission [26].

2.2.1. Generalized offshore power system architecture

A comprehensive offshore power system (OffPS) framework integrates several interconnected subsystems at sea, as shown in Figure 4. These subsystems include power generation, transmission, distribution, consumption, energy storage, intelligence, and environmental considerations [11]. The generalized architecture in Figure 4 serves as a reference for this research, organizing OffPS into seven key components: power generation, transmission, distribution, consumption, energy storage, offshore intelligence, and environmental factors. Each plays a crucial role in managing the flow of electricity—from production to transmission, storage, and conversion [27]. Beyond wind power, tidal stream energy is increasingly vital to OffPS, particularly in areas with strong tidal currents. Notable examples include the Pentland Firth in Scotland and South Africa's Agulhas Current along the Western Cape. These locations benefit from predictable and reliable tidal cycles, offering a consistent energy source that complements the variability of wind and tidal power [28]. This creates a more balanced and resilient renewable energy mix. Energy storage has gained prominence as it mitigates the intermittency of wind and tidal energy sources [24]. Larger wind turbines also help by capturing more energy, reducing overall installation and maintenance costs compared to smaller units. Wind turbines are typically installed across vast areas, forming wind farms connected to national grids. These farms can be located onshore or offshore, though offshore installations often involve higher initial and maintenance costs due to the need for robust foundations and submarine cables. Similarly, offshore tidal turbines face challenges from underwater currents and corrosive seawater, requiring durable construction [29]. While onshore wind farms are more accessible and cost-effective, offshore wind and tidal farms demand advanced transmission technologies. These include series/parallel AC/DC configurations as well as high-voltage AC (HVAC) and high-voltage DC (HVDC) systems, essential for connecting offshore systems to the grid. However, the rapid integration of wind and tidal energy into electrical grids raises concerns about stability, security, and efficiency. As a result, many countries have updated grid codes to govern the connection of large-scale renewable energy projects [30].

The offshore intelligence subsystem plays a critical role in managing, maintaining, and automating OffPS by processing data from all other subsystems, ensuring smooth operations and reliability [18]. The environmental subsystem interacts with natural forces such as weather, hurricanes, tsunamis, and powerful tidal currents, as well as artificial elements like vibration-isolation systems and submarine hulls that protect against deep-sea pressures. These structures also serve as ground terminals and voltage references for OffPS grounding systems [31]. Internal interactions within OffPS form a complex network of data and power connections. Figure 4 illustrates these interactions, with dashed lines representing data flows and solid lines indicating power connections [32]. This conceptual network does not correspond directly to physical systems but provides a broad depiction of how offshore systems function, incorporating the diverse capabilities of wind and tidal energy installations in locations like the Pentland Firth and the Agulhas Current [33].

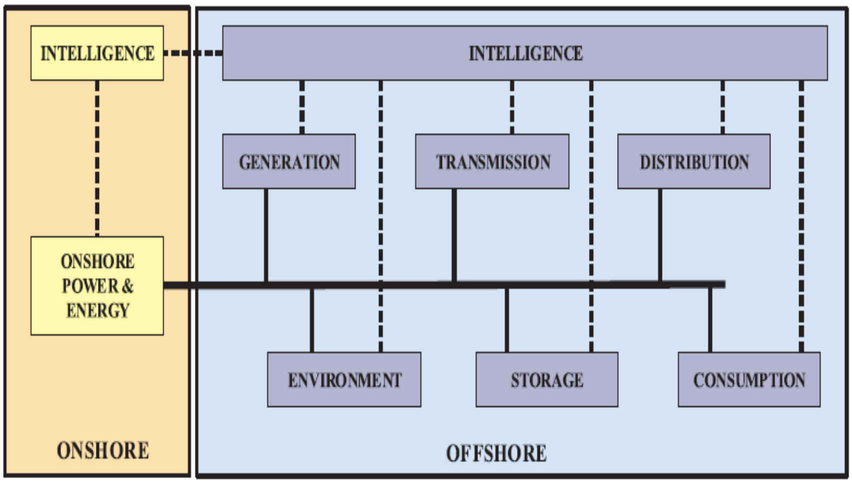


Figure 4. Overall structure of an offshore power system and its various interconnections depicted in the generalized architecture [24].

The following sections delve into an exhaustive exploration of each subsystem in finer detail. Offshore power generation involves the conversion of energy sources into electricity exclusively within the offshore environment [24]. While several energy sources, such as solar, wind, and fossil fuels, exist in both onshore and offshore contexts, some are unique to the oceans, such as waves and tides [34]. These offshore power generation systems are categorized based on their energy source and can include connections to auxiliary systems such as subsea structures and platforms. In this context, these external systems are considered part of the offshore environment, distinct from the primary power generation, transmission, distribution, consumption, energy storage, and intelligence processes [35].

2.3. Overview of offshore technology in development

The development of offshore renewable energy technologies has primarily focused on designing efficient energy conversion systems to harness the kinetic energy of natural resources like wind and tidal currents, which turn the rotor to drive the generator, transforming tidal kinetic energy into electrical power. Unlike wind turbines, tidal systems must contend with the unique challenges of underwater environments, such as water density resistance and marine corrosion [26]. However, the predictability of tidal cycles provides a stable and reliable energy source, making tidal energy a valuable component of the renewable energy landscape [36]. The following section explores the components and design considerations involved in the power conversion chain for tidal current energy systems.

2.3.1. Power conversion chain design for tidal current energy systems

Tidal stream turbine systems share similarities with wind turbines in both design and operation, allowing for effective comparisons in reliability assessment and drivetrain configurations. Although comprehensive data on tidal stream turbine failures are scarce, the available documented cases provide valuable insights into performance challenges [3]. These turbines are typically classified as either vertical-axis or horizontal-axis, with the latter being more common in tidal energy applications [6].

A horizontal-axis tidal stream turbine consists of key components, including rotor blades, a drivetrain, and a generator. The turbine captures the kinetic energy of tidal currents through its rotor blades, converting the water's momentum into mechanical energy [6]. This mechanical energy is then transferred via the drivetrain to the generator, where it is transformed into electrical power. The energy transfer may occur directly through a direct-drive system or via a gearbox that adjusts rotational speed for optimal power conversion [37].

The tidal current energy conversion (TCEC) system is a sophisticated assembly designed to convert tidal currents into electrical power. This system typically includes a turbine, a pitch control system, and an advanced drivetrain. The drivetrain system, as shown in Figure 5, contains components like the main drive shaft, bearings, gearbox, coupling, brake, and generator, all of which are crucial for efficient energy conversion [37].

A key factor to consider is the density of water, which is approximately 800 times greater than air, making tidal energy systems operate under unique conditions. These systems are generally optimized for flow speeds of approximately 3 m/s, which is the velocity at which the system reaches maximum power output [38]. The design of the turbine blades and pitch control must be tailored to the specific site conditions, including tidal speeds exceeding 2.25 m/s and water depths between 25 and 50 m. For efficient power generation, turbines require large swept areas and strong tidal currents, which are relatively rare and typically found in specific geographic features like narrow straits [38].

Key control mechanisms in tidal energy conversion systems include:

- Blade pitch control: Adjusting the blade pitch allows for precise regulation of power capture and mechanical loads. Hydraulic actuators or servo pitch motors facilitate these adjustments, enabling the turbine to adapt to changing tidal conditions.
- Generator torque control: Managing the generator torque is critical for optimizing the conversion of mechanical energy into electricity, allowing for efficient power generation.
- Yaw control: While more commonly used in wind turbines, yaw control systems in tidal turbines may help align the rotor with tidal currents, enhancing energy capture and overall system efficiency [26].

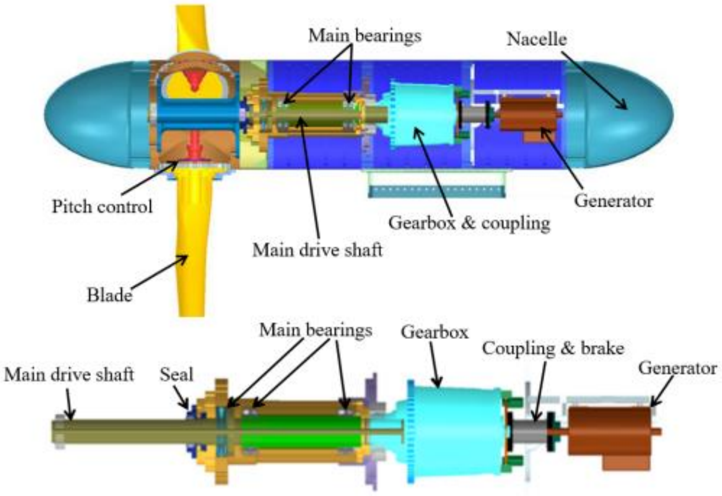


Figure 5. Power conversion chain of TCEC [39].

Gearbox failures have long been a significant challenge in the energy sector, leading to substantial downtime and repair costs [40]. Although much of the focus has been on wind turbines, tidal stream turbines encounter similar issues related to gearbox reliability [23,41]. Gearbox components are standardized, accessible, and cost-effective, yet they are pivotal to the efficient operation of tidal energy systems. Gearboxes, based on mature technology, are widely used across various sectors, including transportation and manufacturing. These components are essential and typically exhibit a higher mean time to repair (MTTR) compared to other subsystems [41]. The extensive theoretical and practical knowledge available for geared systems offers valuable insights for designing geared tidal turbines. By integrating advancements in gearbox design, condition monitoring, and maintenance practices, it is possible to significantly improve the reliability of tidal stream systems and mitigate potential failures [42]. Optimizing tidal stream energy systems requires leveraging these advancements in gearbox technology and maintenance strategies. Such improvements will enhance system performance and reduce downtime, thereby increasing the overall efficiency and reliability of tidal current energy systems [43].

At the core of the power conversion process lies the mechanical transmission system, which facilitates the transfer of kinetic energy from the tidal current to the generator. The design and configuration of this system directly impact the efficiency and reliability of tidal energy conversion. The next section delves into the key role of mechanical transmission, including gearbox designs and alternatives such as direct-drive systems, which are increasingly favored in offshore applications.

2.3.2. Mechanical transmission

In tidal stream energy systems, the gearbox is a crucial component of the mechanical transmission system. Tidal stream turbines typically operate at low rotor speeds due to the slow movement of tidal currents [44]. To convert this low-speed rotational energy into higher speeds required for electricity generation, a gearbox is used. The gearbox increases the rotor's speed from the low revolutions per minute (rpms) generated by the tidal currents to the higher rpms needed by the generator [45]. In some tidal stream systems, particularly those utilizing multi-pole synchronous generators connected to the grid via a power converter, the gearbox may be omitted. These generators are capable of operating efficiently at lower speeds, making a gearless design feasible. This approach is particularly beneficial for offshore applications, where minimizing maintenance is essential due to the challenging environment [46]. By eliminating the gearbox, the system reduces mechanical complexity and maintenance requirements [47]. For tidal turbines with smaller rotor diameters, gearboxes may also be unnecessary. Smaller rotors can achieve higher rotational speeds given the tidal currents, which may directly match the generator's requirements. This enables the use of a direct-drive system, simplifying the mechanical design and reducing maintenance needs. Direct-drive tidal stream turbines are increasingly used in standalone DC applications and battery charging systems [48].

The nacelle houses all critical equipment for the tidal turbine, including the drivetrain components (rotor shaft, gearbox, and bearings), electrical generator, power electronics, and control systems. It connects to the support structure via bearings, allowing for rotation to maintain optimal alignment with the tidal currents. The strategic placement of the drivetrain and associated components within the nacelle ensures efficient operation and facilitates maintenance [49].

2.3.3. Hydrodynamic model and maximum power extraction

Tidal stream turbines (TSTs) harness energy from tidal currents, which are driven primarily by the gravitational forces of the moon and sun. Unlike wind, tidal currents are more consistent and predictable. To understand energy extraction from tidal streams, consider the flow of water through the rotor disk, which represents the swept area of the turbine [34]. The mass flow rate of water ($\frac{dm}{dt}$) through the rotor disk is dependent on the water density [ρ] and the flow velocity U [m/s]. For a uniform flow velocity across the rotor's swept area (A), the mass flow rate is given by [44]:

$$\frac{dm}{dt} = \rho . A . U \tag{1}$$

The instantaneous kinetic power available from the tidal stream is calculated using:

$$\mathrm{P} = \frac{1}{2}\mathrm{\rho . A . V^3}_{\mathrm{flow}} \tag{2}$$

where V_{flow} is the free stream velocity of the tidal current. TSTs cannot extract all the available power due to the need for some residual flow behind the rotor. The theoretical maximum for power extraction is governed by the Betz limit [50].

The primary objective of TSTs is to maximize power extraction from tidal streams. The power delivered to the rotor and the torque developed can be expressed as follows:

$$\mathrm{P} = \mathrm{T\omega} \tag{3}$$

where ω represents the angular velocity of the turbine and T is the torque on the shaft. The angular velocity can be determined by:

$$\lambda = \frac{\mathrm{\omega r}}{\mathrm{V}} \tag{4}$$

where r is the turbine radius, λ is the tip-speed ratio, and V_{flow} is the stream velocity. The torque on the turbine shaft is given by:

$$T = \frac{1}{2}\rho chr{V_{rel}}^{2}C_{T} \tag{5}$$

where C is the blade chord length, V_{rel} is the relative velocity, and C_T is the torque coefficient [34]. Operating the turbine at variable speeds allows for optimal power extraction across a range of tidal flow speeds [49]. Figure 6 shows the characteristic curve for optimal power extraction and illustrates how the turbine's performance aligns with varying tidal flow speeds [51].

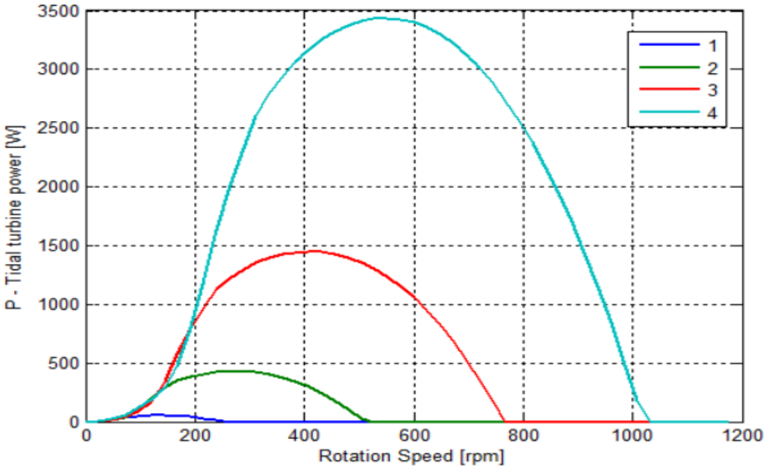


Figure 6. Power characteristics of tidal turbine [49].

The next section presents a hydrodynamic model and discusses strategies for maximizing power extraction from tidal currents.

2.3.4. Tidal stream turbines and offshore variable-speed wind turbines

The recent development of larger tidal stream system turbines has led to a shift from fixed-speed to variable-speed operation. This shift addresses grid code requirements and reduces mechanical loads [50]. Figures 11 and 12 present configurations employing a permanent magnet synchronous generator (PMSG) and a full power converter (FPC), relevant to TSTs [41,52]. By routing all turbine power through converters, the dynamic operation of the PMSG is decoupled from grid frequency variations, ensuring stable grid operation despite fluctuations in tidal stream speed [53]. While the hydrodynamic model focuses on maximizing power extraction from tidal currents, integrating this energy into the grid requires additional components, such as voltage transformers. These transformers ensure that the power output meets the required voltage levels for safe and efficient transmission. The next section examines the role of voltage transformers in tidal energy systems and their significance in grid integration.

2.4. Voltage transformer

The voltage transformer adjusts the turbine's internal voltage, typically between 690 and 1000 V, to match the collector grid voltage, commonly rated at 33 or 36 kV. This transformation incurs power losses that are converted into heat, necessitating dissipation via the cooling system [53]. Many tidal stream turbine systems neglect to fully account for these transformer losses in their control and management systems. Recent developments show that newer and larger turbines are incorporating advanced controllers to mitigate these losses [41,52]. While the voltage transformer plays a critical role in adjusting turbine output to match grid voltage, ensuring optimal energy capture and conversion requires additional subsystems for efficient turbine operation. Among these, the yaw drive is essential for maintaining the turbine's alignment with changing tidal or wind directions, thereby maximizing energy generation. The following section explores the functionality and importance of yaw drive systems in renewable energy technologies.

2.4.1. Yaw drive

The yaw drive is vital in modern horizontal-axis wind turbine yaw systems. It actively adjusts to keep the rotor aligned with changing wind directions, optimizing energy production. A wind vane measures wind direction at the nacelle's rear [53]. Yaw angle errors lead to reduced energy capture, with power losses proportional to the cosine of the yaw error [53,54]. In addition to optimizing turbine alignment, safety mechanisms like the mechanical brake are integral to the reliable operation of tidal stream turbines, especially during emergencies or maintenance. This section examines the mechanical brake's role in ensuring system stability and safety.

2.4.2. Mechanical brake

The mechanical brake is crucial in tidal stream turbines, serving as an emergency backup if other braking systems fail. Positioned between the gearbox and the generator, it also prevents unexpected turbine activation during maintenance. The mechanical brake engages after other braking methods have reduced the turbine speed, minimizing wear [52]. The following section discusses advancements in power electronic converters and their critical role in tidal energy systems.

2.4.3. Power electronic converter

Advancements in power electronics have significantly enhanced the operation of renewable energy [52]. Power electronic converters are essential for interfacing tidal stream and wind turbines with the grid. As tidal turbines operate at variable speeds, their generator’s electrical frequency fluctuates, requiring decoupling from the grid frequency via these converters [51]. This decoupling enables turbines to operate efficiently across varying speeds, enhancing power capture compared to fixed-speed models. Common configurations include gear-coupled double-fed induction generators (DFIGs), where power electronics manage rotor voltage and frequency, or direct-coupled synchronous generators (SGs), with power electronics controlling stator voltage and frequency. Both configurations may use brushless field excitation or permanent magnet excitation [47].

Effective variable-speed operation requires a control system tailored to the specific tidal stream turbine, ensuring maximum power extraction while maintaining stable grid voltage and frequency [54]. As switching frequencies increase to develop more compact and efficient equipment, emissions in the 2–150 kHz frequency spectrum, known as super harmonics, become more pronounced [55]. Key power converters include inverters, rectifiers, DC/DC converters, and DC/AC inverters [56]. Building on the advancements in power electronic converters, integrating these systems into variable-speed turbine configurations has significantly enhanced the efficiency and flexibility of energy systems. The direct-in-line variable-speed turbine with a full-scale power converter represents one such innovative design, addressing key challenges associated with fixed-speed systems. The next section examines the advantages and trade-offs of this configuration in detail.

2.4.4. Direct-in-line variable speed wind turbine with full-scale power converter

In fixed-speed systems, the generator connects directly to the grid (see Figure 9), maintaining a steady rotor rotation determined by grid frequency, gear ratio, and generator pole pairs [16]. Fixed-speed configurations are generally straightforward, reliable, require less maintenance, and are cost-effective [57]. However, they present several drawbacks:

- Limited energy capture: Power extraction depends on the rotational speed of the prime mover and environmental conditions. Variable-speed solutions can improve efficiency by 5%–20% across varying conditions.
- Mechanical stress: Fixed speeds cause torque pulsations, leading to mechanical strain. Systems using squirrel-cage induction generators experience less mechanical stress due to slip compliance during transients.
- Power quality: Mechanical power fluctuations affect both the drive train and the grid, leading to degraded power quality. Fixed-speed systems, particularly those with low-inertia drive trains, can generate noticeable electrical power fluctuations.
- Reactive energy compensation: Squirrel-cage induction generators consume reactive energy, often requiring additional compensation components.

Converters, which serve as interfaces between the load/generator and the grid, are crucial for ensuring reliability, efficiency, and cost-effectiveness. They consist of power electronic devices, driving circuits, protection systems, and control circuits [58].

Currently, two main types of converters are used: grid-commutated and self-commutated converters [59]. Grid-commutated converters, which use thyristors and multiple pulses, generate integer harmonics but lack reactive power control [60]. Variable-speed solutions offer several advantages over fixed-speed systems:

- Decoupling: Power electronics decouple the grid from the generator.
- Enhanced power take-off: Improved alignment between the resource and prime mover speed enhances power take-off.
- Energy storage: The rotor and drive train can act as a flywheel, storing or delivering energy and reducing power fluctuations.
- Reduced stress mechanical stress: Variable-speed systems reduce mechanical stress due to inherent mechanical compliance.
- Full power control: Both active and reactive power can be controlled.

However, variable-speed solutions entail higher costs due to power electronics. Common configurations include fully controllable back-to-back converters in either a double-fed induction generator setup or a full-converter configuration [61]. In the DFIG arrangement shown in Figure 7, the rotor winding connects to the grid via a bidirectional power converter, which typically comprises 30%–40% of the rated power. This configuration enables variable-speed operation and control over active and reactive power within specific limits but requires slip rings, increasing maintenance needs [62].

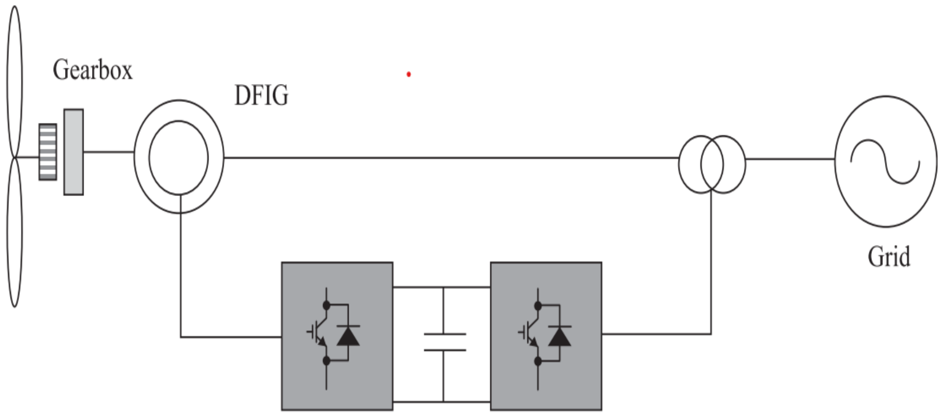


Figure 7. DFIG topology.

Power converters are critical components in tidal stream energy systems, acting as interfaces between the generator and the grid to manage bidirectional power flow [49]. Key considerations for these converters include reliability, efficiency, and cost. They consist of power electronic devices, drive systems, protection circuits, and control mechanisms [59]. The primary converter types used are grid-commutated and self-commutated converters. Grid-commutated converters, utilizing thyristors, produce integer harmonics and lack reactive power control capabilities [61].

Variable-speed systems present several advantages over fixed-speed configurations in tidal stream turbines:

- Grid decoupling: Power electronics enable the decoupling of the generator from the grid, providing greater operational flexibility.
- Enhanced power take-off (PTO): By aligning turbine speed with tidal flow conditions, power extraction is optimized.
- Energy storage: The rotor and drive train can act as a flywheel, storing or delivering energy to mitigate power fluctuations.
- Reduced mechanical stress: Variable-speed operation reduces mechanical stress due to the inherent mechanical compliance of the system.
- Comprehensive power control: Both active and reactive power can be precisely managed.

Presently, the most common configurations involve employing a fully controllable back-to-back converter, either within a double-fed induction generator setup (refer to Figure 8) or in a full-converter configuration (refer to Figure 9) [61]. Despite these benefits, variable-speed systems incur higher costs due to the advanced power electronics required. Common configurations involve fully controllable back-to-back converters, either in a double-fed induction generator (DFIG) setup or a full-converter arrangement [63]. In the DFIG configuration, the rotor winding connects to the grid via a bidirectional power converter, typically accounting for 30%–40% of the rated power. This setup facilitates variable-speed operation and enables control over both active and reactive power within specified limits. However, the requirement for slip rings in this arrangement can increase maintenance demands [62].

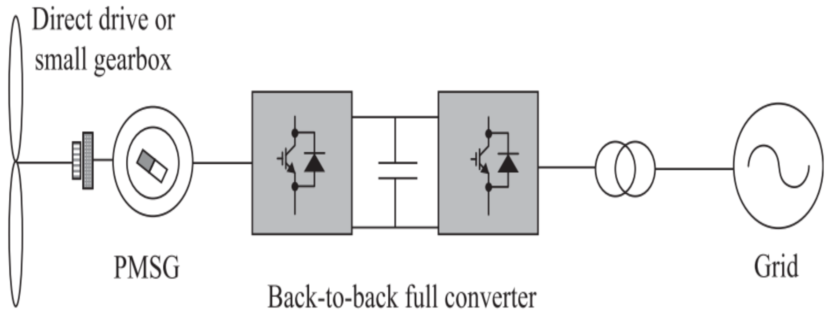


Figure 8. Full converter topology.

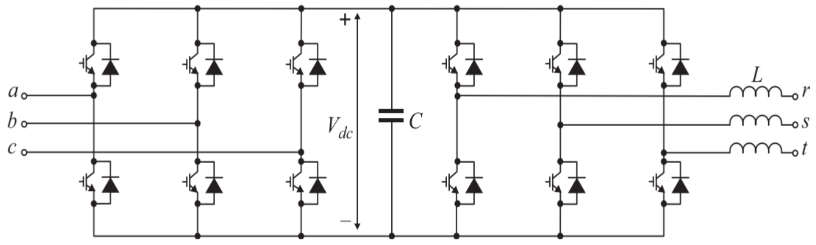


Figure 9. Back-to-back converter.

Power converters are fundamental to the operation of both variable-speed and fixed-speed tidal turbines, acting as interfaces between the generator and the grid. They ensure bidirectional power flow, maintain grid stability, and enable precise control of active and reactive power. In the next chapter, we delve deeper into the design, types, and functionality of converters used in tidal stream energy systems, highlighting their role in improving efficiency and reliability.

3. Converters

This section examines four LV converter configurations, each tailored to specific tidal stream turbine grid connections, typically utilizing standard voltages of 690 and 575 V. Power converters are essential components in tidal stream energy systems, serving as interfaces between the generator and the grid. They enable efficient power conversion, regulate energy flow, and support grid stability in variable operating conditions. The following subsections detail the key converter configurations employed in tidal stream turbines, beginning with the widely adopted full-scale back-to-back two-level voltage source converters (BTB 2L-VSCs).

3.1. Full-scale BTB 2L-VSCs

Figure 10 illustrates a typical Type 4 tidal conversion system (TCS) using full-scale back-to-back (BTB) two-level voltage source converters (2L-VSCs) [63]. These consist of a voltage source rectifier (VSR) and a voltage source inverter (VSI), connected by a DC-link capacitor [64]. Both the VSR and VSI are realized through low-voltage insulated gate bipolar transistors (LV-IGBTs), arranged in a matrix configuration. The DC-link unit, consisting of capacitors arranged in series or parallel, achieves the required voltage and capacitance. This link decouples the generator from the grid, preventing generator transients from impacting grid stability [65].

This mature converter topology is used in approximately 90% of Type 4 tidal stream turbines rated below 0.75 MW and supports a range of tidal stream generators like permanent magnet synchronous generators (PMSG), wound rotor synchronous generators (WRSG), and squirrel cage induction generators (SCIG). The converter's power rating is typically matched to the generator output, so a 0.75 MW generator connects to a 0.75 MW converter. The VSR controls the generator's torque and speed, while the VSI manages the DC-bus voltage and grid reactive power [66].

To minimize switching losses and enhance power density, the VSR and VSI operate with a switching frequency between 1 and 3 kHz. LCL filters are used on the grid side to reduce harmonic distortion in grid currents [67]. Although not shown, generator-side harmonic filters are also required [68]. The entire converter system—filters, rectifiers, DC-link, and inverters—is housed in a cabinet located in the turbine nacelle [69]. After filtering, the AC output is transmitted through cables to a step-up transformer at the tower's base. These low-voltage, high-current AC cables, though costly and prone to transmission losses, benefit from mass production, reducing overall expenses [70].

An example of a widely used commercial converter module is Semikron's SKiiP, known for its compact design and high power density [71]. It integrates heat sinks, semiconductor switches, and gate drivers into a single unit. While full-scale BTB converters are commonly used in small-scale tidal systems for their simplicity and effectiveness, larger systems often employ partial-scale converters to reduce costs and improve flexibility. The next section explores partial-scale BTB 2L-VSC configurations, which are specifically designed for semi-variable speed tidal systems [72].

3.2. Partial-Scale BTB 2L-VSCs

Figure 11 shows a Type 3 tidal conversion system that uses BTB converters in semi-variable speed tidal systems [73]. In this configuration, the stator is directly connected to the grid, while the rotor is linked to the power converter [74]. The converter's power rating is typically around 30% of the generator's total capacity. For example, a 2.5 MW doubly-fed induction generator (DFIG) would use a 0.75 MW converter [75]. The full-scale and partial-scale converters regulate active and reactive power, control DC-link voltage, and maintain grid power factor [76].

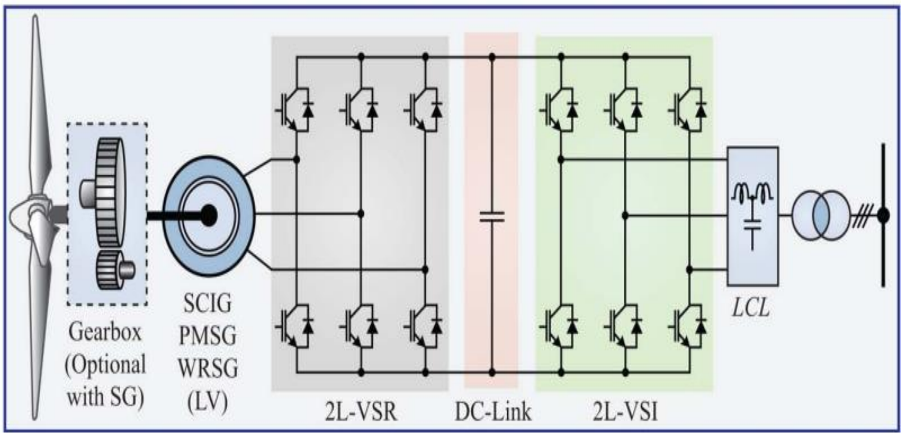


Figure 10. Type 4 TCS with two-level BTB voltage source converters (mainstream commercial power converter configuration) [63].

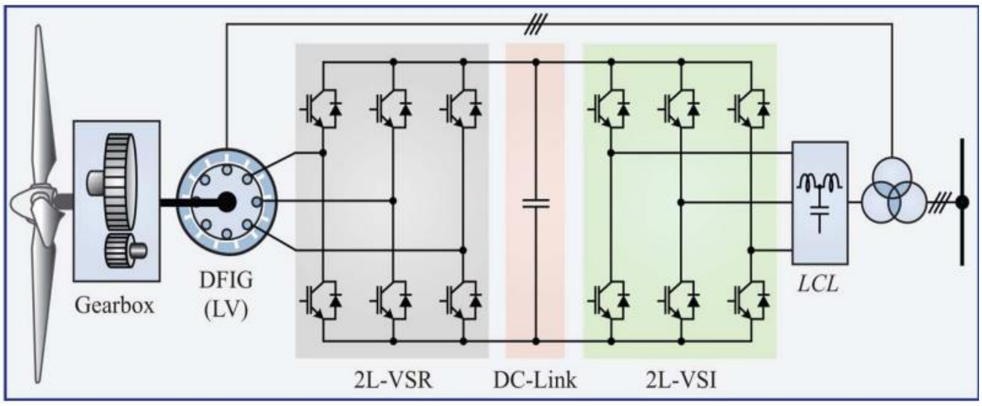


Figure 11. Type 3 TCS with two-level BTB voltage source converters [63].

As the power demands of tidal stream turbines increase, more advanced converter configurations are required. Parallel BTB VSC systems with a common DC-link provide a scalable solution for turbines with power ratings exceeding 0.75 MW.

3.3. Parallel BTB 2L-VSCs with common DC-link

For larger tidal turbines with power ratings above 0.75 MW, multiple BTB VSC modules can be connected in parallel, accompanied by harmonic filters, as shown in Figures 12 and 13 [77]. In the case of Type 3 and Type 4 turbines, connecting VSC modules in parallel increases the current-carrying capacity [78]. This parallel configuration allows for power ratings of 1.5 MW for Type 4 turbines and up to 5 MW for Type 3 turbines [79]. A common DC-link across the converters helps reduce costs and space requirements [80].

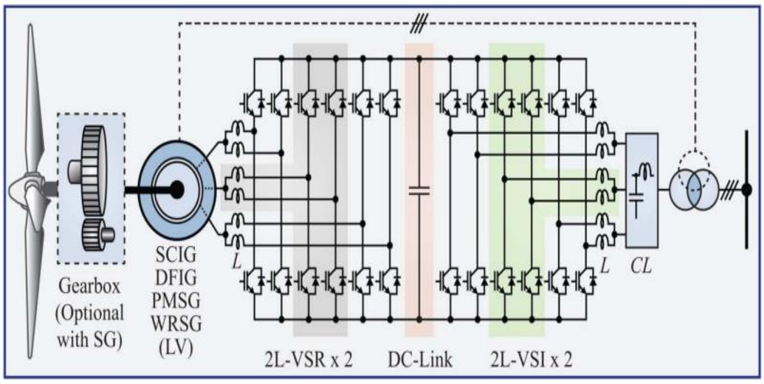


Figure 12. Type 3 and 4 TCS with parallel connected BTB 2L-VSCs and common dc-link [81].

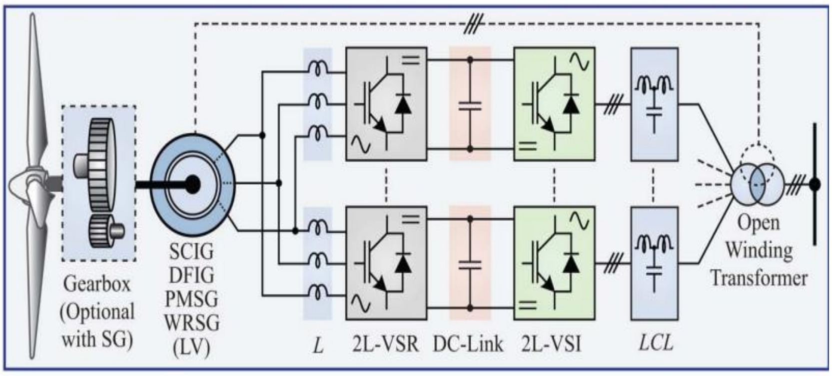


Figure 13. Type 3 and 4 TCS with parallel connected BTB 2L-VSCs, individual DC-links, and open winding transformer [81].

Self-commutated converters, which use pulse width modulation (PWM) and IGBTs, control both active and reactive power [82]. While PWM converters can meet reactive power demands, high-frequency switching generates harmonics, necessitating harmonic filters on both generator- and grid-side converters [83]. Generator-side harmonic filters reduce distortion in the generator's current, thus minimizing magnetic core and winding losses [84]. Grid-side filters ensure compliance with grid harmonic standards [85].

Finally, the grid-side harmonic filter output connects to a three-phase grid via a step-up transformer, switchgear, and circuit breaker [86]. In some cases, the converter can operate at collection point voltage levels, eliminating the need for a step-up transformer [87]. Efficient energy transfer from tidal stream turbines to the grid depends not only on converter technology but also on the grid connection layout. Properly designed grid connections ensure reliable transmission of energy over long distances while maintaining power quality and stability. The next section discusses grid connection layouts and their critical components, such as transformers, AC filters, and DC cables [88].

3.4. Definition of grid connection layout

In modern tidal stream energy systems, two primary transmission approaches are utilized for long-distance power transfer: a) AC collection-AC transmission and b) AC collection-DC transmission, as shown in Figure 13 [16]. The most used method is high-voltage alternating current (HVAC) transmission, depicted in Figure 14(a). HVAC is widely adopted due to its straightforward design and well-established technology. Typically, the generated voltage in tidal stream turbines is around 700 V, which is then stepped up to medium voltage levels such as 33 kV or, in specific cases, 66 kV, to facilitate transmission [17].

To handle over-voltage and charging current issues in subsea cables, shunt reactors are employed for power compensation. This ensures improved transmission capacity and efficiency, enabling smooth and reliable transfer of energy from offshore tidal systems to onshore grids [89].

3.4.1. Transformers and phase reactors

In tidal stream energy systems, a trio of single-phase transformers is employed to match the AC bus voltage with the input requirements of the power converter [89]. These transformers are equipped with tap changers for precise voltage control, enabling adjustments as needed. The design simplicity is attributed to the reduced harmonic content inherent in voltage source converter (VSC) high-voltage direct current (HVDC) systems [90]. This lower harmonic distortion eliminates the need for complex filtering solutions, leading to a more straightforward transformer configuration [91].

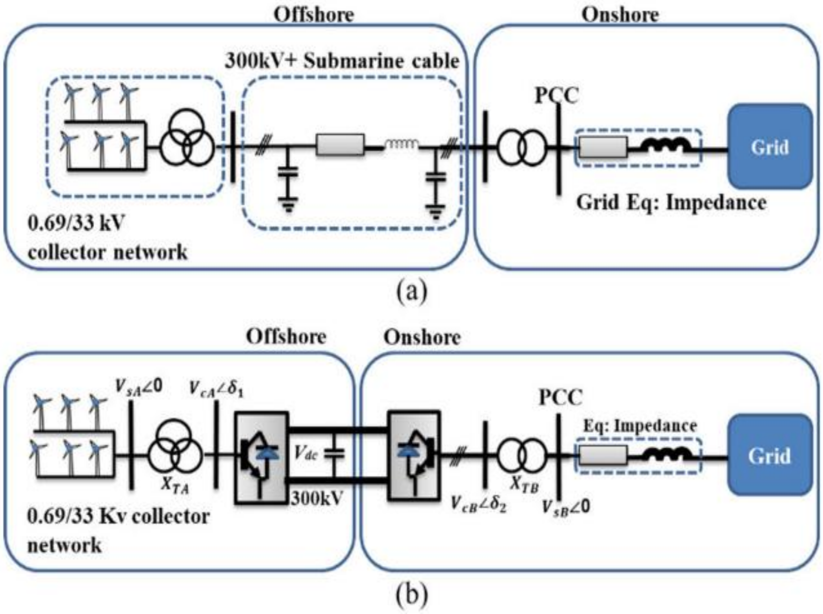


Figure 14. Standard (a) HVAC and (b) HVDC connections in offshore wind farms with elevated voltage levels [92].

3.4.2. AC filters

In tidal stream energy systems, managing high-order harmonics in AC output currents and voltages is critical [92]. These harmonics must be controlled to avoid interference with the AC system, as uncontrolled harmonics can cause equipment malfunctions or disrupt communication signals [89]. To achieve this, transmission systems use either passive or active high-pass filters. These filters help maintain nearly sinusoidal currents and voltages in the AC system. Thanks to their low harmonic distortion and lack of need for reactive power compensation, these filters can be designed to be compact and simple [90].

3.4.3. DC cables and breakers

DC cables and breakers are essential components within the DC transmission system, working alongside DC links and earth electrodes. The development of DC cable technology has been driven by challenges in conventional cables, which are often heavy, difficult to install, and prone to faults [91]. Modern DC cables feature improved insulation, reduced power losses, lighter designs, and greater flexibility, making them suitable for applications such as submarine or overhead links [93]. In addition, hybrid DC breakers have emerged as a promising alternative to traditional mechanical or electronic switches. These hybrid breakers offer faster response times, enhanced efficiency, and greater reliability, with modular designs that allow easy adaptation to specific voltage and current demands [94].

3.4.4. DC capacitors and filters

DC capacitors and filters are critical in mitigating DC voltage ripple caused by the switching process in the converter's IGBTs [34]. To achieve this, the system uses two identical stacks of DC capacitors, each connected to a pole and grounded [90]. Additionally, DC filters can be applied on the transmission side to reduce interference with nearby metallic circuits. Thanks to the low harmonic content in the currents and voltages of VSC HVDC systems, these filters can be designed to be compact and straightforward [95].

3.4.4.1. HVDC system configurations

HVDC converters (Figure 15), which consist of rectifiers and inverters, provide flexibility in their interconnection through DC links, supporting various configurations [33]. These configurations include mono-polar HVDC systems, which can utilize ground return, metallic return, or a grounded midpoint [88]. Other configurations are back-to-back HVDC systems, bipolar HVDC systems (with variations such as bipole [95], bipole with metallic return, or bipole with series-connected converters), and multi-terminal HVDC systems, as shown in Figure 16 [96].

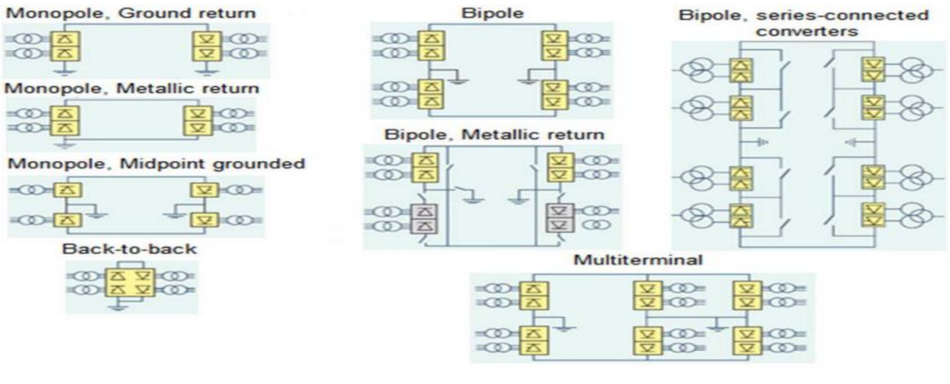


Figure 15. Different configurations of HVDC systems [97].

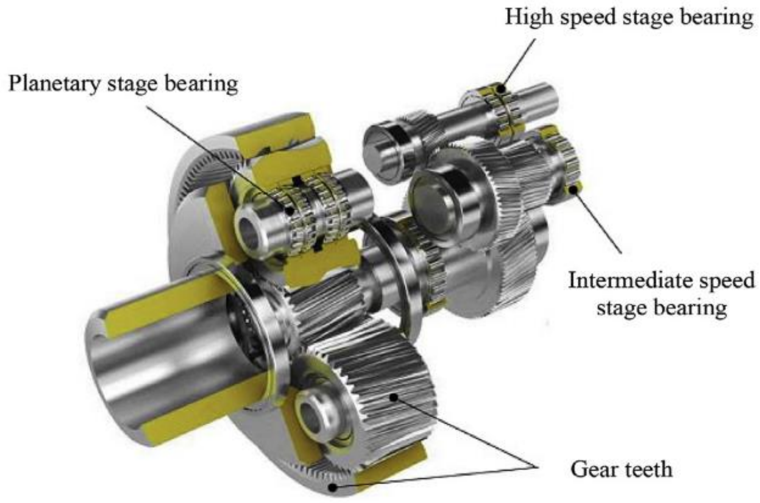


Figure 16. Typical planetary gearbox [26].

While power converters and grid connection layouts are vital for transmitting energy from tidal turbines to the grid, the mechanical transmission system is equally important for converting tidal flow into rotational energy for electricity generation. The following section focuses on mechanical transmission, including gearbox configurations and emerging trends in direct-drive systems.

3.5. Mechanical transmission

The gearbox is a crucial element of the mechanical transmission system. In large-scale wind turbines with significant rotor diameters, the rotor's rotational speed is typically low (approximately 18–50 rpm), which is insufficient for the efficient operation of generators that typically run between 1200 and 1800 rpm [45]. To address this mismatch, a gearbox is installed between the rotor’s output shaft and the generator’s input shaft, as shown in Figures 17 and 18, increasing the rotor speed to the required rpm for optimal power generation [47]. However, in systems utilizing multi-pole synchronous generators that are connected to the grid via a power converter, which electrically isolates the generator from the grid, the gearbox can be eliminated. This gearless configuration is particularly beneficial in offshore applications, where reduced maintenance is essential [49].

For wind turbines with smaller rotor diameters, the gearbox may also be unnecessary. A smaller rotor diameter results in a shorter distance traveled per revolution, potentially leading to a higher rotational speed that is compatible with the generator’s requirements. This allows for a direct connection between the rotor and generator, similar to systems utilizing power converters. Smaller direct-drive wind turbines are commonly employed in standalone DC applications, such as battery charging [53].

The nacelle houses all of the turbine's key components, including the drive system (comprising the rotor shaft, gearbox, and bearings), the electrical generator, power electronics, yaw drive, mechanical brake, and control system, as shown in Figure 5. Since the nacelle must rotate to align with the wind direction, it is connected to the tower via bearings. The manufacturer’s design choice to position the drive system and associated components above this rotational bearing is depicted in Figures 20–22 [98].

Figure 17. Geared tidal stream turbines: (a) Sea Gen tidal stream turbine (© Simec Atlantis Energy) [99].

According to the NREL gearbox reliability database, wind turbine gearbox reliability has improved substantially since 2013. Despite facing logistical challenges and a higher mean time to repair (MTTR) for offshore tidal turbines relative to onshore wind turbines, these advancements are significant [11]. Currently, gearbox failure rates are below 15%, with bearing failures representing 76% of these failures, while electrical system failures account for more than 25% [36]. The analysis highlights a notable decline in reliability for both standard and optimized gearboxes when compared to other industrial gearbox applications relevant to tidal stream turbines indicated in Figures 19 and 20. This decline is attributed to specific implementation factors; however, future gearbox designs remain unaffected [94]. This finding emphasizes the importance of both optimization and maintenance in improving gearbox reliability [100].

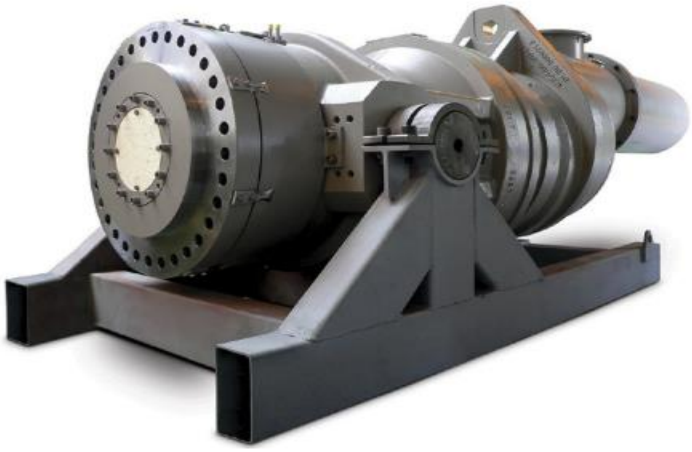


Figure 18. 650 kW planetary gearbox coupled with the generator of the MCT Sea Gen tidal stream turbine [101].

Figure 19. 1.5 MW planetary gearbox from the Mey Gen project [101].

Figure 20. 500 kW planetary gearbox employed in the TGL EMEC demonstrator project [102].

3.5.1. Addressing gearbox challenges

Addressing gearbox challenges in offshore tidal stream turbines necessitates adherence to rigorous operational and maintenance protocols. Effective lubrication is essential for optimal gearbox and transmission performance [6]. It mitigates friction, prevents excessive wear and heat generation, and preserves the integrity of critical components, such as gears, bearings, and seals. Lubrication issues can arise from contamination, degradation, leakage, or insufficient lubricant levels, potentially leading to increased noise, vibration, elevated temperatures, corrosion, and premature component failure [41]. To enhance gearbox reliability and longevity in challenging offshore environments, it is imperative to implement proactive measures to address these issues before they lead to failures [46]. Another prevalent maintenance challenge in tidal stream turbines involves alignment and balance issues. Proper alignment entails the precise positioning of shafts, gears, and bearings, while balance ensures the even distribution of mass and forces across rotating parts [57]. Misalignment and imbalance, often caused by improper installation, adjustment, or wear, can increase stress, vibration, noise, and accelerated component wear. These issues may also affect the efficiency and accuracy of power transmission [102].

Significant attention has been given to various configurations of permanent magnet generators for tidal stream turbines. The rim-driven concept is a notable option for direct-drive drivetrain systems, akin to the Open Hydro design (see Figure 21) [103]. In the rim-driven topology, the generator is positioned on the outer edge of the turbine, offering potential hydrodynamic efficiency advantages over a POD system, where the generator is housed within a nacelle [104]. Research has increasingly focused on various configurations of permanent magnet generators for tidal stream turbines. One promising approach is the rim-driven design, similar to the Open Hydro concept (see Figure 22) [105]. By positioning the generator on the turbine's outer edge, this design has the potential to improve efficiency compared to traditional nacelle-based systems [106].

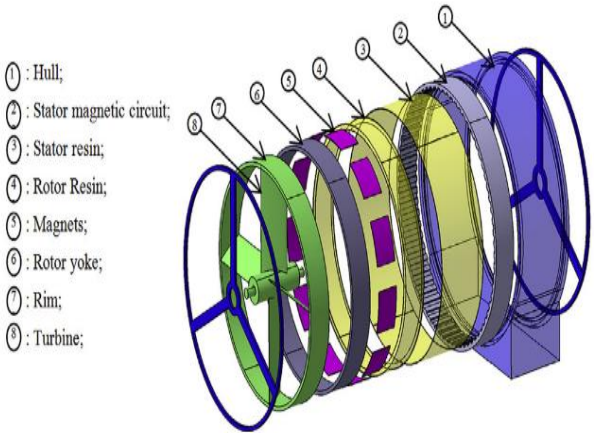


Figure 21. The rim-driven concept using a radial flux permanent generator [6].

Figure 22. The concept of rim-drive utilizing a radial flux permanent generator [6].

4. Synchronous generators in tidal current energy converters (TCECs)

Marine current turbines can be classified in several ways, often with overlapping categories. This study focuses on categorizing these devices based on their interaction with water motion. The primary classifications are:

- Horizontal-axis turbines
- Vertical-axis turbines
- Oscillating hydrofoil

To enhance the marine current velocity passing through the turbine and improve power capture, ducted structures are employed. These structures use the Venturi effect to channel flow toward the rotors, applicable to both horizontal and vertical turbines. This design approach increases the marine current speed in front of the rotor, potentially enhancing power output by up to 40% compared to turbines without ducts [6]. Additionally, it reduces turbulence and minimizes adverse effects on the rotor.

In tidal current energy converters (TCECs), turbines are equipped with two distinct types of synchronous generators: axial-flux and radial-flux direct-drive permanent magnet (DDPM) generators. The choice between these generators depends on the specific configuration requirements. Axial-flux generators are commonly used in pod-type structures, while radial-flux generators are employed in rim-driven configurations, as illustrated in Figure 23(a) [38]. For large-diameter radial-flux DDPM generators, a hollow center turbine structure, shown in Figure 23(b), is advantageous [106]. Radial-flux DDPM generators have traditionally been favored due to their development from induction generators [107]. However, axial-flux DDPM generators offer distinct benefits, such as increased compactness and power density, making them superior to conventional radial-flux DDPM generators in certain applications. Both axial and radial-flux DDPM generators, used in direct-drive systems, have garnered significant attention in both academic and industrial research [108].

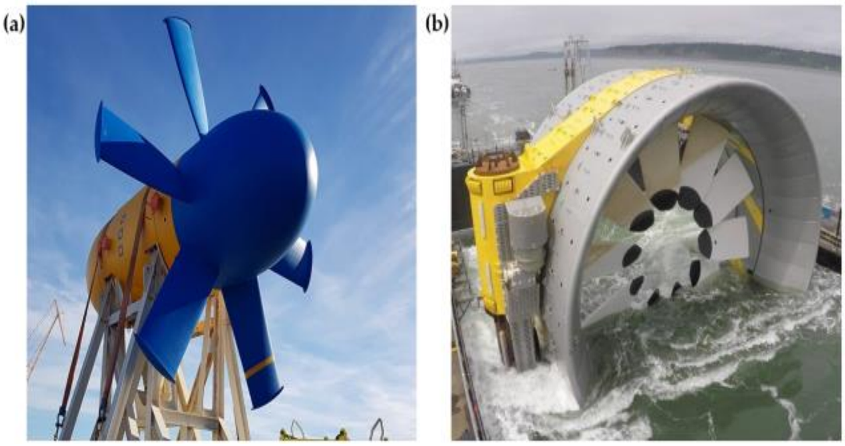


Figure 23. The pod-type structure exemplified by the Sabella D10-1000 tidal current turbine. (b) The rim-driven structure harnessed by the Open Hydro tidal current turbine [38].

Mechanical transmission systems deliver rotational energy to the generator, where it is converted into electrical power. The type and configuration of the generator plays a crucial role in determining the efficiency and reliability of tidal current energy converters (TCECs). The next section delves into synchronous generators, which are widely used in TCECs for their high efficiency and adaptability to variable-speed operations [108].

4.1. Single open-rotor horizontal-axis devices

A prevailing trend within major tidal energy device developers involves the utilization of a shared design foundation—the three-bladed, axial rotor concept indicated in Figure 24. This design approach, informed by the extensive operational expertise garnered from the wind industry, has become a prominent choice. Norway established a 300-kW grid-connected model in 2003. They have also commenced the development of their HS1000 1 MW turbine, scheduled for deployment by 2010. This innovative turbine is entirely submerged and follows a fixed yaw concept, meaning it remains stationary while its blades rotate with the tide's change. Consequently, the blades are required to have a symmetrical cross-section. The drivetrain is expected to incorporate a gearbox and a high-speed induction generator [109].

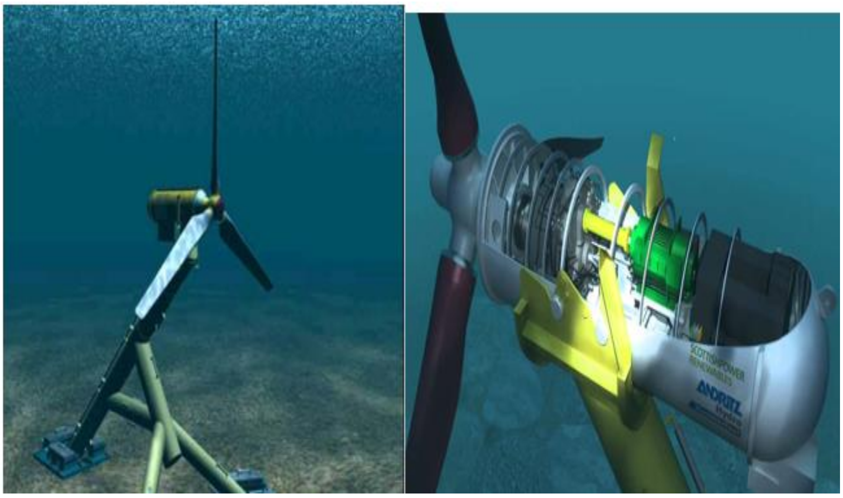


Figure 24. Single open-rotor horizontal-axis device (© Hammerfest Strøm AS) [109].

The turbine incorporates a robust system with multiple layers of redundancy, ensuring continuous operation even during faults or failures. It features an advanced condition monitoring system that predicts potential issues, enabling proactive maintenance [38]. Designed for a 25-year operational lifespan, the turbine includes three scheduled servicing intervals at 6¼ years. With a total mass of 150 tons, it can be installed and retrieved using standard dynamically positioned (DP) construction vessels. Figure 25 illustrates this design, which integrates established wind sector principles with emerging tidal energy technologies [38].

Figure 25. The in-stream tidal turbine known as AR1500, which is anchored to the seabed, originates from SIMEC Atlantis [109].

The Sea Gen turbine, developed by Marine Current Turbines (MCT), was the world's first commercial-scale tidal turbine. Commissioned in July 2008 in Strangford Lough, Northern Ireland, it marked a significant advancement in tidal energy. The Sea Gen project, featuring two 600 kW turbines, had a total capacity of 1.2 MW and required a £12 million investment [38]. The model has been generating 5 GWh of power, meeting the annual energy needs of 1,500 households, as shown in Figure 26. Throughout its operational life, Sea Gen contributed 11.6 GWh to the grid before decommissioning in July 2019 [110]. Installed in May 2008, it was transported to Strangford Lough's mouth by barge, weighing 1000 tons with a 43 m wingspan. Designed by Peter Fraenkel, it operated like an *underwater windmill*, harnessing tidal currents to rotate its rotors. Built at Harland and Wolff shipyards in Belfast, Sea Gen was secured to the seabed in 14 days. It initially produced 150 kW of electricity during commissioning in July 2008, reaching full capacity by November 2008 [111].

With a mobile cross arm on a single 3 m diameter supporting pile, Sea Gen's twin rotors activated when tidal currents exceeded 1 m/s, achieving rotor tip speeds of approximately 12 m/s—approximately one-third of wind turbine speeds. The twin blades operated at a constant 14 rpm, driving a gearbox system [111].

The project, in partnership with ESB Independent Energy, supplied power to about 1,500 homes, with grid connection managed by Northern Ireland Electricity [20]. Deploying Sea Gen in the energetic tides of Strangford Lough presented unique technical challenges. As a pioneering underwater windmill, Sea Gen set a new precedent in tidal energy. Strangford Lough was a notable tidal hotspot in UK and Irish waters, alongside Anglesey, the Pentland Firth, and the Channel Islands [111].

Figure 26. Sea Gen [111].

In the summer of 2011, Atlantis Resources Corporation (now SAE Renewables) deployed its AR1000 tidal turbine at Berth 6 of the Fall of Warness tidal test site (see Figure 27). The AR1000 is a 1 MW horizontal-axis turbine, rated for a flow speed of 2.65 m/s, with an 18 m rotor diameter and a total weight of approximately 140 tons. The turbine was mounted on a 1,300-ton gravity-based structure and, when fully assembled, stood 22.5 m (73 feet) tall. Its control systems, including power conditioning and monitoring equipment, were housed in a dedicated control cabin on the island of Eday [21].

Following prototype testing at the European Marine Energy Centre (EMEC), the company advanced to the next-generation turbine, the AR1500. The AR1500 is being deployed as part of the Mey Gen project in the Pentland Firth. By March 2023, four 1.5 MW turbines had been installed at the Mey Gen site, which collectively generated 51 GWh of electrical energy for the national grid [111].

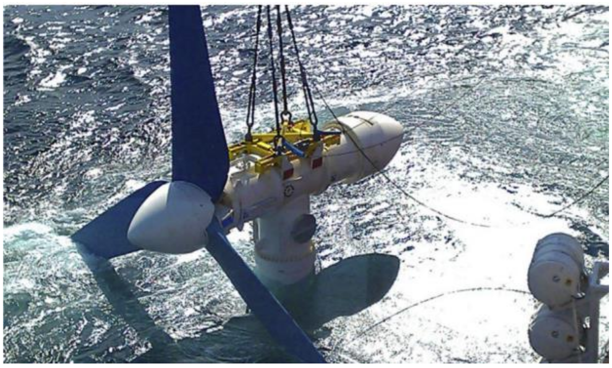


Figure 27. AR1000 tidal stream turbine (© Simec Atlantis Energy) [20].

Haiming I (10 kW) represents China's first long-term demonstration of a submarine vertical-axis tidal current power generation system (TCPGS), as illustrated in Figure 28. This power station, measuring 9.0 m × 7.5 m × 6.5 m and weighing 20 tons, is equipped with a horizontal-axis fixed-pitch turbine, an expansion-type deflector, and a direct-drive permanent magnet synchronous generator (PMSG). The station is supported by a three-legged base frame that can be raised for maintenance. Additionally, the platform incorporates a 180° self-adjusting reversing mechanism, allowing it to efficiently accommodate bidirectional currents [112].

Figure 28. Haiming I: 10 kW submarine vertical-axis TCPG [112].

Hai Neng II (2 × 100 kW), also known as the Zhaitang Island Isolated Hybrid Power Demonstration Station, is equipped with a cruciform carrier, two columns, and four flexible mooring systems, as illustrated in Figure 29. Each column supports a horizontal-axis variable-pitch turbine with a 12 m diameter [10]. These turbines are directly coupled to low-speed permanent magnet synchronous generators (PMSGs), each with a capacity of 100 kW, and are designed to operate in bidirectional tidal currents. The turbines have a rated flow velocity of 1.7 m/s, with a cut-in speed of 0.6 m/s and a cut-out speed of 2 m/s [11].

Figure 29. "Hai Neng II" 2 × 100 kW floating horizontal-axis TCPGS [11].

NTU and NTOU's collaboration led to the development of the Floating Kuroshio Turbine (FKT) system. Laboratory tests of a 1/25 scale model demonstrated a power generation capability of 850 W at a towing speed of 1.45 m/s. A feasibility study for a 1/5 scale model is underway, with expected power outputs of up to 20 kW [113].

The NSYSU team introduced the floating nozzle-diffusor duct (NDD) power generation system, depicted in Figure 30. Deployed near the Penghu cross-sea bridge in 2013, this system achieved a power take-off (PTO) of 5 kW during on-site testing. A new design iteration with a circular nozzle-diffusor duct is projected to triple the PTO compared to the previous model [113]. Additionally, a collaboration between NSYSU, Tainan Hydraulics Laboratory (THL), and Wanchi Steel Industry Company developed a 50 kW Kuroshio Ocean current power harvester. During a 60 h open-water towing test conducted in southeast Taiwan in 2016, the system achieved an average output of 26 kW at a current speed of 1.27 m/s [113].

Figure 30. Prototype of Floating Kuroshio Turbine (FKT) [113].

One such innovation involves the incorporation of ducted horizontal-axis devices, which enhance energy capture and resilience through refined flow dynamics. The following section delves into the design and performance benefits of these ducted systems, offering a new perspective on optimizing tidal energy extraction.

4.2. Ducted horizontal-axis devices in tidal turbines: enhancing efficiency and performance

The use of tidal currents presents unique design opportunities for turbines, particularly with ducted horizontal axis devices (see Figure 31). Unlike wind turbines, tidal turbines benefit from smaller rotor diameters, which facilitate the integration of ducting mechanisms to enhance flow dynamics. This innovation improves energy capture per unit of rotor area [114].

Ducted systems offer several advantages for tidal turbines. They enhance resilience to off-axis flow disturbances, a challenge often encountered by wind turbines. Additionally, supporting turbine blades at their extremities is feasible, which enhances load resistance and structural integrity. Key to the design of these turbines is their adaptability to tidal flow variations. Turbines must operate efficiently in both directions to accommodate changing tidal flows. Incorporating bi-directional rotors is essential for this purpose. As depicted in Figure 32, this approach redefines energy extraction potential from tidal currents, increasing efficiency, resilience to flow fluctuations, and performance under varying tidal conditions [115].

Figure 31. Illustration of ducted horizontal-axis tidal turbines (Open Hydro) [28].

The next section explores multiple open-rotor horizontal-axis devices, highlighting their potential to enhance energy generation capacity and operational efficiency in tidal stream systems.

4.3. Multiple open-rotor horizontal axis devices

Various rotor concepts aim to maximize generating capacity on each foundation, overcoming limitations imposed by single rotor sizes. These concepts address issues such as asymmetric loading, dynamic behavior during failures, and maintenance considerations, as illustrated in Figure 32.

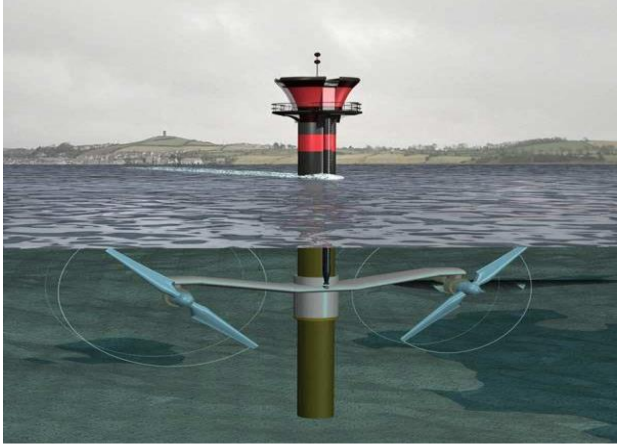


Figure 32. Multiple open-rotor horizontal-axis device (© MCT) [28].

4.4. Transverse axis devices

The Darrieus-type wind turbine and vertical-axis marine current turbines function as lift-based systems with the generation axis perpendicular to the flow [114]. While they may have lower theoretical efficiency compared to horizontal-axis machines, they offer benefits in structural efficiency and maintenance. Some designs are exploring ducting to enhance energy capture. A significant concept is the modular tidal fence array, where multiple devices are interconnected. Economic considerations include the size of the required ducting, as shown in Figure 33 [114].

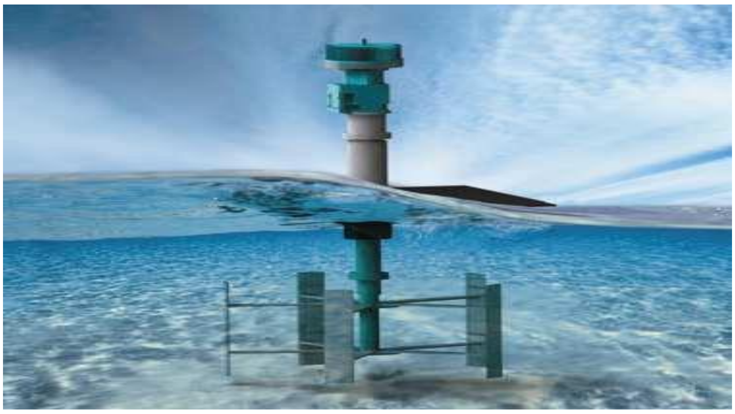


Figure 33. Transverse axis devices [114].

Table 1 summarizes experimental twin-rotor tidal current turbines worldwide. Most of these turbines are in the demonstration phase and have not yet reached commercial deployment [116]. The floating catamaran, among various floating mooring platforms, is particularly promising. It provides a spacious deck, facilitates maintenance and deployment, and adapts well to varying water depths and complex seabed topographies [117].

Table 1. Pilot floating two-rotor tidal current turbines in the world [11].

Institutions	Location	Turbine name	Turbine number	Platform	Total capacity	Operation year
MCT-Atlantis Resources	Kyle Rhea (Scotland, UK)	Sea Gen	2	Pile foundation	2 × 600 W	≥2016
AK-1000	Singapore	AK-1000	2	Seabed mounted	2 × 500 W	≥2010
SMD Hydro Vision Ltd	Orkney, UK	Tidel	2	Floating foundation	2 × 500 W	≥2006
National Taiwan Ocean University	Coast of Taiwan	Kurshio	2	Floating foundation	2 × 10 W	≥2016
Harbin Engineering University	Zhejiang, China	Hai Neng I	2	Floating foundation (catamaran)	2 × 150 W	≥2010
Harbin Engineering University	Qingdao, China	Hai Neng II	2	Floating foundation (catamaran)	2 × 100 W	2013
Harbin Engineering University	Zhejiang, China	Hai Neng III		Floating foundation (catamaran)	2 × 300 W	≥2013

While the development of individual tidal energy devices continues to evolve, hybrid configurations that integrate multiple renewable energy sources present a compelling solution for overcoming the limitations of standalone systems. By combining wind and tidal stream technologies, hybrid systems capitalize on the complementary characteristics of these resources, ensuring greater reliability and efficiency in electricity generation. The following section examines the growing trend toward multi-energy systems, emphasizing the benefits of integrating wind and tidal energy technologies into a unified framework.

5. Hybrid configurations integrating wind and tidal stream technologies

Exclusive reliance on wind energy for electricity generation is significantly affected by environmental variability. By integrating multiple renewable sources—such as wind and tidal, each with unique characteristics and advantages—it is possible to mitigate individual limitations and enhance overall system efficiency. Recent developments reflect a growing trend toward multi-energy complementary systems.

5.1. Hybrid system combining offshore wind and tidal turbines

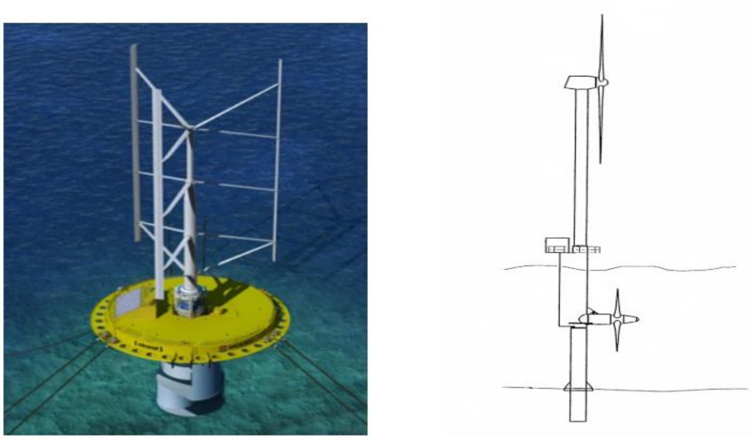
Hybrid energy models that combine tidal and wind power technologies are increasingly explored. These systems typically feature separate subsystems for tidal and wind energy, sharing a common platform [118]. Combining wind and tidal energy can stabilize power output and reduce fluctuations. However, optimizing multi-energy systems requires advanced assessment technologies to account for the varying characteristics of different energy sources [119].

5.2. Offshore wind and tidal concepts

Hybrid systems that merge wind and tidal technologies are still under development. Two notable designs include:

- Savonius Keel and Wind Turbine Darrieus (SKWID), shown in Figure 34, is a unique prototype developed by Mitsui Ocean Development and Engineering Company (MODEC). This system combines a Savonius current turbine with a Darrieus wind turbine and is designed for deployment off the coast of Japan. Its primary goal is to provide reliable backup power to isolated islands, offering a sustainable energy solution for remote locations [120].
- Marine Current Turbines' Patented Device: Inspired by the Sea Gen tidal apparatus, this concept features multiple tidal turbines mounted on a single-column structure. Though still in the conceptual phase, it proposes elevating turbines above water to improve efficiency [120].

Combining the outputs of tidal and wind turbines results in a total annual energy generation of 96.41 GWh, which is double that of using tidal turbines alone [121].



(a) (b)

Figure 34. (a) MODEC's SKWID, Savonius Keel and Wind Turbine Darrieus. (b) Marine Current Turbine's patented turbine that combines air and water flow [119].

The Hybrid Offshore Wind and Tidal Turbine (HOTT) system integrates tidal current generation to manage wind power fluctuations, as shown in Figure 35 [120]. This hybrid approach aims to stabilize power production and enhance system reliability, particularly for remote islands where extending the electricity grid is economically unfeasible [121]. This approach offers a viable solution for sustainable energy collection, with future research focusing on storage, grid integration, power regulation, cost optimization, and environmental impact assessment [122].

Various connection methods are available, with the DC bus-based approach selected for its cost-effectiveness and simplified control [123]. The focus remains on capital expenditures (CAPEX) and operational expenditures (OPEX), which are critical for optimizing energy production costs. Addressing potential instability from renewable energy integration will be essential as cumulative renewable capacity increases [124].

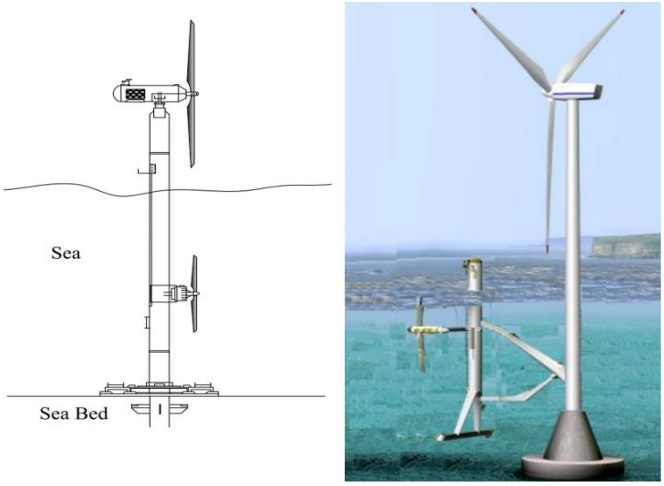


Figure 35. Illustration depicting the concept of a hybrid offshore wind-tidal (HOTT) system [125].

6. Conclusions

The integration of offshore wind and tidal stream technologies offers a transformative approach to addressing the increasing energy demands of coastal regions. This hybrid approach provides a sustainable pathway toward decarbonization, with tidal energy emerging as a vital component due to its predictability and advancing technology. Although challenges such as cost-effectiveness, scalability, and reliability persist, this study highlights the significant potential of hybrid systems, particularly those leveraging resources like the Agulhas Current, to enhance energy stability, reliability, and efficiency.

Key developmental pathways identified in this study include advancing large-scale turbines for grid integration for localized marine applications. To further the practical adoption of these systems, future research must address the technical and economic challenges in a focused and systematic manner.

Future research directions

To guide continued progress, the following specific areas are proposed for future exploration:

1. **Advanced materials and structural designs**

- Investigate innovative materials, including corrosion-resistant alloys and composites, to enhance durability and reduce operational costs in harsh marine environments.
- Explore biomimetic designs inspired by aquatic organisms to improve turbine efficiency and minimize ecological disruption.

2. **Computational methodologies and AI integration**

- Develop AI-driven optimization tools to enhance turbine performance, predictive maintenance, and control strategies for hybrid wind-tidal systems.
- Incorporate machine learning in energy management systems and power converter design to improve grid integration and real-time adaptability.

3. **Energy storage solutions**

- Focus on hybrid storage systems combining short-term (e.g., super-capacitors) and long-term (e.g., advanced battery technologies) solutions to stabilize power supply.
- Explore modular and scalable storage designs tailored to the unique intermittency profiles of wind and tidal energy.

4. **Power conversion and grid integration**

- Develop advanced converter technologies to improve power quality, reduce harmonic distortion, and ensure seamless integration into national grids.
- Investigate HVDC and advanced AC transmission systems for efficient energy transport from offshore systems to onshore grids.

5. **Environmental impact and ecosystem integration**

- Conduct detailed impact assessments to ensure minimal disruption to marine ecosystems, with a focus on species migration patterns and habitat preservation.
- Implement AI- and IoT-enabled adaptive monitoring systems for real-time assessment and mitigation of ecological effects.

Broader prospects

Looking ahead, scaling pilot projects into full-scale commercial installations will be critical, particularly in regions with high energy potential, such as the Agulhas Current. Success in this domain will require robust interdisciplinary collaboration among engineers, environmental scientists, economists, and policymakers. Additionally, fostering international partnerships and sharing best practices from successful projects can accelerate technological innovation and cost reduction in offshore hybrid energy systems. By addressing these challenges and seizing growth opportunities, hybrid wind-tidal systems can play a pivotal role in achieving global sustainability and energy resilience goals.

Use of AI tools declaration

The authors declare that no Artificial Intelligence (AI) tools were used in the creation of this article, including in the drafting, editing, or data analysis processes.

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Conflict of interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

Author contributions

Ladislas Kangaji led the research, conducted the literature review, and was responsible for the collection and organization of review papers. He also drafted the manuscript and coordinated the writing process. Atanda Raji provided critical insights, guided the development of the research methodology, and played a key role in reviewing and revising the manuscript. Efe Orumwense contributed to the conceptual framework of the study and provided valuable feedback during the manuscript editing process.

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