

## TOPICAL REVIEW

# Powering the Sea: Challenges and Trends in Tidal Energy Integration, Power Converter Technology, and the Path Forward

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**ABSTRACT** The global demand for sustainable energy has shifted interest in Marine Renewable Energy (MRE) sources. Tidal energy is particularly attractive within this domain due to its predictability and high capacity factors. However, practical and large-scale deployment remains constrained by challenges in resource variability, subsea reliability, and grid compliance. This review provides a focused and comprehensive assessment of tidal energy systems, particularly emphasizing Power Electronic Converters (PECs) as the pivotal enabler of efficient energy extraction, control, and grid integration. A structured challenge-mitigation framework is developed across three domains: resource assessment, converter topologies, and grid interaction, revealing unresolved issues in long-term reliability, converter robustness, and system-level stability. Forward-looking research directions are also identified, including hybrid tidal-renewable integration, modular and multiport PEC architectures, and advanced monitoring frameworks, all expected to accelerate technology readiness and support cost-effective scaling. This review offers a roadmap for transitioning tidal energy toward dependable, cost-effective, and sustainable expansion by bridging insights across the resource, converter, and grid domains.

**INDEX TERMS** Tidal energy, grid integration challenges, power converter architecture, technology advancements.

## I. INTRODUCTION

Fossil fuel-based conventional power systems are undergoing a significant transformation due to fuel depletion, climate change, and global price instability [1]. The year 2024 was recorded as the warmest on record, according to an analysis by the National Oceanic and Atmospheric Administration (NOAA), underscoring the urgency of transitioning to cleaner energy sources [2]. Additionally, the International Energy Agency (IEA) outlook 2022 revealed a concerning trend:

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the number of people without access to modern energy is increasing for the first time in a decade [3]. Approximately 75 million individuals who recently gained access to electricity may lose that access due to affordability issues, while 100 million people could resort to traditional biomass for cooking. Moreover, energy-related carbon dioxide emissions surged to 37.8 Gt in 2025, marking the all-time high [4]. This underscores the urgent need to explore alternative clean energy sources to achieve the net-zero emissions target.

The ocean has abundant untapped energy from tides, waves, currents, and temperature gradients. Marine Renewable Energy (MRE) encompasses technologies that harness

these resources to generate electricity sustainably [5]. Among these, tidal energy, generated from the regular rise, fall, and flow of seawater, stands out for its high reliability, strong energy density, and highly predictable nature, which is driven by the gravitational pull of the moon and sun. These characteristics make tidal energy inherently more reliable and grid-compatible than other marine sources, such as wave energy, and significantly more stable than intermittent land-based renewables like wind and solar [6]. However, extracting tidal energy and delivering it to the power grid involves significant challenges at various technical and operational levels [7], [8].

These challenges arise from the harsh marine environment, the complexities of grid integration, and the critical role of Power Electronic Converters (PECs) in tidal energy applications. PECs are essential for optimizing energy harvesting and ensuring tidal systems' stable and resilient integration into the grid. Power converters enhance the efficiency and reliability of these systems by enabling greater control flexibility. However, the high penetration of PECs in modern MRE-based power systems introduces new dynamics and operational challenges [9]. Hence, identifying these challenges and analyzing both existing and emerging mitigation strategies is the first obligation towards transferring power from ocean to wire.

Recent state-of-the-art reviews have addressed the challenges associated with tidal energy, covering aspects such as technical reliability, social and environmental considerations [7], geographical resource assessment [10], and economical factors [11]. Table 1 summarizes the recent state-of-the-art in addressing the challenges of tidal energy conversion by exploring three critical aspects: the inherent challenges of the energy source, the difficulties in its grid integration, and the complexities associated with PECs. Literature [12] delves into technical aspects, including resource assessment, modeling, control systems, and failure analysis. It highlights the growing significance of emerging technologies such as Artificial Intelligence (AI), data analysis, blockchain, and the Internet of Things (IoT) in shaping the future of tidal energy systems.

Another review [13] presents the state-of-the-art Tidal Current Energy Converters (TCEC) technological developments in China regarding scale, efficiency, reliability, and other innovations. The paper also describes the current challenges and future trends of large-sized turbines for grid connection and small-scale turbines for diverse applications in marine environments. Furthermore, a comprehensive examination of tidal range and tidal stream energy resources, feedback mechanisms, and environmental interactions is provided in another review [14]. Reference [15] assesses Germany's tidal energy potential along the North Sea coast, identifying a practical resource of 66.6–565.8 GWh/year while highlighting the need for technology advancements for shallow waters and low-current conditions.

A comprehensive review in [16] covers hybrid wave-tidal converters, analysis methods, technology gaps, and future research opportunities. Life Cycle Assessment (LCA) studies evaluating the environmental performance of wave and tidal energy technologies are reviewed in [17], offering insights into their sustainability. Reference [18] offers an overview of the current state of ocean energy research, emphasizing research beyond technological advancements and highlighting key research gaps and future directions.

Despite these extensive reviews, the literature on the applications and challenges of PECs in marine environments remains limited in scope. For example, [19] provides insights into tidal energy technologies and briefly discusses the role and architecture of PEC topologies. However, it does not comprehensively explore the converter control strategies, hybrid AC/DC interfacing schemes, or mitigation techniques for PEC-related constraints such as switching losses, bidirectional flow, or marine-induced stresses. Similarly, [20] focuses primarily on early-phase cost modeling for tidal energy farms and includes preliminary references to PEC selection and deployment. Yet, it treats electrical systems largely as closed-box elements without analyzing their influence on efficiency, reliability, or fault resilience, leaving a gap in techno-economic evaluations of converter choices.

Additionally, [21] offers a focused review on frequency converters' technical maturity and reliability in subsea applications. While it effectively highlights stress factors such as pressure, temperature, and insulation degradation, the study is limited to general-purpose subsea PECs and does not consider application-specific nuances of tidal energy systems, such as flow directionality, transient load behavior, or grid support functionality.

Some literature also discusses the challenges associated with the optimal placement of power converter devices, which are crucial for simplifying Power Take-Off (PTO) systems and reducing energy costs. This concern becomes increasingly important with the development of large-scale tidal turbines [22]. However, the review does not elaborate on how converter placement influences system-level metrics like control response time, harmonic distortion, or maintenance accessibility under tidal conditions. Emerging approaches, such as subsea nacelles or floating platforms, are acknowledged but lack quantitative performance benchmarking or design optimization strategies.

In [23], a review of tidal current turbine configurations and control strategies is presented, highlighting differences in cost and failure rates between various turbine types. Nonetheless, the study limits its discussion on PECs to basic configurations, with minimal attention to advanced modulation techniques, thermal protection, or converter-fault ride-through capabilities. Furthermore, [24] discusses key technical issues, including reliability-centered configuration, interconnection, environment management, and biofouling. While it contributes significantly to Subsea Electric Power

TABLE 1. Overview of research articles addressing MRE challenges.

Ref.	MRE Source	Grid Integration	PECs	Core Technical Focus and Contributions
[7]	✓	✗	✗	Comprehensive resource overview; lacks focus on grid interfacing or PECs.
[11]	✓	✓	✗	Discusses system-level integration; converter technologies not addressed.
[12]	✓	✗	✗	Focus on MRE resource characteristics; converter and grid domains absent.
[13]	✓	✓	✗	Explores integration at system level; PEC roles not discussed.
[14]	✓	✗	✗	Resource and hydrodynamic review; no PEC or integration strategies.
[15]	✓	✗	✗	Focused on design standards and reliability; lacks converter or grid insight.
[16]	✓	✗	✗	Discusses project planning aspects; omits PECs and integration frameworks.
[17]	✓	✗	✗	Emphasis on lifecycle analysis; no system or PEC-level discussion.
[18]	✓	✓	✗	Economic and impact analysis; converter architecture not covered.
[19]	✓	✓	~	Reviews turbine and PEC advancements; limited discussion on mitigation and integration frameworks.
[20]	✓	~	~	Emphasizes early-phase cost modeling with basic PEC and grid representation; lacks technical integration details.
[21]	✗	✗	✓	Focused on PEC reliability modeling for subsea applications; does not address tidal-specific integration.
[22]	✓	✗	✓	Discusses PECs in general; lacks discussion on integration strategies.
[23]	✓	✓	~	Strong on turbine configuration/control; limited insight into hybrid PEC roles and integration methods.
[24]	✓	~	~	In-depth analysis of SEPG and PEC reliability; lacks full mitigation strategy framework.

Note: ✓ = Fully Addressed; ~ = Partially Addressed; ✗ = Not Addressed

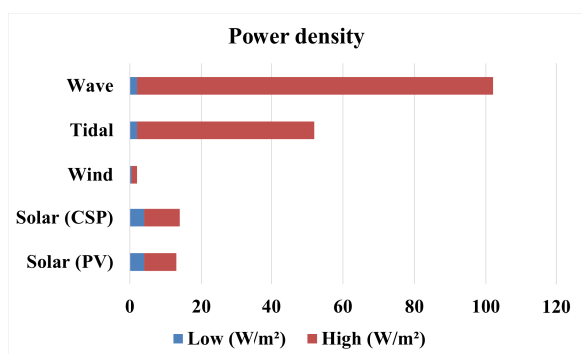


FIGURE 1. Power density of renewable energy [25].

Grid (SEPG) reliability, it does not fully explore the integration of PECs with grid-side control, or the cross-domain mitigation strategies that jointly address converter, grid, and resource variability.

A. CONTRIBUTION OF THE PAPER

Despite the growing body of research, there remains a gap in comprehensive studies that systematically address the challenges of tidal energy systems. While prior works have examined individual aspects of tidal technologies and PECs in isolation, a holistic perspective that integrates these dimensions and explores their interrelated challenges and solutions is still lacking.

This review addresses these key gaps in existing tidal energy literature by offering a unified, challenge-driven analysis of tidal resource characteristics, PEC roles, and grid integration complexities. Unlike previous studies that

consider these aspects in isolation, this work adopts a system-level view across three domains: tidal source variability, PEC adaptation and control, and grid interfacing challenges.

Key contributions include:

- A structured challenge-solution framework spanning source, converter, and grid domains.
- Detailed discussion on PEC topologies (AC/DC, Back-to-Back (BTB), AC/AC), and marine-specific deployment needs.
- Insights into advanced grid integration techniques, including virtual inertia, droop control, and power quality enhancement.
- Evaluation of emerging technologies such as packaging, pressure-tolerant PECs, smart enclosures, and monitoring techniques.
- Identification of future research needs, including modular converter architectures, hybrid tidal systems, and co-optimized control schemes.

This paper provides a holistic foundation for advancing PEC-integrated tidal energy systems and supports future development of robust, scalable tidal energy infrastructures.

B. ORGANIZATION OF THE PAPER

The rest of the paper is organized as follows: Section II reviews the current state of MRE, with particular attention to tidal generation. Section III discusses the challenges and existing solutions related to tidal generation, grid integration, and the application of PECs. Section IV reviews various PEC architectures used in tidal systems. Section V explores advancements in PEC development in tidal applications,

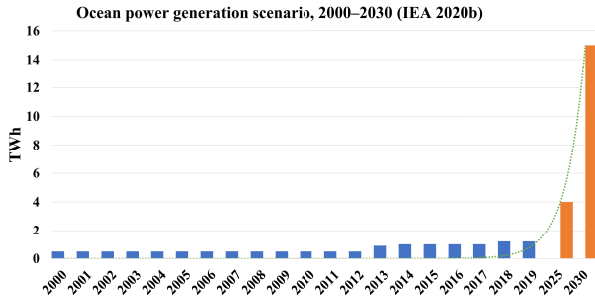


FIGURE 2. Ocean power generation scenario, 2000–2030 [29].

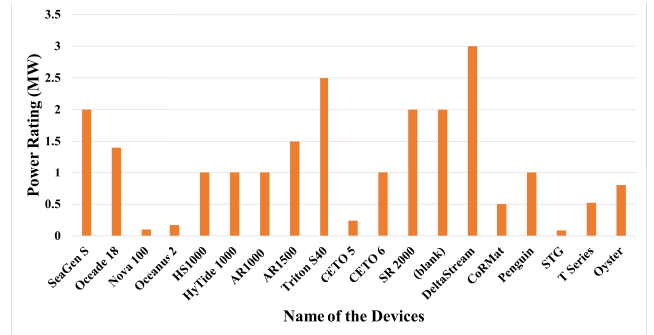


FIGURE 4. Power rating of candidate machine [30].

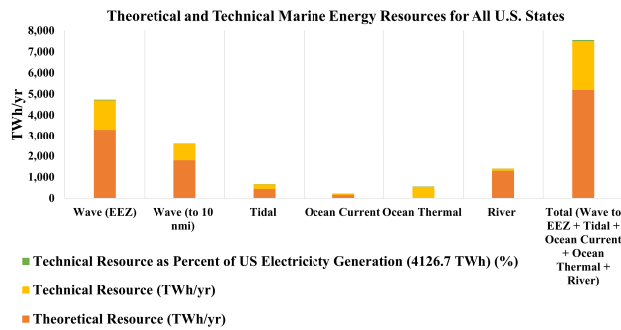


FIGURE 3. Theoretical and technical marine energy resources for all U.S. states [5].

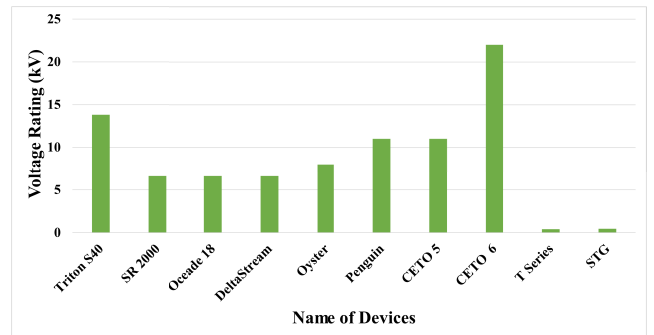


FIGURE 5. Voltage rating of candidate machine [30].

focusing on Wide-Bandgap (WBG) technologies, packaging considerations, and reliability enhancements. Section VI outlines potential future research directions. Finally, Section VII concludes the paper with key insights and closing remarks.

## II. CURRENT STATUS OF MRE ENERGY

Inflation in energy costs, growing environmental pollution, and demand for efficient energy benefit the market for renewable energy. The future energy market is moving towards a decentralized supply model, where tapping into different distributed energy resources becomes essential for efficient and quality power supply. Renewable energy, dominated mainly by wind and solar, contributes about 20% to all electricity in the United States, which is steadily increasing. However, unpredictability and low capacity of wind and solar sources have led to demand for alternative renewable energy sources. Tidal energy, a key subset of MRE, stands out due to its high power density, strong capacity factor, and predictability (Fig. 1). Compared to many other renewable sources, tidal systems offer distinct advantages in dependability, durability, and long-term reliability [26]. These characteristics make tidal energy one of the closest renewable candidates to dispatchable and load-following generation [27], positioning it as a strong alternative to conventional power sources.

In addition, the predictability of tidal resources can complement the variability of wind and solar, reducing reliance on

large-scale storage or backup gen-sets. Studies such as [28] advocate integrating tidal systems with other renewables to partially mitigate intermittency while improving system reliability and lowering generation costs, particularly in coastal and islanded regions. According to the IEA, ocean energy generation is projected to grow by more than 33% by 2030 (Fig. 2) [29], a trajectory that aligns with global net-zero emission targets for 2050. Amid the COVID-19 crisis, the global market for Ocean Energy, estimated at 58.7 Thousand Kilowatts in the year 2020, is projected to reach a revised size of 348.1 thousand Kilowatts by 2026, growing at a Compound Annual Growth Rate (CAGR) of 35.4 % over the analysis period.

According to the United States Department of Energy (DOE) estimates, the combined technical potential of MRE resources, including tidal, ocean current, ocean thermal, and riverine, is approximately 2,300 Terawatt-Hour per year (TWh/yr), equivalent to 57% of total U.S. electricity generation in 2019 (Fig. 3) [5]. Within this portfolio, tidal energy has seen significant technological progress. Fig. 4 and Fig. 5 illustrate the power and voltage ratings of machines currently available for commercial tidal energy generation [30]. Historically, a 1 MW capacity was regarded as the standard rating for horizontal-axis Tidal Energy Converters (TECs). With continued field trials and demonstrations, device ratings have steadily advanced from the kilowatt scale to multi-megawatt units. These TECs are deployed in floating and seabed-mounted configurations, reflecting

**TABLE 2.** List of operational MRE power plants [31], [32], [33].

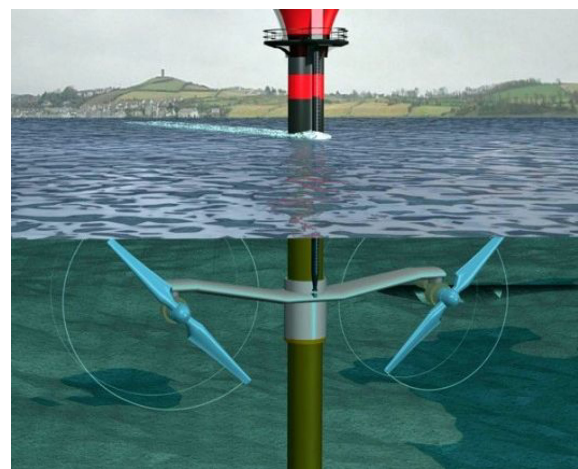
Tidal Project	Technology Developer	Place	kW
Sustainable Marine	Sustainable Marine	Grand Passage, Nova Scotia	280
Jiangxia Tidal Power Plant	China Long Yuan Power Group Corporation	Wenling, Zhejiang Province	4100
Haishan Tidal Power Plant	Haishan Tidal Power	Maotian Island, Zhejiang Province	250
La Rance Barrage	EDF	La Rance estuary, Brittany	240000
LHD Tidal Current Energy Demonstration Project	Hangzhou United Energy Corporation	Xiushan Island, Zhejiang Province	1700
OceanQuest	HydroQuest	Bréhat-Paimpol test site, Brittany	1000
Sabella D10 Brittany	Sabella	Ushant island	1000
Sihwa Lake Tidal Power Station	K-Water	Ansan, Gyeonggi, Korea	254000
Uldolmok Tidal Pilot Power Plant	KIOST	Jindo, Korea	1500
MeyGen	SIMEC-Atlantis Energy	Pentland Firth, Scotland	6000
ITEG	Orbital Marine Power/EMEC	Orkney Islands, Scotland	2000

**TABLE 3.** List of underdeveloped tidal powe plants [31], [32].

Project	Technology Developer	Place	kW
ORPC Cook Inlet Under	Ocean Renewable Power Company (ORPC)	Cook Inlet, Alaska	5000
Floating Tidal Energy Commercialisation (FloTEC), Scotland Under	Orbital Marine Power/EMEC	Orkney Islands, Scotland	6000
Holyhead Deep	Minesto	Holyhead, North Wales	80000
Aquantis Advanced Turbine Technology	Aquantis	New Zealand	-
GEMSTAR Demonstration II	Seapower Scrl	Messina, Thyrrenian Sea	300
NIOT Off-grid hydrokinetic turbine	NIOT	Andaman & Nicobar	5
Phares	Sabella	Ushant island, Brittany	1000
Flowatt	Hydroquest	Raz Blanchard, Normandie	17500
Zhoushan Tidal Current Energy	China Three Gorges Corporation (CTG)	Hulu Island, Zhejiang Province	450
Uisce Tapa Project	Andrtiz Hammerfest Hydro	FORCE site, Nova Scotia	9000
Sustainable Marine	Sustainable Marine	FORCE site, Nova Scotia	9000
Nova Innovations	Nova Innovations	Petit Passage, Nova Scotia	1500
Big Moon Power	Big Moon Power	Minas Passage, Nova Scotia	5000
Jupiter Hydro	Jupiter Hydro	Minas Passage, Nova Scotia	2000
New East Energy	New East Energy	Minas Passage, Nova Scotia	800



**FIGURE 6.** Verdant power tidal turbine [34].



**FIGURE 7.** SeaGen turbine at Strangford Lough [37].

adaptability to marine environments. Examples of operational and developmental tidal projects, along with their power ratings, are summarized in Table 2 and Table 3 ([31], [32], [33]).

Fig. 6 shows the Verdant Power tidal turbine at the East River of New York City. It was the first licensed tidal power project deployment in the U.S. [34], [35]. The project is a grid-connected array of tidal power turbines that furnishes the metrics for system performance and operational costs. This helps demonstrate the MRE project as a distributed generation for alternative global market opportunities. SeaGen turbine at Strangford Lough

is shown in Fig. 7. This 1.2 MW project is reported as the world’s first large commercially installed tidal generator [36], [37]. Although decommissioned between 2016 and 2019, it played a crucial role in advancing the understanding of tidal stream technology throughout its operational lifespan. Additionally, Fig. 8 illustrates the Open Hydro turbine at the European Marine Energy Centre (EMEC) tidal test site, representing the first and longest-standing tidal turbine [38].



FIGURE 8. Open hydro turbine at EMEC tidal test site [38].

### III. KEY CHALLENGES IN TIDAL SYSTEMS: INSIGHTS AND SOLUTIONS

Harnessing energy from tidal resources and delivering it to the power grid entails complex challenges spanning environmental, economic, and technical domains [8]. The harsh marine environment leads to issues such as corrosion, biofouling, and mechanical wear, which elevate failure rates and complicate system maintenance and monitoring. Additionally, the Levelized Cost of Energy (LCOE) for tidal energy remains significantly higher, often twice that of fossil fuel-based systems, requiring innovation in device design, deployment, and control strategies to improve cost competitiveness.

Although tidal energy offers highly predictable generation patterns, its non-dispatchable nature and phase-shifted multi-site profiles can create challenges in matching supply with instantaneous grid demand [39]. Grid integration is further complicated by the oscillatory power output associated with tidal cycles and power ramping during tidal phase transition, which can introduce fluctuations in voltage and frequency [40], [41], [42]. These issues necessitate robust PECs capable of regulating power quality, maintaining synchronization, and ensuring safe and reliable grid interfacing.

While PECs enable control flexibility and dynamic grid support, their deployment in marine environments introduces additional concerns such as pressure tolerance, thermal cycling, and humidity management. Therefore, addressing the full spectrum of tidal energy integration requires careful coordination of resource harvesting, converter reliability, and grid compatibility.

To systematically analyze these issues, the challenges are categorized across the key stages of the tidal energy conversion and delivery process:

- 1) Resource-side challenges specific to tidal energy conversion,
- 2) Grid integration challenges, and
- 3) Power electronic converter challenges for robust and efficient operation in tidal settings.

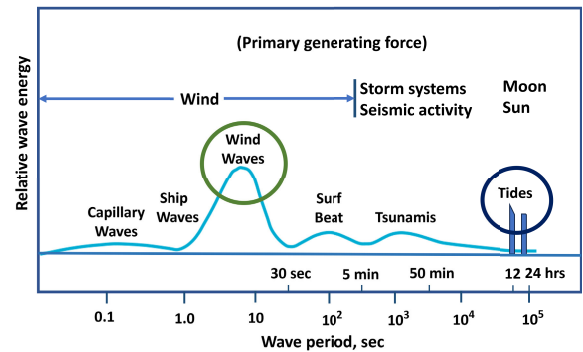


FIGURE 9. Tidal variation time-scale [43].

### A. MAJOR CHALLENGES AND MITIGATION STRATEGIES IN ENERGY EXTRACTION AND CONVERSION FROM TIDAL SOURCES

The challenges associated with tidal sources include dealing with resource assessment, energy extraction, optimized PTO design, economic viability, overcoming logistical hurdles, managing environmental impacts, and conducting reliable system reliability assessments. These key challenges of tidal energy resource, with mitigation strategies, research gaps, and technology maturity, are summarized in Table 4.

#### 1) CHALLENGES IN TIDAL RESOURCE/SITE ASSESSMENT

Tidal stream turbine deployment is constrained by site-specific flow velocity, depth, and directional consistency. Most current technologies require spring tide velocities above 2.5 m/s and water depths between 25–50 m, limiting suitable locations [39]. Shallow sites suffer from wave-induced turbulence, while deeper sites incur high installation costs and lower current speeds. Additionally, bidirectional flow misalignment between ebb and flood tides can reduce energy capture efficiency [39]. Beyond flow dynamics, seabed conditions, grid proximity, and maintenance access critically shape the feasibility of tidal projects. Rocky or unstable seabeds raise foundation costs, while distant sites face expensive cabling and substations. Moreover, environmental and regulatory limits often exclude resource-rich areas, such as marine habitats or navigation routes [44], [45]. High-resolution 3D hydrodynamic modeling and hub-height Acoustic Doppler Current Profiler (ADCP) measurements have improved site characterization, yet uncertainties remain due to spatial variability and limited long-term field data [35], [46]. Advanced turbine designs operating at lower cut-in speeds, integrating environmental datasets, and yaw-capable turbines are emerging strategies, though many require further validation and standardization [5], [27].

#### 2) CHALLENGES IN ENERGY EXTRACTION

Tidal energy's predictability and substantial energy density render it an appealing solution to address the global energy crisis. Unlike wave energy, which is highly intermittent and variable over both spatial and temporal scales [47], tidal

**TABLE 4. Challenges of tidal energy resources: Mitigation strategies, references, research gaps, and technology maturity.**

Identified Challenges	Tidal-Specific Issues	Mitigation Strategies	References	Research Gaps	Technical Maturity
<b>Resource / Site Assessment [39], [44], [45]</b>	• Velocity thresholds	Low cut-in speed turbines	[39], [46]	Techno-Eco Trade-off at sub-optimal speeds	Medium
	• Depth constraints	High Resolution 3D hydrodynamic modeling	[35], [39], [46]	Computational cost vs. scalability in large domains	Medium
	• High Spatial & temporal variability	ADCP-based velocity & turbulence profiling	[35], [46]	Sparse long-term field data	Medium
	• Directional flow misalignment	Yaw-enabled turbine designs	[39]	Limited commercial trials	Low
	• Uncertain resource exploitability	Integrate environmental data	[5], [46]	Lack of standard techno-ecological frameworks	Medium
<b>Variability &amp; Intermittency [47]–[51]</b>	• Non-dispatchable; phase-shifted multi-site profile	Resource forecasting	[27], [46], [52]–[54]	Limited high-resolution forecasting multi-site models	Medium
	• Mismatch with demand peaks	Load forecasting & DSM	[55]–[58]	Limited real-time grid integration	Medium
	• Limited generation windows due to tidal cycles	Energy storage / flexible gen.	[59]–[61]	Optimal ESS sizing under tidal profiles	Medium
	• Site-dependent intermittency	Hybrid / multiple plants	[62]–[64]	Advanced hybrid dispatch & tidal-phase based site selection	Medium
<b>High LCOE [65]–[78]</b>	• High O&M and capital cost (marine deployment)	Cost-based analytical evaluation	[77, 79]–[82]	Site/device-specific cost models including uncertainty/reliability	Medium
	• Limited access; harsh environment	Advanced LCOE evaluation tools	[20], [77]	Limited lifecycle-based tidal cost assessment	Low
	• Inefficient PTO increases cost	Simplified PTO + advanced control	[11], [41], [83]–[85]	Real-time validation in harsh conditions	Medium
	• Underused spatial energy synergy	Synergistic/co-located systems	[86]–[90]	More field-tested evidence on cost savings	Medium
	• Limited use of advanced semiconductor devices	WBG / hybrid devices	[91]–[94]	Marine-grade WBG reliability & cooling are underexplored	Low
<b>Biofouling &amp; Corrosion [95]–[97]</b>	• Accelerated seawater degradation	Composite/novel materials	[98]–[100]	Lack of long-term marine performance data	Medium
	• Bioaccumulation on surfaces	Eco-friendly antifoulants	[101]	Effectiveness & environmental compatibility are underexplored	Low
	• Salt corrosion in mechanical & electrical PTO	Special paints/chemicals	[102]	Durability under salinity/pressure variation	Medium
<b>Transportation &amp; Installation [103], [104]</b>	• Harsh weather & tidal currents	Folding turbines	[103], [104]	Limited commercial deployment	Medium
	• Costly specialized vessels/equipment	Specialized tools/equipment	[26], [105]	Limited availability; high capex	Medium
	• Remote/difficult site access	Co-located deployment	[87], [86]	Inter-technology compatibility; layout optimization is underexplored	Low
<b>Reliability Assessment [106]</b>	• Harsh conditions limit monitoring	Real-time monitoring	[106], [107]	Low-power subsea sensor integration & advanced monitoring tools	Medium
	• Inaccurate failure prediction	Prognostic methods	[108]–[110]	Real-time condition-based prognosis is not mature (tidal)	Low
<b>Environmental Impact [26], [111]</b>	• Uncertain habitat impacts	Noise/chemical emission monitoring	[111], [103], [104]	Cumulative long-term impact studies are still emerging	Low
	• EMF exposure in aquatic life	EMF shielding/reduction	[26], [112]	Need for more empirical validation on migratory species	Low
	• Local hydrodynamic changes	Hydrodynamic optimization	[87], [86]	Energy capture–ecosystem trade-offs	Medium

**Note:** Technology Maturity levels: High = commercially deployed; Medium = validated in pilots/prototypes; Low = conceptual/early stage.

energy exhibits significantly less variability compared to other renewable energy sources, such as wind and wave energy [43], [48] (Fig. 9). While tidal energy systems exhibit multi-hour variability patterns similar to solar photovoltaic (PV) systems, the underlying converter design, control strategies, and deployment environments differ significantly. PV systems typically operate in terrestrial, low-humidity environments, often without the need for extensive galvanic isolation or pressure-tolerant enclosures. In contrast, tidal energy systems demand robust subsea or floating converter architectures, capable of withstanding hydrostatic pressure, corrosion, and biofouling over long operational lifetimes.

Moreover, tidal power electronics must support bidirectional power flow, particularly in reversing tidal streams, and require adaptive Maximum Power Point Tracking (MPPT) tailored to nonlinear hydrodynamic profiles. This differs from irradiance-driven MPPT in PV systems. Additionally, power converters in tidal systems often feature high-frequency isolation, modular redundancy, and thermal resilience, reflecting marine-specific operational constraints.

Although lessons from solar PV systems, such as thermal management or modular design, can inform aspects of tidal converter development, direct translation is limited. This review highlights marine-specific challenges in power conversion, grid interfacing, and control—areas where existing PV-oriented solutions fall short. As such, the paper underscores the need for dedicated PEC innovations aligned with tidal energy systems' physical and operational realities.

Despite the predictability, tidal energy is still intermittent in nature. Its generation remains intermittent, governed by natural cycles—diurnal (once daily), semidiurnal (twice daily), and fortnightly spring-neap patterns [49], [50]. While the extent of variability is relatively low compared to other renewable sources [51], it remains inherently dynamic as it has a limited window for electricity generation.

This intermittency and variability of tidal energy sources make them non-dispatchable, diminishing the reliability and consistency of electricity generated from tidal streams. To mitigate this inherent intermittency and variability of tidal energy resource forecasting [27], [46], [52], [53], [54], coupled with accurate load forecasting and Demand Side Management (DSM) strategies [55], [56], [57], [58], offer improved predictability and system coordination. Additionally, integration of energy storage systems [59], [60], [61] and implementation of hybrid or co-located renewable power plants [62], [63], [64] have proven effective in dealing with the challenges posed by intermittency and variability of these energy sources.

### 3) OPTIMIZED DESIGN OF THE PTO SYSTEM

Optimized design of the PTO system is crucial for ensuring the commercial viability and efficient utilization of tidal energy resources [65]. As the most significant component of a TEC, the PTO system encompasses all elements that connect the hydrodynamic energy absorber (turbine blades) with the electrical grid. This includes the generator, power converter,

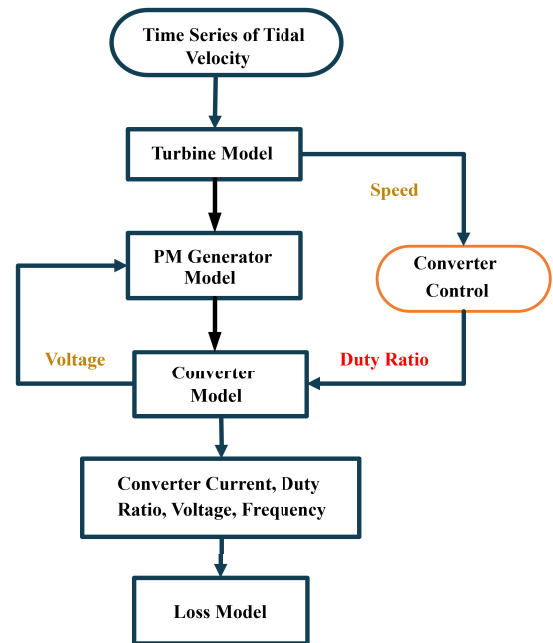


FIGURE 10. PTO models of tidal energy conversion system.

cabling infrastructure, and associated electrical conditioning equipment, as shown in Fig. 10 [66].

A well-designed PTO not only maximizes energy capture but must also account for the harsh marine environment. Optimal site selection significantly affects PTO configuration. Though easier for access and maintenance, shallow waters can result in wave-induced turbulence affecting system stability. Conversely, deeper waters benefit from more consistent tidal flows but introduce complexity in subsea installations, cable routing, and maintenance. Accessibility, durability, and reliable health monitoring systems are therefore vital, particularly given the lower technological maturity of tidal PTO systems [26].

The electrical PTO architecture plays a central role in this context. Among the generator options, the most prevalent are Doubly-Fed Induction Generators (DFIGs) and Permanent Magnet Synchronous Generators (PMSGs), each offering unique benefits and challenges for tidal applications [23].

DFIGs, typically used with a speed-up gearbox, allow variable-speed operation and reduced converter rating (33%), lowering costs but introducing mechanical complexity, maintenance needs, and slip-ring degradation risks in marine environments. PMSGs, particularly in direct-drive form, offer high efficiency, compactness, and improved reliability by eliminating gearboxes and brushes, though they demand full-scale converters, effective thermal management, and face risks of magnetic degradation. Semi-direct drive PMSGs provide a compromise by using a low-ratio gearbox to cut complexity and size while still requiring full converters and robust control.

Another promising PTO option is the hydraulic-PMSG system, where tidal energy is converted to hydraulic pressure,

**TABLE 5. Electrical PTO components in tidal energy systems: Challenges and emerging solutions.**

Component	Key Challenges	Emerging Trends / Solutions
<b>Generator [23]</b>	<ul style="list-style-type: none"> <li>• Corrosion, sealing, and biofouling in marine settings</li> <li>• Torque–speed mismatch in low-flow conditions</li> <li>• Size/weight limitations on floating devices</li> <li>• Gearbox failures in DFIG-based systems</li> <li>• Direct-drive PMSGs require full-scale converters</li> <li>• Hydraulic PTOs show lower efficiency (~34%)</li> </ul>	<ul style="list-style-type: none"> <li>• Direct-drive PMSGs tailored for slow tidal flows</li> <li>• Superconducting machines for compact, high-power density</li> <li>• Advanced encapsulation and anti-fouling coatings</li> <li>• Modular and lightweight designs to ease O&amp;M</li> <li>• Reliability-driven designs to reduce lifetime cost</li> </ul>
<b>Power Electronic Converters (PECs) [67], [68]</b>	<ul style="list-style-type: none"> <li>• Marine insulation, sealing, and pressure protection</li> <li>• Heat dissipation and thermal cycling stress</li> <li>• Fault ride-through in weak or isolated grids</li> <li>• Trade-off in converter location (onboard vs. onshore)</li> </ul>	<ul style="list-style-type: none"> <li>• Modular Converters for MVDC links</li> <li>• Wide-bandgap devices (Silicon Carbide (SiC), Gallium Nitride (GaN)) for efficiency</li> <li>• Encapsulated, pressure-tolerant marine PECs</li> <li>• Active liquid and phase-change cooling</li> </ul>
<b>Cabling and Connectors [69], [70], [71]</b>	<ul style="list-style-type: none"> <li>• Dynamic umbilical cables overengineered from oil &amp; gas, driving high costs</li> <li>• Fatigue from cyclic bending, torsion, and bidirectional tidal currents</li> <li>• Seabed abrasion, scouring, and insulation breakdown in harsh seabeds</li> <li>• High cost and complexity of wet-mate subsea connectors</li> <li>• Multiple generator integration risks (frequency mismatch, circulating currents)</li> </ul>	<ul style="list-style-type: none"> <li>• Tailored dynamic cable designs for moderate depths and tidal-specific loading</li> <li>• Armored, fatigue-resistant cables with embedded fiber-optic sensing</li> <li>• Wet-mateable HV connectors for modular arrays</li> <li>• Lazy-wave/J-lay layouts with bend restrictors and buoyancy modules</li> <li>• MVDC common-bus architectures for multi-device aggregation</li> </ul>
<b>Switchgear and Protection [72], [73]</b>	<ul style="list-style-type: none"> <li>• Corrosion and dielectric breakdown subsea</li> <li>• Slow fault detection and clearing underwater</li> <li>• Complexities in bidirectional power flow protection</li> </ul>	<ul style="list-style-type: none"> <li>• Compact vacuum/interrupter-based marine switchgear</li> <li>• Digital relays with high-speed communication</li> <li>• Advanced subsea isolation and fault-tolerant topologies</li> <li>• AI-assisted event detection and reconfiguration</li> </ul>
<b>Control Systems [19], [83]</b>	<ul style="list-style-type: none"> <li>• MPPT under oscillatory, reversing flows</li> <li>• Multi-converter coordination and stability</li> <li>• Sensor degradation in subsea conditions</li> </ul>	<ul style="list-style-type: none"> <li>• AI-based adaptive MPPT and supervisory control</li> <li>• Redundant marine-grade sensing networks</li> <li>• Real-time hybrid control for tidal + storage/grid</li> </ul>

stored in accumulators, and reconverted to mechanical torque via hydraulic motors driving the generator. This approach improves damping and power density, and allows placement of electrical components above water for easier maintenance. The main drawback lies in reduced transmission efficiency, with studies reporting 34% overall efficiency compared to 44% for gearbox-based systems [23].

PECs are essential in tidal PTO systems, as neither DFIGs nor PMSGs provide grid-compliant output. Back-to-back PECs, comprising a generator-side rectifier, DC link, and grid-side inverter, enable variable speed operation, grid synchronization, reactive power control, and fault ride-through. Converter location is another key design choice: onboard units offer finer control but face harsh subsea conditions, while onshore solutions, as in MeyGen, simplify maintenance but require longer dynamic cabling [67], [68]. The challenges associated with PECs and their existing mitigation strategies are examined in detail in Subsection III-C, while Sections IV and V present different PEC architectures along with recent advances in their application.

Subsea power cables are a critical enabler of tidal energy systems, ensuring reliable transmission of electricity from offshore devices to the onshore grid. Their design and survivability are strongly influenced by converter type, platform

configuration, and site conditions. For bottom-mounted tidal turbines, relatively static seabed-laid or buried cables are often sufficient, but challenges such as abrasion on rocky seabeds, scouring on sandy substrates, and costly trenching requirements persist [67], [69]. In contrast, floating tidal platforms require dynamic umbilical cables capable of withstanding cyclic bending, torsion, and transverse loading induced by waves and bi-directional tidal currents. Recent reviews highlight that these cables are particularly prone to fatigue in armour wires, fretting of conductors, and insulation degradation under repeated loading [70].

Mitigation strategies include lazy-wave or J-lay configurations, bend stiffeners, buoyancy modules, and hydrodynamic fairings to reduce transverse loading and prevent violations of minimum bending radius limits [67], [69], [70]. However, overengineering inherited from the oil and gas sector and reliance on expensive wet-mate connectors continue to inflate costs for marine energy applications. Addressing these gaps will require application-specific cable designs optimized for moderate depths and reversing tidal flows, rather than direct adaptation of offshore wind or oil and gas solutions.

Additionally, integrating multiple variable-speed tidal generators poses risks of frequency and voltage instability, typically resolved by converting outputs to DC. Modern

systems increasingly adopt Medium Voltage DC (MVDC) architectures, where individual converters feed a common DC bus linked to a central inverter, reducing cabling costs, improving scalability, and enhancing reliability [71].

Moreover, switchgear and protection systems in the PTO stage are essential for isolating faults, providing overcurrent protection, and maintaining safe operation between the generator–converter assembly and the transmission network. Existing designs largely adapt offshore wind and oil & gas solutions, yet tidal-specific subsea switchgear remains underdeveloped and costly. Recent studies emphasize that condition monitoring with AI techniques can enhance fault detection and extend PTO lifespan, while challenges persist in coordinating protection under bidirectional tidal flows ([72], [73]). Reliable, marine-grade protection is indispensable for efficient and safe PTO operation.

In summary, PTO design in tidal energy requires balancing generator choice, PEC topology, converter placement, cable design, protection, and aggregation strategy. Table 5 summarizes these components, their challenges, and emerging solutions for robust and scalable deployments.

#### 4) ECONOMIC SUSTAINABILITY

Another significant barrier of tidal energy, which requires extensive research, is the higher LCOE; as per estimation, tidal energy devices have an LCOE much higher than other renewable energy sources (Fig. 11) [74], [75], [76]. Tidal energy ventures are not expected to be commercially adopted unless they can substantiate their economic feasibility [77]. Many factors influence the estimation of LCOE, including the installed capacity, constancy of the resource (which affects capacity factor), technology readiness level, and cost uncertainty [75]. However, according to [78], with technologically-specific factors, various fixed and variable geographical indicators must be considered to evaluate the optimal locations for development and deployment activities. That is why a comprehensive PESTLE (Political, Economic, Social, Technological, Legal, and Environmental) analysis and cost based analysis [77], [79], [80], [81], [82] are required to evaluate LCOE. Moreover, advanced tools, including a specialized LCOE calculation tool for TECs and array design data ([20], [77]), are essential to significantly lower the LCOE of MRE technologies. This reduction is crucial for achieving commercialization and competitiveness with renewable sources like offshore wind.

Development of an advanced control algorithm and simplifying the PTO systems are required to lower the overall cost [111], [41], [83], [84], [85]. Additionally, synergy amongst different MRE sources [86], [87], [88], [89], [90] and incorporation of WBG and hybrid switching devices [91], [92], [93], [94] can be instrumental in reducing the overall energy cost.

#### 5) MANAGING ENVIRONMENTAL IMPACTS

The harsh and variable ocean environment also challenges harnessing energy from the ocean. Biofouling and corrosion are some of the significant challenges that not only increase

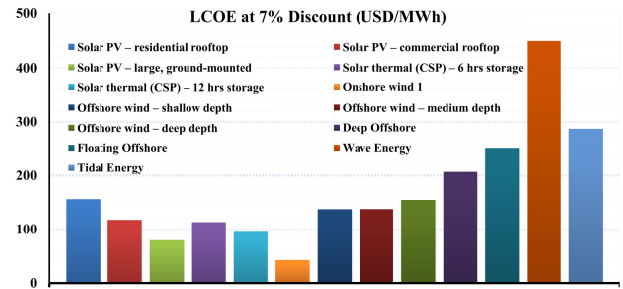


FIGURE 11. LCOE of renewable energy sources in the united states [76].

the rate of failure and the cost of the devices [95], [96] but also increase the complexities of their maintenance and monitoring. Biofouling could decrease the efficiency of turbine blades up to 70% [97]. In [95], computational fluid dynamics simulations are conducted for different fouling scenarios, and results showed a 13% decrease in power coefficient for the design operating condition (Tip Speed Ratio (TSR): TSR=4). The effect proved to be more drastic for higher TSRs. Research regarding composite and novel materials [98], [99], [100], use of eco-friendly antifoulants [101], and specialized paints [102] are critical in addressing the challenge of biofouling.

#### 6) OVERCOMING LOGISTICAL HURDLES AND RELIABILITY ASSESSMENT

Transportation and installation of the power conversion systems pose extra barriers [103], [104]. Advanced numerical tools, specialized and automated equipment [26], [105] with Co-located deployment [86], [87] are promising solutions to reduce these challenges. Reliability assessment is another crucial challenge that needs to be addressed as maintenance and monitoring of these devices become formidable tasks while confronting oceanic conditions. Adapting advanced monitoring [106], [107] and real-time prognostics and diagnostics [108], [109], [110] are essential in conducting the reliability assessment. The deployment of this energy conversion unit can also introduce different environmental challenges, including pollutants [103], [104], [111], Electromagnetic Fields (EMFs) [26], [112], and Hydrodynamics [86], [87].

Tidal energy faces challenges such as variability, intermittency, high LCOE, biofouling, corrosion, complex logistics, environmental concerns, and reliability issues. Addressing these requires advancements in energy storage, cost-effective designs, durable materials, environmental monitoring, and robust assessment methods. As detailed in Table 4, existing solutions target these issues to support sustainable development. Although ocean energy technologies remain in the Research and Development (R&D) phase with high investment costs, learning effects and technological improvements could lower LCOE to USD 124–221/MWh for tidal by 2030. However, uncertainties persist due to site-specific factors [76].

**TABLE 6. Challenges in grid integration of tidal energy: Mitigation strategies, references, research gaps, and technology maturity.**

Identified Challenges	Tidal-Specific Challenges	Existing Solutions	References	Research Gaps	Technology Maturity
<b>Power Quality [113]</b>	<ul style="list-style-type: none"> <li>• Bidirectional flow causes oscillations</li> <li>• Slack tide leads to zero-flow zones</li> <li>• Flow reversal causes voltage dips</li> </ul>	Energy storage systems	[114], [115]	Optimal ESS sizing for cyclic tidal profiles under marine constraints	Medium
	<ul style="list-style-type: none"> <li>• Rapid tidal flow variations cause power swings and flicker</li> <li>• Control logic struggles under bidirectional phase-shifts</li> </ul>	Power smoothing controllers	[116]–[119]	Lack of dynamic/adaptive tuning under phase-shifting, bidirectional flow	Medium
	<ul style="list-style-type: none"> <li>• Weak grid coupling leads to poor voltage regulation</li> <li>• Inadequate local VAR support affects grid voltage stability</li> <li>• Harsh marine conditions stress electronics</li> </ul>	Custom power electronic devices	[41], [120]–[122]	Device reliability under marine stress is underdeveloped	Medium
	<ul style="list-style-type: none"> <li>• Slack tides lead to predictable but unavoidable power interruptions</li> </ul>	Hybrid energy sources	[123], [124]	Hybrid control for tidal-RE systems lacks field validation	Low–Medium
	<ul style="list-style-type: none"> <li>• Turbulence and changing torque profiles affect the torque-speed track</li> <li>• Flow direction changes degrade energy capture</li> </ul>	Control strategies	[18], [125]–[127]	Lack of robust, standardized control under unsteady tidal flow	Medium
	<ul style="list-style-type: none"> <li>• No tidal-specific grid codes</li> <li>• TECs lack Ride-through and Reactive power support</li> </ul>	Grid code integration	[126], [128]	Grid codes not adapted for tidal converters	Low
<b>Power System Stability [129]–[133]</b>	<ul style="list-style-type: none"> <li>• Tidal ramping stresses grid dynamics</li> </ul>	Dynamic modeling	[113], [130]–[133]	High-fidelity tidal plant models lacking	Medium
	<ul style="list-style-type: none"> <li>• Remote grids lack inertia and strength</li> </ul>	Control techniques	[129], [134]–[137]	Low inertia adaptation in marine grid	Medium
	<ul style="list-style-type: none"> <li>• Voltage/reactive imbalance in tidal phases</li> </ul>	Reactive power management	[138]–[140]	Real-time VAR control in TECs is not standardized	Low–Medium
	<ul style="list-style-type: none"> <li>• Islanded TECs show weak frequency/voltage stability</li> </ul>	Energy storage system support	[134], [141]–[143]	Co-optimization with storage is not well explored	Medium
<b>Protection &amp; Security [144]–[149]</b>	<ul style="list-style-type: none"> <li>• Subsea faults are hard to detect in real-time</li> </ul>	Smart/adaptive protection schemes	[150], [151]	Adaptive protection under bidirectional fault current is not mature	Medium
	<ul style="list-style-type: none"> <li>• Marine conditions accelerate device wear</li> </ul>	Fault-tolerant devices/controllers	[147], [152]–[155]	Few validated marine-grade fault devices	Low–Medium
	<ul style="list-style-type: none"> <li>• Fault isolation is slow in hybrid undersea links</li> </ul>	Fast-switching protection devices	[156]–[158]	Delayed coordination in hybrid undersea cables	Low
	<ul style="list-style-type: none"> <li>• Real-time monitoring is limited by subsea communication</li> </ul>	Advanced communication	[159], [160]	Limited subsea sensor communication robustness	Medium
<b>Inertia [161]</b>	<ul style="list-style-type: none"> <li>• PEC-interfaced TECs decouple mechanical inertia from the grid</li> </ul>	Virtual inertia-based inverters	[162]–[169]	Inertia emulation under tidal variability is not fully validated	Low
	<ul style="list-style-type: none"> <li>• TECs cannot autonomously support frequency or initiate black-start</li> </ul>	Synchronous energy storage systems	[142], [170]–[173]	Combined inertia and black-start not validated	Low
<b>Ancillary Services [60], [174]</b>	<ul style="list-style-type: none"> <li>• TECs not equipped for autonomous restart</li> </ul>	Fault ride through	[60], [175]	Ride-through control not included in TEC specs	Low
	<ul style="list-style-type: none"> <li>• Limited voltage/frequency support in tidal converters</li> </ul>	Voltage/frequency regulation	[174], [176], [177]	Capability limited in grid-following converters	Low–Medium
	<ul style="list-style-type: none"> <li>• TEC-based islanded systems lack black-start mechanisms</li> </ul>	Black start strategies	[178], [179]	Few studies on black start in TEC-based islanded grids	Low

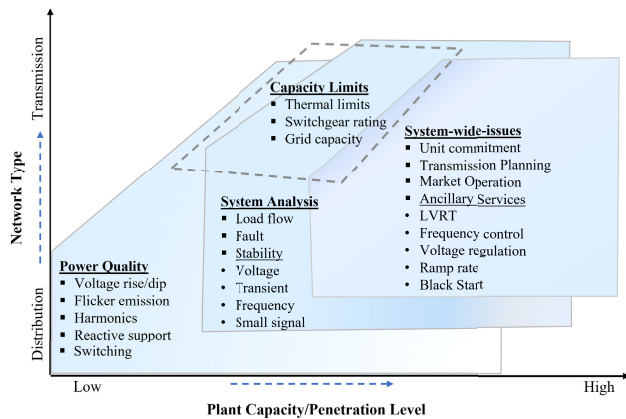


FIGURE 12. Impact of tidal integration on the grid [50].

## B. KEY CHALLENGES AND SOLUTIONS IN GRID INTEGRATION OF TIDAL SYSTEMS

After generating energy from tidal sources, the main challenge is the efficient integration of generated energy into the grid for different applications. The harsh, corrosive environment, variability, and intermittency of energy sources not only restrict energy generation but also pose challenges while integrating with the main grid. Reference [43] explains the possible grid integration issues and their solutions. These issues are outlined in Fig. 12, spanning power quality, system stability, protection/security, lower inertia, and the provision of essential ancillary services. This subsection provides a comprehensive review of these challenges and explores existing solutions developed to address them, fostering the seamless integration of tidal into the broader energy landscape. All these challenges, the corresponding mitigation strategies, the identified research gaps, and the current technological maturity levels are summarized in Table 6.

### 1) POWER QUALITY CHALLENGES

As previously discussed, tidal energy's predictability offers advantages over other MRE and RE sources by reducing short-term power quality concerns. Nonetheless, its non-dispatchable nature, site-specific phase shifts, and power ramping during tidal transitions can still lead to oscillatory injections, complicating grid stability in weaker or isolated networks. In [113], a water-to-wire comprehensive dynamic model of a generic tidal current device is presented. The analysis is done under varying water flows, device settings, and diverse operational conditions unique to tidal applications. The inherent power fluctuation causes stability and power quality issues in the grid. Short- and long-term flicker severity becomes more critical in integrating these variables and fluctuating energy sources with a weak grid.

Several mitigation strategies have been developed to address power quality challenges associated with tidal energy systems. Energy storage systems help buffer the oscillatory power output and smooth the supply injected into the grid [114], [115]. Advanced power-smoothing

control algorithms have also been proposed to reduce fluctuations and enhance grid stability [116], [117], [118], [119]. Furthermore, the integration of custom power devices, such as Flexible AC Transmission System (FACTS) systems, offers improved voltage and frequency regulation in weak or remote grids [41], [120], [121], [122]. Combining these solutions with an optimized energy mix can further enhance system resilience and reduce the severity of power quality disturbances [123], [124].

In most conventional configurations, the generator output is regulated solely through an AC–DC converter, with MPPT techniques applied to maximize energy extraction and enable basic grid integration. While effective for efficiency, this approach provides limited capability in addressing grid compliance, fault ride-through, or multi-device coordination, thereby reinforcing the need for advanced supervisory control schemes [18], [125], [126], [127] and standardized grid integration strategies [126], [128].

### 2) STABILITY CONCERNS

Power system stability is another challenge. Stability is mainly classified as Rotor angle, frequency, and voltage stability. In [129], the structure of modern power systems, different levels of control, and the nature of stability problems are explored. Besides, before connecting tidal energy with the main grid, it is imperative to develop comprehensive dynamic modeling of the entire system [130], [131], [132]. The model should not only meticulously incorporate the time series variation of tidal flow velocity but should be usable in simulations of normal operation and operation in the presence of grid dynamics [133].

Due to uncertainties in tidal energy plants, it is necessary to use a robust and intelligent control strategy for the optimal power sharing among terminals and also to maintain the stability of the system [134], [135], [136]. An in-depth analysis of research in microgrids based on small-signal, transient, and voltage stability, as well as a comparison of different existing controllers, is required to improve the stability of TECs. In [124] and [137], it is concluded that properly selecting control strategies can effectively improve system stability. Moreover, maintaining and managing adequate reactive power reserves is crucial to ensure a stable and reliable power grid. In [138], [139], and [140], the key impact of reactive power control and optimization on system stability under different dynamics is analyzed. Integration of energy storage systems has been extensively explored to enhance the dynamic stability and reliability of tidal power networks, providing short-term buffering against tidal variability and grid disturbances [141], [142], [143].

### 3) SYSTEM PROTECTION AND SECURITY

Assessing protection and security measures also presents a notable challenge in TEC. The impact of a fault on tidal-based power plants depends mainly on the fault's nature, amplitude, location, generating machines, and grid(stiff/weak). Providing the necessary protection to safeguard equipment and

personnel in the Rotech Tidal Turbine and the distribution network installation is discussed in [144]. In [145], the behavior of a grid-tied tidal power plant is analyzed under different types of short circuits while considering the impact of water rip on the stability. The results show that the tidal power plant system is susceptible to the three-phase short circuits and becomes quickly unstable. Reference [146] analyzes the performance of tidal turbines based on control strategies and suggests using Sliding Mode Control (SMC) as a nonlinear control for high-power applications. Reference [147] shows the resiliency of the higher-order SMC controller in case of a grid fault. Moreover, fault currents in the grid-connected and islanded systems are significantly different [148]. In that case, the protection of the tidal systems cannot be achieved with the same approaches used in the conventional distribution systems.

Safety and fault analysis are critical when designing a protection scheme. A proper safety model provides an appropriate confidence level in the protection system [149]. Moreover, developing intelligent and adaptive protection schemes becomes critical in ensuring system protection and security [150], [151]. Additionally, advancements in power electronics, coupled with the evolution of high-speed protection devices, are enhancing the fault tolerance of the entire system. Hence, integrating these fault-tolerant [152], [153], [154], [155] and fast switching power converters and protection units [156], [157], [158] with advanced control and communication algorithms [159], [160] can significantly enhance the overall system reliability and security.

#### 4) LOWER INERTIA AND ANCILLARY SERVICES

In conventional power systems, synchronous machines and loads significantly contribute to inertia, ensuring the stable operation of the entire system. However, inertia is becoming an additional challenge with the higher integration of power converter-based systems in modern power systems. Besides, most loads are also interfaced using PECs, further reducing the overall system's inertia. This reduction in inertia causes frequency deviations and a high Rate of Change of Frequency (ROCOF), which leads to instability [161].

To address these challenges, different techniques like virtual inertia-based inverters [162], [163], virtual inertia control, virtual inertia scheduling, an approach to estimate inertia constant [164], [165], [166], [167], [168], [169], and synchronous energy storage system [142], [170], [171], [172], [173] have been explored. These techniques mainly involve mimicking the conventional synchronous machines' behaviors to maintain the system stability.

Other significant barriers stem from the provision of essential ancillary services such as Fault Ride Through (FRT) [60], [175], Voltage frequency regulation [176], [177], and Black start strategies [178], [179]. These services are crucial in maintaining grid stability and resiliency, especially given tidal's non-dispatchability.

In summary, integrating tidal energy into existing power grids presents multifaceted challenges related to power

quality, stability, system protection/security, lower inertia, and essential ancillary services.

### C. MAJOR CHALLENGES OF PEC AND EXISTING SOLUTIONS FOR THE TIDAL APPLICATION

PECs with proper controllers and energy storage systems can mitigate most of the challenges related to the grid integration of the tidal energy source. However, PECs have challenges, primarily when employed in the severe and wavering oceanic environment. PECs provide a buffer between the source and the grid, but these nonsynchronous devices bring further issues in the case of islanded and grid-integrated distributed energy sources. In [9], various challenges and opportunities of PEC in subsea applications are discussed. This subsection delves into the challenges faced by PECs in tidal applications, exploring existing solutions that address issues ranging from placement and reliability to thermal management and advanced design considerations.

#### 1) OPTIMUM PLACEMENT OF PECs

A primary objective of tidal energy development is the reliable supply of electric power to the utility grid, with the PTO system playing a central role in enabling efficient transfer. The placement of PECs within the PTO is therefore critical, as it directly influences transmission requirements, power quality, and system economics. In standalone or nearshore deployments, energy is typically consumed locally, minimizing the need for extensive cabling or storage. Conversely, long-distance transmission becomes unavoidable in offshore or grid-connected systems, and the design and location of PECs significantly affect efficiency and reliability.

Industry practice demonstrates three dominant strategies: placing converters onshore, on floating platforms, or in subsea/seabed-mounted installations [180]. Onshore placement is often preferred due to easier access and simplified maintenance, but it requires long dynamic cables that introduce reflected wave phenomena and noise-related challenges, necessitating multiple filters for mitigation [181], [182], [183], [184]. Subsea or seabed-mounted converters avoid long and complex cabling, reduce mooring requirements, and benefit from the high thermal capacity of seawater as a natural heat sink [9], [185], [186], [187], [188]. However, these systems face harsher operating environments, higher failure risks, and far more complex repair logistics, which can significantly increase Operational and Maintenance (O&M) costs [67], [70]. Floating platform converters provide an intermediate solution, balancing accessibility with reduced cable length, though they are exposed to platform motion and marine stresses.

A comparative assessment by [180] evaluated multiple system architectures against LCOE and recommended offshore placement of PECs for large-scale projects above 30 MW. Nevertheless, the choice of PEC location must also account for technology readiness, redundancy, and grid compliance requirements. Subsea PECs remain at a lower Technology Readiness Level (TRL) compared to onshore converters, with

**TABLE 7. Challenges of PECs in tidal applications: Mitigation strategies, references, research gaps, and technology maturity levels.**

Identified Challenge	Tidal-Specific Challenge	Existing Solution	Reference	Research Gap	Technology Maturity
<b>Optimum Placement of PECs [9], [180]</b>	• Long cable runs from shore introduce EMI and losses	Onshore	[181]–[184]	Long transmission paths introduce signal delay, EMI, and reactive power issues not yet optimized for tidal converter operation	Low–Medium
	• Harsh marine conditions limit converter durability, access, and O&M cost	Offshore	[9], [185]–[188]	Subsea converters lack validated designs for long-term exposure to cyclic tidal pressure, thermal gradients, and marine growth.	Low
<b>Installation &amp; Maintenance [189]</b>	• Subsea PECs require costly maintenance with Remotely Operated Vehicles (ROVs) & high downtime costs	Modular PECs; underwater access	[107], [189], [190]	Modular PEC designs suitable for remote underwater replacement and ROV-based maintenance are still underexplored.	Low
<b>Reliability &amp; MTBF [67]</b>	• High humidity and pressure reduce component lifetime	Reliability Modeling	[21], [191], [192]	Marine-specific failure models limited	Medium
	• Tidal load cycles cause faster wear-out	Lifetime Analysis	[193]–[196]	Lifetime degradation under low-frequency, bidirectional flow and seasonal loading is poorly quantified	Medium
	• Degradation effects not incorporated into control logic	Lifetime-Based Control	[197]–[199]	No dynamic control strategy yet integrates real-time aging feedback from PECs operating under tidal profiles	Medium
	• Sensors corrode or drift in marine environments	Condition-Based Monitoring	[200]–[202]	Robust CBM under marine stress untested for TEC	Medium
<b>Thermal Management [203]</b>	• Inadequate heat dissipation in sealed marine housings	Thermal Cooling	[204]–[208]	Marine cooling solutions are underexplored	Low–Medium
	• Active systems consume power and are hard to maintain	Active Thermal Control	[209]–[211]	Field-proven marine-active cooling is lacking	Low–Medium
	• Dynamic gradients exist in submerged environments	Thermal System Modeling/Monitoring	[212]–[214]	Transient thermal behavior not well modeled	Medium
	• Ingress of moisture leads to internal condensation	Enclosure Design	[215]–[217]	Few PEC housing designs offer long-term moisture-proofing, pressure resistance, and corrosion protection	Low
	• Standard TIMs degrade due to marine pressure and corrosion	Advanced Thermal Interface Materials	[218]–[220]	Standard TIMs degrade under subsea pressure and are not marine-certified for long-duration use	Low
<b>PEC Design for Tidal [221]–[224]</b>	• Fault detection in tidal systems is delayed due to inaccessibility	Diagnostics and Prognostics of Faults	[221]–[225]	Tidal converters lack fast, marine-resilient fault detection and diagnosis schemes under submerged conditions	Medium
	• Tidal systems face unique faults (pressure, flow-induced torque)	Fault-Tolerant PEC	[226]–[229]	Compact marine fault-tolerant designs not tested	Low
	• Deep-sea pressure affects insulation, structure	Design of Pressure-Tolerant PEC	[9], [230]–[232]	Very few converter designs are pressure-rated for deepwater tidal deployments	Low
	• Self-repair logic must work under turbulent subsea faults	Self-Diagnostic/Healing Design	[226], [233]–[235]	No autonomous fault recovery schemes are validated for subsea PECs with restricted sensor access	Low
<b>Health Analytics &amp; Diagnostics [236], [237]</b>	• Tidal PECs are hard to access; real-time health data is limited	Real-Time Modeling	[41], [236]	Analytics under subsea noise and latency unexplored	Low–Medium
	• Digital twins struggle to capture dynamic marine effects	Digital Twin-Based Diagnostics	[237]–[240]	No tidal-specific DT frameworks validated	Low–Medium

unresolved challenges in fault ride-through, redundancy, and marine-proof housings, while onshore solutions, though less efficient, offer proven reliability and maintainability [67], [126]. Hence, optimum placement is not universal but depends on farm size, distance from shore, O&M accessibility, and system maturity.

Based on [189] and [190], maintenance of PECs in tidal and offshore systems remain key challenges due to restricted accessibility and harsh marine environments. Reference [189] propose active thermal control strategies to extend converter lifetime and delay maintenance intervals, reducing operational downtime and cost. Reference [190] further highlight that maintenance policies and failure intensity strongly influence system reliability and lifecycle economics, emphasizing the need for condition-based and predictive maintenance frameworks. Together, these studies underscore that integrating thermal management, reliability modeling, and optimized maintenance scheduling is critical for ensuring long-term PEC performance in offshore tidal applications.

## 2) RELIABILITY AND HIGHER MTBF

Reliability stands as a critical concern for tidal energy developers, notably regarding the converters. According to three SSE reports, prominent manufacturers such as ABB and Siemens reported a Mean Time Between Failures (MTBF) of 15 to 16 years. These calculations consider regular servicing every two to three years. However, it is proposed that service intervals for device-based converters can be extended to five years. This extension is attributed to the dust-free subsea environment, reducing the need for frequent filter replacements [67]. These MTBF figures and maintenance intervals will be essential in a developer's decision on which turbines to use and the subsequent array layout.

Hence, the utilization of reliability modeling encompassing advanced methodologies of lifetime analysis plays a critical role in the widespread application of TEC [21], [191], [192]. In [21], the Voltage Source Inverters (VSI)-based 3-level Diode Front End configuration, despite being the latest technological developments, a basic system offers MTBF of just four years. However, when deployed in pressure-compensated enclosures in a deep water setting with redundant subsystems, the MTBF can exceed 20 years. In the case of the Current Source Inverter (CSI)-based Active Rectifier configuration, a basic system can provide an MTBF of only three years. In contrast, attaining an MTBF of more than 25 years is possible under similar conditions. The results obtained provide confidence in realizing reliable multi-megawatt subsea PECs.

When designing a power converter for tidal applications, the reliability of power converter devices also needs to be considered. For efficient application, the lifespan analysis of power converter devices [193], [194], [195], [196] is required. Reliability and lifetime of power converter devices can be further improved either by active thermal or lifetime control based active methods [197], [198], [199] or by condition monitoring based passive methods [200], [201], [202].

## 3) EFFICIENT THERMAL/HUMIDITY MANAGEMENT

Maintaining efficient thermal and humidity management in the oceanic environment is another crucial concern [203]. Managing thermal conditions efficiently in marine environments involves several key aspects like thermal cooling methods [204], [205], [206], [207], [208], active thermal control strategies [209], [210], [211] and Modeling and monitoring of thermal systems [212], [213], [214]. The studies by [215], [216], and [217] consider enclosure design, while other studies [218], [219], [220] concentrate on implementing advanced thermal interface materials to improve the thermal management.

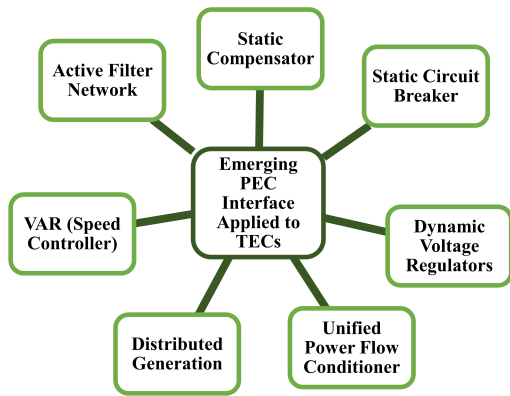
## 4) DESIGN OF PECs FOR TIDAL APPLICATION

Another area that warrants further research is the design of PECs for subsea applications. When exploring PECs for tidal systems, several critical facets emerge. One of the foremost concerns is the diagnostics and prognostics of faults, which revolves around the ability to detect and predict faults within the converters. Studies such as [221], [222], [223], [224], and [225] discuss various methodologies and technologies employed to identify and anticipate potential failures in these systems. In parallel, fault-tolerant design strategies have been investigated to ensure continued operation under fault conditions. Approaches outlined in [226], [227], [228], and [229] include redundancy mechanisms, reconfigurable architectures, and fault isolation techniques aimed at maintaining system integrity despite failures or disruptions.

Additionally, the harsh environmental conditions encountered in subsea applications pose unique challenges for PEC design. Works such as [9], [230], [231], and [232] address these challenges by focusing on the development of converters capable of withstanding high-pressure marine environments. This includes considerations such as material selection, structural robustness, and specialized packaging to ensure durability and reliability. Furthermore, innovative functionalities like self-diagnostic and self-healing capabilities are being integrated into PECs to enhance operational longevity and reliability. Research in [226], [233], [234], and [235] explores these advanced systems, which involve embedded monitoring, adaptive control, and even self-repair mechanisms designed to minimize downtime and extend converter lifespan.

## 5) HEALTH ANALYTIC AND DIAGNOSTICS SYSTEMS

In the realm of tidal energy applications, health analytics, and diagnostics systems harness real-time modeling techniques [41], [236] to monitor and optimize the performance of PECs and infrastructure. By continuously analyzing data from sensors embedded in tidal turbines and other marine energy systems, these systems can provide insights into operational parameters such as power output, efficiency, and structural integrity. Additionally, the integration of digital twin-based diagnostics [237], [238], [239], [240] enables the creation of virtual replicas of these converters, allowing for predictive



**FIGURE 13.** Emerging PEC interface applied to TEC.

maintenance and performance optimization. By leveraging real-time modeling and digital twin technologies, marine energy operators can proactively identify issues, minimize downtime, and maximize the efficiency and reliability of marine energy generation, thus advancing the viability and sustainability of this renewable energy source.

In conclusion, the challenges and solutions discussed in this subsection highlight the complexities and advancements in optimizing PECs for tidal applications. By addressing placement considerations, reliability enhancement, thermal management, design adaptations, and implementing health analytics, the tidal sector can elevate the efficiency and sustainability of power conversion technologies in the dynamic marine environment. The referenced works serve as valuable resources, offering insights and methodologies for developing and improving PECs in tidal applications. Table 7 delves into these specific methodologies, technologies, or design paradigms to address critical challenges in applying PECs for tidal applications.

## IV. POWER CONVERTER ARCHITECTURE

### A. SIGNIFICANCE OF PEC FOR TEC

Power electronics are central to tidal energy systems, ensuring efficient conversion of variable marine currents into stable, grid-compliant power. Advances in compact, reliable converters have improved efficiency, control flexibility, and durability in harsh subsea environments, supporting progress toward net-zero goals. In tidal PTOs, PECs enable maximum power extraction, voltage regulation, reactive power support, and smooth transitions between grid-connected and islanded modes for both AC and DC integration (Fig. 13).

### B. POWER CONVERSION FOR TEC

All tidal energy systems will contain a generator and a converter somewhere in the electrical chain, and this arrangement will dictate the design of the tidal farm. The converter will ensure that the output of the device is at a constant voltage and frequency so that it can be easily aggregated. Converters in tidal energy systems can be placed in the

turbine nacelle (subsea), in an offshore hub (either subsea or surface-mounted), or within a large substation located offshore or onshore, depending on the system architecture and power level [180]. Due to the non-dispatchability of tides, it becomes important to ensure a stable and smooth energy transfer. PECs play the role of steady power transfer and grid interface with the help of control algorithms [241]. Generally, power electronics converters can be categorized into AC/DC, DC/DC, DC/AC, and AC/AC. Fig. 14 gives a general classification of power converters used for marine energy applications.

### C. CLASSIFICATION OF POWER CONVERTERS

The connection of the offshore-generated power to the onshore main grid or load is one of the critical aspects of tidal sources. The power conversion for tidal sources can be mostly classified into three categories, Fig. 15 [242], [243]:

- Generator side passive AC/DC/AC conversion
- Active/ Back-to-Back AC/DC/AC conversion
- Power conversion without intermediate DC link

The generator-side converter can adjust the electric field to optimize power output. The grid-side converter can adjust the phase angle between the generated voltage and the current, enabling the control of reactive power output.

#### 1) GENERATOR SIDE PASSIVE AC/DC/AC CONVERTER

Power electronic conversion systems in tidal energy must bridge the generator output with grid requirements while surviving harsh marine conditions. Passive rectification, which employs diode-based AC/DC conversion without active switching, has emerged as a promising architecture for minimizing cost and complexity. Such systems offer robust operation, simplified maintenance, and lower Operational and Capital Expenditures (OPEX/CAPEX), particularly in submerged and modular tidal applications with limited access. The absence of active switching components and the ability to be encapsulated in pressure-resistant, corrosion-proof housings make passive rectifiers especially suitable for long-term submerged deployment [180], [244].

Despite these advantages, the lack of controllability in passive converters introduces critical limitations. Diode bridge rectifiers provide no control over power factor or harmonic performance, limiting the ability to extract maximum energy from variable-speed tidal generators [245]. To mitigate these challenges, hybrid solutions have been proposed that combine passive rectifiers with DC-DC converters or other auxiliary power conditioning stages. For instance, a diode bridge cascaded with a boost converter allows voltage regulation and compatibility with standardized inverter-based grid interfaces [246], [247]. The configuration illustrated in Fig. 16 ensures smoother power delivery despite fluctuating tidal flow, with grid-side converters controlling real and reactive power. Likewise, the Dynamic Tidal Power (DTP) concept in Fig. 17 uses a diode rectifier and DC chopper with

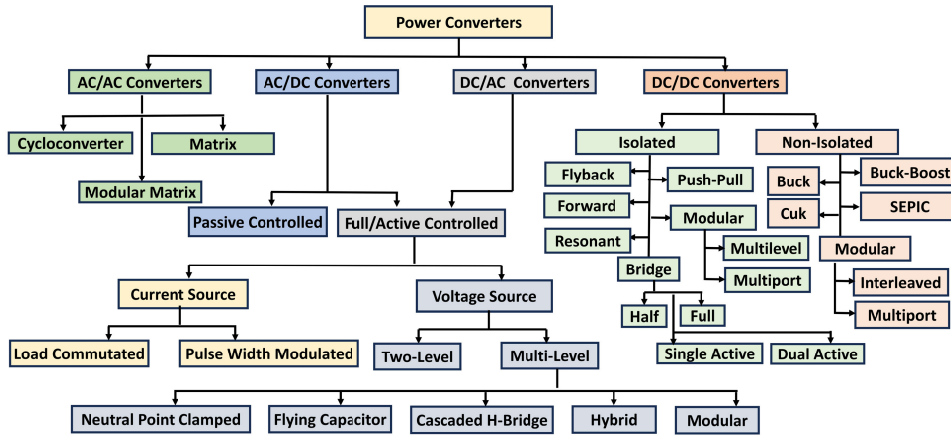


FIGURE 14. General classification of power converters.

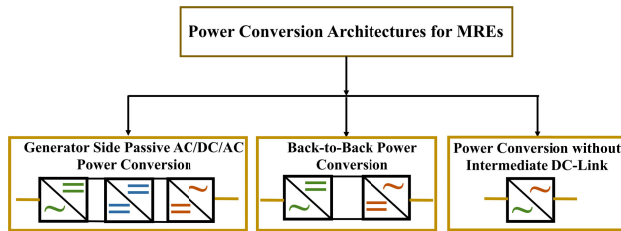


FIGURE 15. Connection topology.

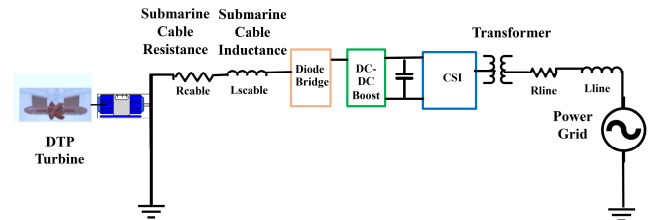


FIGURE 17. Diode rectifier-based power conversion setup for Dynamic Tidal Power (DTP) [247].

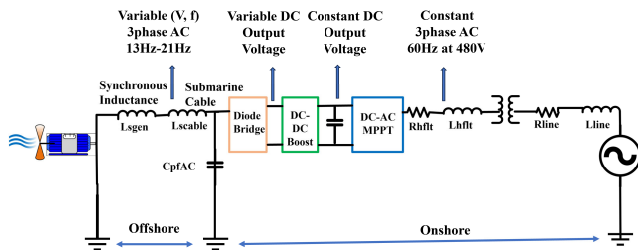


FIGURE 16. Single line diagram of diode bridge-based AC/DC/AC conversion for tidal power applications [246].

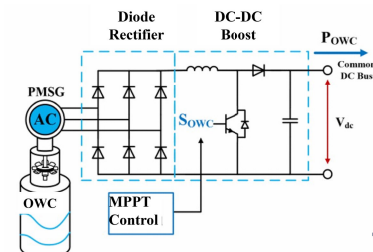


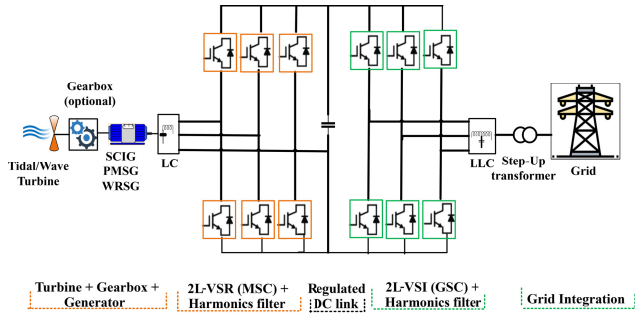
FIGURE 18. Diode rectifier based OWC power conversion system [248].

PID control to maintain a stable DC bus voltage under varying substation distances.

For Oscillating Water Column (OWC) power conversion, [248] builds a DC microgrid arrangement employing a diode bridge rectifier on the OWC generator side, as illustrated in Fig. 18. The intermediate DC-DC boost converter implements the MPPT control scheme to optimize the OWC system’s output, maximizing energy harvesting efficiency.

The configuration is also proposed for Low Voltage DC (LVDC)-based Multi-Use Platforms (MUPs), where modular tidal, wind, and solar sources interface with a shared low-voltage DC bus. [249] presents a simulation-based LVDC framework showing that the integration of passive rectifiers with boost converters enhances system reliability, supports modular deployment, and improves fault resilience via coordinated control of parallel DC-DC converters.

In practical tidal deployments, passive rectification has already been adopted. Nautricity’s 500 kW CoRMaT device uses a diode bridge and capacitive filtering to output 3.6 kV DC, enabling straightforward connection of multiple units in a radial MVDC array [67]. The onboard passive approach simplifies the nacelle and enables cost-effective offshore array aggregation, though commercial-scale MVDC deployment still awaits offshore demonstrators. Similarly, ABB has proposed using diode rectifiers in submerged tidal nacelles, enabling passive MVDC collection at  $\pm 5\text{--}7.5$  kV levels for reliable and low-maintenance operation [180]. In this setup, each turbine outputs DC via passive rectification and connects to a subsea hub that aggregates 2–8 turbines at  $\pm 5$  kV, transmitting power to an onshore substation. A 30 MW tidal farm can be realized without any surface offshore infrastructure, improving reliability and reducing



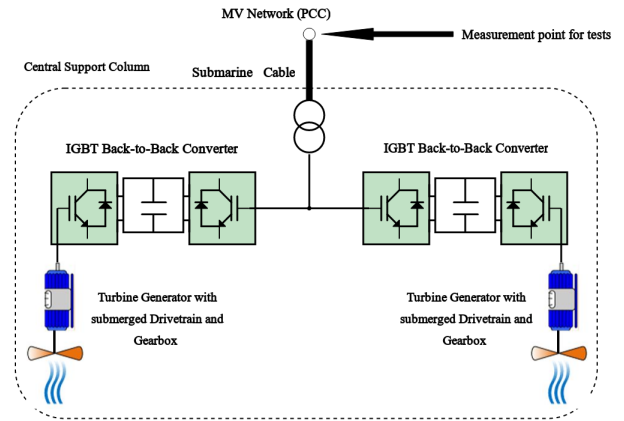
**FIGURE 19. Basic structure of AC/DC/AC active back to back converter topology.**

OPEX and CAPEX. For larger deployments, multiple such units can be combined, though offshore substations may become necessary at higher scales. This concept, adapted from shipboard LVDC systems, is now considered for medium voltage tidal networks where balanced outputs across turbines can be ensured.

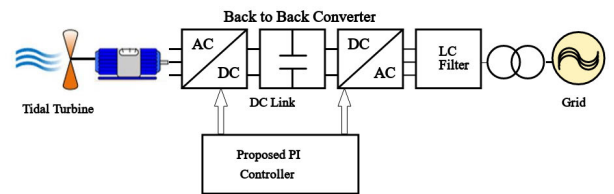
However, passive front ends offer limited dynamic response and lack voltage or frequency control. Even with DC chopper stages or capacitor-based smoothing, they cannot address voltage sag, fault ride-through, or weak grid interactions without external support. To overcome these drawbacks, active auxiliary devices—such as Static Synchronous Compensators (STATCOMs) or Modular Multilevel Converters (MMCs) have been explored in related offshore wind and shipboard studies for voltage support and frequency stabilization [250], [251], [252]. While such solutions are not yet widely demonstrated in tidal projects, their architectural principles are increasingly relevant as tidal systems evolve toward larger, grid-forming arrays with tighter performance demands.

In summary, passive rectification simplifies converter design, lowers OPEX and potentially CAPEX, and provides reliability benefits well suited for submerged tidal deployments. However, to enable scalable LVDC or MVDC architectures and meet grid compliance requirements, control-capable components, such as cascaded DC-DC converters or active grid-side inverters, are essential. As offshore MVDC networks evolve and demonstration projects mature, hybrid converter frameworks combining passive front-ends with active control stages are expected to be pivotal in delivering cost-effective, scalable, and maintainable tidal energy systems. In this context, BTB Voltage Source Converters (VSCs) continue to serve as the core technology for real-time power control, bidirectional flow, and grid support functions in practical tidal deployments.

Several other studies also employ BTB converters in tidal energy contexts to enable advanced control, MPPT, and grid synchronization under harsh ocean conditions [23], [40], [256], [257], [259], [260], [261], [262]. Collectively, these contributions highlight the importance of BTB configurations in delivering high efficiency, low harmonics, and robust transient response in tidal applications.



**FIGURE 20. Schematic of SeaGen AC/DC/AC IGBT-based BTB tidal power conversion system [258].**

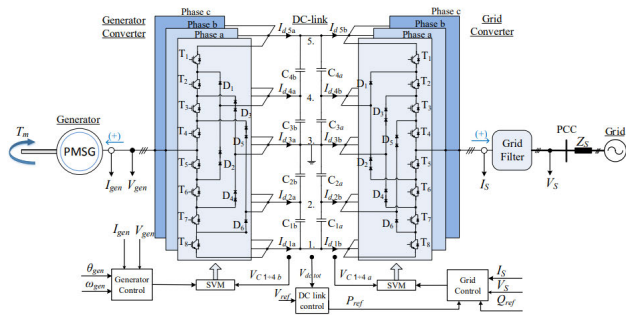


**FIGURE 21. Intelligent energy-based modified super twisting control setup using back-to-back energy conversion system [135].**

## 2) ACTIVE AC/DC/AC CONVERTER

An active AC/DC/AC converter is typically implemented in a BTB topology, where two VSCs are interconnected via a common DC-link capacitor or inductor. This architecture is widely adopted in tidal and other MRE systems for grid integration and power quality improvement [40], [253], [254], [255], [256], [257]. As illustrated in Fig. 19, both converter stages utilize active semiconductor devices such as IGBTs or SiC-MOSFETs, enabling fully bidirectional power flow and decoupled control of generator- and grid-side variables. The device selection typically balances the high current-handling capability of IGBTs against the higher switching frequency capability and lower switching losses offered by MOSFETs.

BTB converters are particularly well-suited for variable-speed tidal energy conversion systems, as they enable precise control of generator-side torque, speed, and power factor independently of grid-side disturbances. By maintaining a regulated and stiff DC-link voltage, BTB converters suppress current harmonics and dampen grid-side transients, enhancing power quality. This architecture accommodates a wide range of generator types typically employed in tidal applications, including Squirrel Cage Induction Generators (SCIG), DFIG, PMSG, and Wound Rotor Synchronous Generators (WRSG) [242]. Given the decoupled nature of energy conversion across the AC/DC and DC/AC stages,



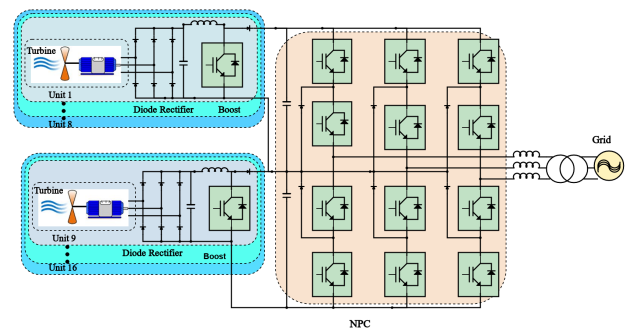
**FIGURE 22.** 5-level NPC generator drive converter for kite tidal power conversion [264].

BTB configurations are often categorized as two-stage power electronic converters.

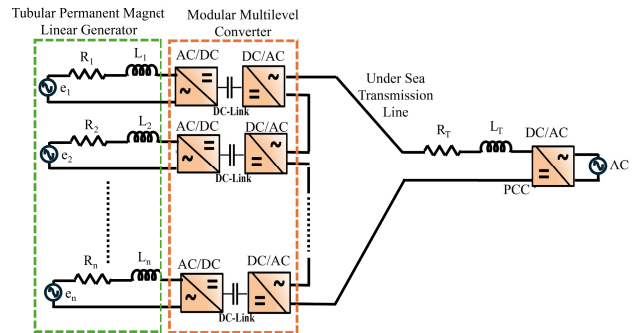
Tidal-specific deployments validate the practical viability of BTB conversion. In [258], the 1.2 MW SeaGen tidal energy system utilizes BTB IGBT-based converters to synchronize the outputs of two horizontal-axis turbines. The combined output is transferred via an underwater cable to an 11 kV shore grid. The single-line representation of the system is shown in Fig. 20. Further expanding on BTB control strategies, [135] proposes an adaptive passivity-based super-twisting algorithm with a fractional-order PID controller for a PMSG-based marine current energy system. The proposed controller enhances performance under swell-induced disturbances and parametric uncertainties, as shown in Fig. 21. These works demonstrate the suitability of BTB converters for both large-scale grid-connected tidal farms and smaller-scale islanded deployments. Notably, tidal turbine arrays can be placed sparsely in terms of location; a full active converter provides much improved site-based phase synchronization, allowing scalability of tidal energy sources.

As MRE systems expand toward larger arrays and deeper offshore deployment, MVDC transmission is gaining relevance for reducing submarine cable losses, eliminating reactive power needs, and improving system economics [263]. However, standard two-level VSCs face voltage and thermal limitations. To overcome these, [264] introduces a five-level Neutral Point Clamped (NPC) converter for subsea kite power conversion. The system employs two cascaded NPC stages for high-voltage operation using low-voltage-rated switches. Advanced space-vector modulation ensures DC-link capacitor balancing, while a 50 kVA SiC-based prototype demonstrates improved efficiency, reduced cable losses, and low output harmonics. Fig. 22 illustrates the architecture, offering a scalable solution for high-power tidal converters.

Distributed power conversion has gained traction as a scalable architecture for marine renewables. For instance, [265] introduced a modular medium voltage conversion interface for the Wave Dragon platform (Fig. 23), where each generator employed a diode rectifier and boost converter stage before interfacing with a shared NPC converter.



**FIGURE 23.** NPC-based multi-generator drive for wave dragon platform [265].

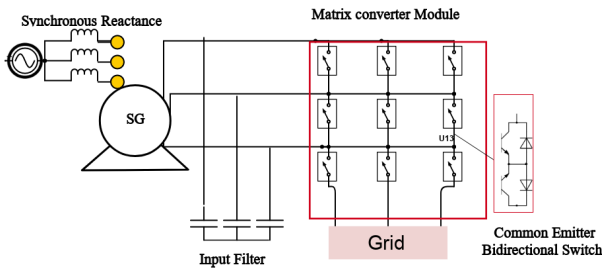


**FIGURE 24.** MMC converter for wave power conversion [266].

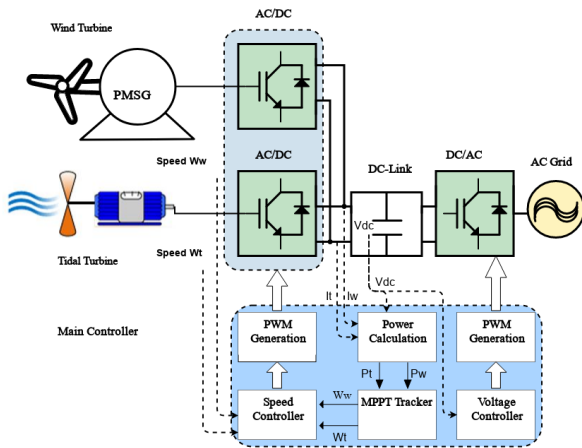
Although developed for wave energy, this modular approach is directly relevant to tidal arrays, where decentralized rectification could reduce subsea cable loading and simplify multi-turbine scalability.

MMCs have also emerged as a promising option for medium and high power marine applications (Fig. 24). By cascading multiple submodules per phase, MMCs can synthesize multilevel voltages with low harmonic distortion, reducing or even eliminating bulky AC filters while enabling efficient operation at lower switching frequencies. Recent studies in wave energy conversion have explored MMCs to drive linear generators with multiple coils, providing fine-grained flux and torque control as well as improved transmission efficiency through series-connected windings [266], [267]. While these studies are wave-focused, their modularity, scalability, and high efficiency make MMCs attractive for tidal PTO systems, particularly for large-scale arrays requiring MVDC collection and reliable long-distance transmission.

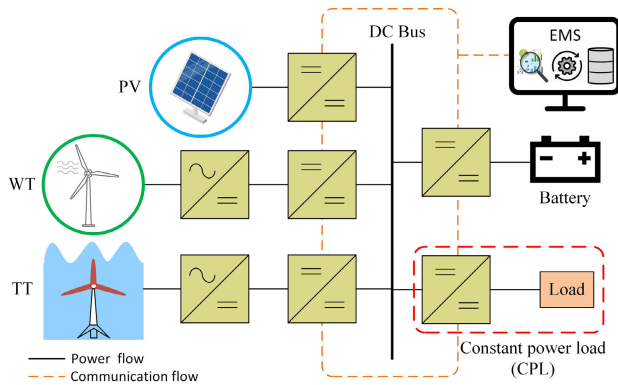
Despite offering reduced switching losses and excellent harmonic performance, MMCs face implementation challenges—such as high submodule energy storage, complex balancing control, and limited improvement in conduction losses over optimized two-level converters [268]. Nonetheless, their scalability and waveform quality make MMCs a compelling future choice for high-voltage tidal farms.



**FIGURE 25. Matrix converter with a synchronous generator for tidal power conversion [270].**



**FIGURE 26. Hybrid offshore wind and tidal turbine energy harvesting system with independently controlled rectifiers [273].**



**FIGURE 27. Off-grid DC microgrid integrating photovoltaic panels, wind turbines, tidal energy converters, and battery energy storage [124].**

In conclusion, although modular converter topologies offer significant potential for future large-scale tidal deployments, two-level and multi-level VSCs remain the most mature, widely demonstrated, and operationally reliable options in present tidal energy applications.

3) POWER CONVERSION WITHOUT INTERMEDIATE DC LINK  
In both passive and active conversion units, generator output undergoes rectification to convert it into DC voltage before

utilizing a grid-connected inverter to deliver tidal energy to the power grid. However, the power efficiency of this approach is compromised due to energy losses in the AC–DC conversion process via the rectifying circuit. A more desirable solution to enhance electricity production from MRE converters is direct AC–AC conversion [269], which indicates the absence of passive components such as the DC link capacitor and inductor in the converter design. A simulation-based model of a matrix converter for the tidal current power generating system is developed in [270] to run the Synchronous Generator (SG) in place of the conventional BTB converter.

Control of the synchronous generator is carried out with a direct matrix converter and space vector modulation. Fig. 25 shows the matrix converter schematic for tidal current conversion. Matrix converters offer potential advantages for tidal energy systems, including compact design, high efficiency, low harmonic distortion, and the absence of bulky DC link components, making them suitable for constrained marine environments. However, their adoption remains limited due to output voltage constraints, sensitivity to tidal flow-induced voltage variations, complex control requirements, higher conduction losses, and the cost of bidirectional switching devices. Additionally, limited field deployment and commercial availability restrict their current use in marine applications [271]. This is mainly owing to difficult commutation loop design, complex control, and a lack of reliability/aging analysis for harsh marine and tidal environments, especially in the case of high-power submerged generator systems.

In conclusion, PECs play a critical role in tidal energy systems, linking the PTO units with the grid while enabling control, power quality, and system adaptability in marine environments. Various topologies, from simple diode rectifiers to advanced VSCs, NPCs, MMCs, and matrix converters, offer complexity, control, and scalability trade-offs. Passive rectifiers provide robust and low-maintenance operation but lack grid support features. In contrast, VSC-based systems enable full control over active/reactive power, while MMCs offer high scalability and superior harmonic performance. Matrix converters remain largely experimental due to complex control and marine sealing concerns. Table 8 summarizes the comparative evaluation of these converter types for tidal energy applications.

**D. PECS FOR INTEROPERABILITY WITH OTHER DE SOURCES**

The synergy of tidal energy with other renewable sources, such as wind, wave, and photovoltaic energy, is increasingly recognized for its potential to smooth out generation variability and improve overall system efficiency. However, this integration introduces complex control and conversion challenges due to these resources’ heterogeneous and intermittent nature. PECs are the backbone of this integration by enabling dynamic power balancing, MPPT, and real-time coordination between subsystems.

**TABLE 8. Comparative evaluation of power electronic converters for tidal energy applications.**

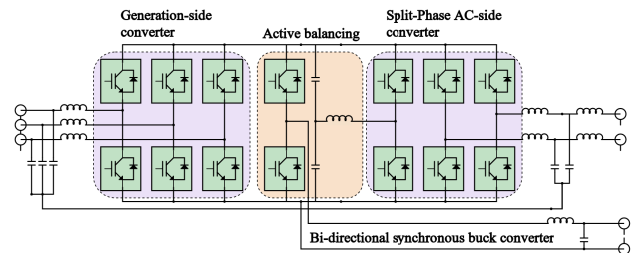
Feature / Topology	Diode Rectifier (Passive)	2-Level VSC (BTB)	Multilevel VSC	MMC	Matrix Converter
<b>Deployment Context</b>	MVDC arrays via modular turbine aggregation (e.g., ABB $\pm 5\text{--}7.5$ kV)	Shallow offshore/near-shore; shore-side coupling (e.g., Seagen)	Submerged kite systems with onboard multilevel conversion	Centralized High Voltage DC (HVDC) hubs or marine substations	Lab-stage only; no tidal-specific deployment
<b>Offshore Suitability</b>	Excellent for sealed nacelles and low-maintenance arrays	Moderate; distance-limited	Optimized for deep-sea kite platforms	Highly scalable and modular for utility-scale arrays	Unproven under marine stress and complex control
<b>Onshore/Near-shore Use</b>	Not preferred; lacks controllability	Field-demonstrated in grid-connected pilots	Tested in near-shore pilot setups	Too complex/costly for near-shore	No real-world validation
<b>Control Capability</b>	None (passive only)	Full AC-side control (PWM)	PWM with multilevel balancing	Advanced modulation and redundancy	Direct modulation; real-time intensive
<b>Reactive Power Control</b>	None	Yes	PWM-based Q control	Excellent Q control	Possible, but unstable subsea
<b>Bidirectional Power Flow</b>	No	Yes	Yes	Yes	Yes
<b>Power Factor Control</b>	No; fixed PF	PWM-based control	Controllable PF via modulation	Near-unity PF possible	High control accuracy needed
<b>Harmonics / EMI</b>	High harmonics; needs bulky filtering	Moderate EMI; manageable with filtering	Low THD; better harmonic performance	Very low THD; EMI-optimized	EMI; underwater applications unresolved
<b>Marine Robustness</b>	Highly robust in sealed nacelles	Moderately rugged; some maintenance needed	Validated for deep-sea deployment	Component-heavy; sensitive to marine conditions	Unproven in wet environments
<b>MW-Scale Scalability</b>	Scalable via modular MVDC aggregation	Scalable	Scalable via modular deployment	Highly scalable; 10–100 MW+ feasible	Scalable via modular architectures
<b>Application Maturity</b>	Used in ABB tidal trials and LVDC simulations (e.g., MUP)	Validated in Seagen and EU projects	Commercial prototypes by Minesto	Proposed for marine HVDC; proven in offshore wind	Conceptual only; not tidal-ready

**Note:** Multiport Converters are also gaining attention for TECs, as they can integrate multiple tidal generators and storage devices within a single converter stage, reducing component count and improving efficiency [272].

For instance, [273] proposed a hybrid wind–tidal configuration using PWM-controlled rectifiers and a dq-frame PMSG model to implement MPPT control (Fig. 26). In [261], a reliability evaluation method for wind–tidal–battery systems considers power-dependent failure rates of PECs, emphasizing their sizing and operational impact in coastal deployments. Reference [16] provides a broad review of hybrid wave–tidal systems and identifies key limitations, such as weak subsystem coupling and lack of hybrid testbeds. The study advocates for co-simulation frameworks, nonlinear control, and techno-economic analysis to accelerate deployment.

Control strategies and hardware architectures are vital in hybrid MRE microgrids. In [124], a hardware-validated Energy Management System (EMS) for a standalone PV–wind–tidal–battery microgrid demonstrated enhanced power quality via coordinated control as shown in Fig. 27. Similarly, [127] used rule-based and optimization-based control in a DC microgrid to improve flexibility.

MultiPort Converters (MPC) have shown promising potential for MRE integration. Reference [272] propose a multiport DC-DC converter tailored for tidal energy applications, integrating multiple tidal turbines, via DC generators and PMSGs, into a unified DC bus. Complementing this, [274] proposes an MPC-based architecture for a wave energy

**FIGURE 28. A multiport converter topology based on synchronous bi-directional buck converter [274].**

converter emulation platform that integrates storage and split-phase AC loads via a 400 V DC bus, utilizing SiC power devices to minimize passive components and enhance marine adaptability. Due to the high switching frequency capabilities, SiC power devices enable a compact system design with smaller passive component sizes [264]. The SiC-based marine power conversion setup is shown in Fig. 28.

To highlight emerging trends and real-world implementations, Table 9 provides a comparative overview of hybrid energy systems involving tidal energy, spanning both industrial prototypes and academic initiatives. These projects explore synergistic integration of tidal with wind, wave, solar,

TABLE 9. Hybrid energy systems involving tidal energy: Industrial and academic initiatives.

Project / Study	Category	Energy Sources	Status	Highlights	Reference
PH4S (GEPS Techno)	Industrial	Solar, Wind, Tidal, Wave	Prototype tested offshore (France)	Combines 4 renewable energy sources with battery/supercapacitor; aims to reduce intermittency	[275]
SKWID (MODEC)	Industrial	Wind, Tidal	Deployment failed (2014)	Vertical-axis turbines for bidirectional wind/tidal current capture	[276]
SeaGen W (MCT)	Concept	Wind, Tidal	Remained conceptual	Wind turbine mounted on tidal turbine monopile	[277]
Hexifloat (Hann Ocean)	Concept	Solar, Wind, Tidal, Wave	Concept patented (2012)	Floating platform harnessing four marine energy sources	[278]
HOT-PC	Academic	Wind, Tidal	Lab Prototype	Tidal used as flywheel to smooth wind fluctuations	[123]
Energy management system for a hybrid islanded DC microgrid	Academic	PV, Wind, Tidal, Battery	Experimental	Validated EMS in DC microgrid with control and hardware test bench	[124]
Supervisory energy management of a hybrid DC-microgrid	Academic	PV, Wind, Tidal, Battery	Simulation	Predictive supervisory control and dynamic energy sharing strategies	[127]
Floating wind-wave-tidal hybrid system	Academic	Wind, Wave, Tidal	Experimental	Investigated hydrodynamic response and motion suppression under freak waves	[279]
Hybrid Wind-Tidal Microgrid for NZ Off-grid Community	Academic	Wind, Tidal	Case Study	Real-world feasibility study for off-grid hybrid system in New Zealand	[64]

and storage systems, reflecting the growing importance of multi-resource coordination for reliability and dispatchability in marine environments.

V. IMPROVEMENT IN CURRENT FOOTPRINT OF PEC FOR TIDAL APPLICATIONS

Tidal energy conversion is rapidly evolving, driven by the pressing need for sustainable and efficient renewable energy sources. In pursuing enhancing the current footprint of tidal and marine energy converters, many promising avenues exist for research and development. These avenues, when coupled with the utilization of WBG devices and associated technologies, hold immense potential to not only improve performance but also bolster reliability and cost-effectiveness [91], [92], [93], [94]. This section delves into the potential for improving the existing footprint of tidal energy systems, considering critical materials and technologies, including WBG devices, and addressing associated advantages and challenges.

A. ENHANCING TIDAL ENERGY SYSTEMS: LEVERAGING WBG TECHNOLOGIES

Exploring cutting-edge materials and technologies is crucial to optimizing current tidal energy systems. The development and integration of WBG devices, including SiC and GaN power devices, hold immense potential (Fig. 29 [280]). Their adoption could address long-standing compactness, efficiency, and reliability challenges in harsh marine environments.

Compared to conventional silicon devices, WBG semiconductors operate efficiently at much higher switching

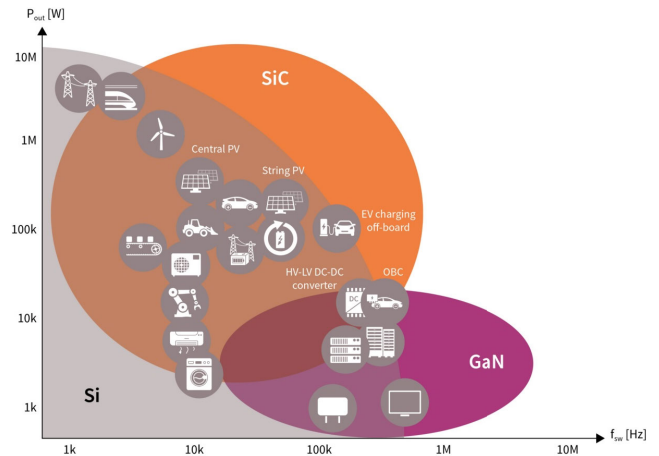


FIGURE 29. Power-frequency plane of Si, SiC, and GaN for different applications [280].

frequencies, enabling more compact and lightweight converter designs. This attribute is especially advantageous for tidal energy converters, where subsea installations demand space-efficient hardware and reduced structural loads [264], [281]. A defining feature of SiC and GaN devices is their lower conduction and switching losses, which translates into higher conversion efficiency, an essential factor for maximizing power capture from tidal flows and limiting thermal stress in enclosed marine housings [282]. In addition, higher power density enabled by WBG devices supports smaller converter footprints, reducing installation complexity and potentially lowering overall O&M costs [283].

Despite these benefits, integrating WBG devices into tidal PTOs poses unique challenges. Specialized gate drivers are required to fully exploit high-frequency switching, ensuring their long-term reliability under subsea pressure, corrosion, and thermal cycling is non-trivial. Furthermore, higher switching frequencies increase Electromagnetic Interference (EMI), which can disrupt sensitive instrumentation and communication links in tidal arrays. Therefore, effective EMI suppression and marine-grade packaging solutions are critical for realizing the full potential of WBG-based converters in tidal energy systems [284], [285], [286].

### B. PACKAGING CONSIDERATIONS

Efficient and reliable packaging of power devices is crucial in the challenging marine environment [287]. Various techniques and strategies enhance reliability in tidal systems. Press-Pack-Based Plate Soldering, utilizing pressure and soldering, forms a robust connection between power devices and heat sinks or substrates. It ensures good thermal performance and withstands marine challenges, such as temperature fluctuations and moisture exposure [185]. Sintering technology offers a reliable alternative to conventional chip soldering by minimizing corrosion risks in marine environments. It allows direct bonding of power devices to substrates, improving durability and performance in harsh conditions [288]. For interconnections in marine applications, corrosion-resistant alloys can be explored as alternatives to traditional bond wires, improving the durability and reliability of power devices [289].

### C. RELIABILITY ENHANCEMENTS

Power converters and their components should be designed with reliability as a primary consideration [21], [191], [192]. This involves choosing materials and components that withstand the harsh marine environment, including corrosion-resistant coatings [102], [290], and encapsulations [215], [216], [217]. Optimizing power electronics layout for better cooling and reduced mechanical stress enhances reliability [204], [205], [206], [207], [208]. Developing accurate thermal models for power devices is essential [213], [214], [291], aiding in predicting and managing temperature rise critical for marine environments. These models can guide Effective thermal management strategies, including advanced cooling techniques [292]. Different control strategies, like junction temperature monitoring and hybrid control, optimize thermal performance [209], [210], [211], preventing overheating and ensuring safe, reliable operation, meeting stringent tidal reliability requirements.

Integrating WBG devices into tidal energy systems brings significant benefits, such as improved efficiency and increased power density. However, key challenges must be addressed to fully unlock their potential, including designing reliable gate drivers, mitigating EMI, improving packaging, and ensuring durability in harsh marine conditions. Progress depends on collaboration between researchers, engineers, and

industry experts. By working together, they can overcome technical barriers, drive innovation, and create a sustainable future for tidal.

## VI. FUTURE RESEARCH WORK

The future of tidal energy conversion is poised for transformative advancements driven by PECs and related technologies. To further advance the research boundaries for enhanced reliability, improved efficiency, and minimized costs, research must focus on several critical areas:

- Designing innovative converter topologies and advanced control strategies tailored to tidal energy systems, utilizing the high switching frequencies and low power losses offered by WBG devices.
- Improving thermal management techniques for an extended lifespan of tidal energy converters, with adaptive cooling solutions that respond dynamically to operating conditions.
- Addressing failures caused by humidity in submerged converters through focused research on moisture-resilient materials and protective strategies to enhance reliability.
- Advancing PEC architectures for tidal energy systems with designs that improve fault tolerance, reduce maintenance, and bolster operational resilience, ultimately lowering the LCOE.
- Designing modular, flexible, and scalable universal converter platforms that can adapt to various tidal sources, simplifying development and validation processes.
- Exploring the use of MMC structures for subsea MV/HVDC transmission, enabling efficient energy transfer from offshore farms to onshore grids with minimal losses.
- Enhancing competitiveness through efforts to reduce the LCOE by improving system reliability and operational resilience.
- Developing real-time simulation platforms for PTO controllers and hardware validation, enabling rigorous testing and accelerating the deployment of cutting-edge tidal technologies.

## VII. CONCLUSION

Tidal energy represents a predictable yet underexploited renewable resource, with practical deployment still constrained by technological, environmental, and economic barriers. This review has presented a structured assessment of these challenges across the resource, converter, and grid domains, emphasizing the pivotal role of PECs in achieving reliable, efficient, and grid-compliant operation. By explicitly linking tidal resource variability with converter performance and system-level integration, the analysis demonstrates how innovations in converter topologies, adaptive control strategies, and marine-grade reliability directly influence energy capture, stability, and long-term scalability.

At the resource level, challenges such as bidirectional flow, slack tides, turbulence, and site-specific hydrodynamics

demand advanced forecasting, adaptive control algorithms, and hybridization with complementary renewables or storage systems. While predictive tools and hybrid configurations show promise, standardized frameworks and field-scale validation remain limited.

At the grid-integration level, weak marine grids, limited fault ride-through, insufficient VAR support, and the absence of tidal-specific grid codes hinder wider adoption. Mitigation strategies are being explored, such as grid-forming converters with droop, virtual inertia, storage support, and adaptive protection. However, tidal-specific standards, large-scale demonstration of ancillary services, and validated real-time tidal plant models are urgently needed to enable reliable grid compliance.

On the converter side, subsea PECs face harsh marine conditions, including pressure, corrosion, and thermal cycling, which limit lifetime and accessibility. Current deployments rely predominantly on mature two- and multilevel VSCs, while advanced modular concepts such as MMCs, multi-port converters, and WBG-based designs offer compelling advantages in scalability, efficiency, and power density but remain at low technology readiness. Ensuring fault tolerance, reliable packaging, subsea cooling, higher MTBF, and condition-based monitoring through digital twins represents a critical research frontier.

Taken together, this challenge–mitigation framework highlights that converter innovations alone are insufficient; progress in tidal energy requires integrated advances across the resource, converter, and grid domains. Looking ahead, modular PEC architectures, digital twin–based health analytics, and hybrid tidal–renewable integration are expected to accelerate the transition toward resilient, grid-forming tidal systems. Equally critical will be establishing tidal-specific grid codes, marine reliability standards, and large-scale demonstration projects that validate these technologies under real conditions.

By enabling higher energy stability, improved reliability, and reduced maintenance through smart converter designs and predictive diagnostics, the proposed framework directly supports the industrial scalability and cost competitiveness of tidal energy technologies. This holistic pathway strengthens the commercial readiness of tidal systems—bridging the gap from prototype research to bankable, utility-scale deployment and positioning tidal power as a reliable contributor to the global net-zero transition.

## REFERENCES

- [1] F. Merahi and H. Mernache, "Optimal torque control for power optimization in PMSG based wind energy conversion system for an autonomus mode operation," in *Proc. 19th Int. Multi-Conf. Syst., Signals Devices (SSD)*, May 2022, pp. 1222–1227.
- [2] *Global Climate Report for April 2024*, Nat. Centers Environ. Inf. (NCEI), Asheville, NC, USA, Jun. 2024. Accessed: Apr. 1, 2025. [Online]. Available: <https://www.ncei.noaa.gov/access/monitoring/monthly-report/global/202413>
- [3] *World Energy Outlook 2022—Analysis*, Int. Energy Agency (IEA), Paris, France, Oct. 2022. Accessed: Apr. 1, 2025. [Online]. Available: <https://www.iea.org/reports/world-energy-outlook-2022>
- [4] *Global Energy Review 2025: Co<sub>2</sub> Emissions*, Int. Energy Agency (IEA), Paris, France, Oct. 2022. Accessed: Apr. 1, 2025. [Online]. Available: <https://www.iea.org/reports/global-energy-review-2025/co2-emissions>
- [5] L. Kilcher, M. Fogarty, and M. Lawson, "Marine energy in the United States: An overview of opportunities," Nat. Renew. Energy Lab. (NREL), Golden, CO, USA, Tech. Rep., Feb. 2021. Accessed: Jun. 1, 2025, doi: 10.2172/1766861.
- [6] D. Preziuso, G. García-Medina, R. O'Neil, Z. Yang, and T. Wang, "Evaluating the potential for tidal phase diversity to produce smoother power profiles," *J. Mar. Sci. Eng.*, vol. 8, no. 4, p. 246, Apr. 2020.
- [7] M. S. Chowdhury, K. S. Rahman, V. Selvanathan, N. Nuthammachot, M. Suklueng, A. Mostafaeipour, A. Habib, M. Akhtaruzzaman, N. Amin, and K. Techato, "Current trends and prospects of tidal energy technology," *Environ., Develop. Sustainability*, vol. 23, no. 6, pp. 8179–8194, Jun. 2021.
- [8] M. Z. A. Khan, H. A. Khan, and M. Aziz, "Harvesting energy from ocean: Technologies and perspectives," *Energies*, vol. 15, no. 9, p. 3456, May 2022.
- [9] K. Rajashekara and H. Krishnamoorthy, "Power electronics for subsea systems: Challenges and opportunities," in *Proc. IEEE 12th Int. Conf. Power Electron. Drive Syst. (PEDS)*, Dec. 2017, pp. 986–991.
- [10] D. Khojasteh, D. Khojasteh, R. Kamali, A. Beyene, and G. Iglesias, "Assessment of renewable energy resources in Iran; with a focus on wave and tidal energy," *Renew. Sustain. Energy Rev.*, vol. 81, pp. 2992–3005, Jan. 2018.
- [11] E. Segura, R. Morales, J. A. Somolinos, and A. López, "Techno-economic challenges of tidal energy conversion systems: Current status and trends," *Renew. Sustain. Energy Rev.*, vol. 77, pp. 536–550, Sep. 2017.
- [12] V. Khare and M. A. Bhuiyan, "Tidal energy-path towards sustainable energy: A technical review," *Cleaner Energy Syst.*, vol. 3, Dec. 2022, Art. no. 100041.
- [13] Y. Si, X. Liu, T. Wang, B. Feng, P. Qian, Y. Ma, and D. Zhang, "State-of-the-art review and future trends of development of tidal current energy converters in China," *Renew. Sustain. Energy Rev.*, vol. 167, Oct. 2022, Art. no. 112720.
- [14] S. P. Neill, K. A. Haas, J. Thiébot, and Z. Yang, "A review of tidal energy—Resource, feedbacks, and environmental interactions," *J. Renew. Sustain. Energy*, vol. 13, no. 6, Nov. 2021, Art. no. 062702.
- [15] A. Korte, C. Windt, and N. Goseberg, "Review and assessment of the German tidal energy resource," *J. Ocean Eng. Mar. Energy*, vol. 10, no. 1, pp. 239–261, Feb. 2024.
- [16] P. Chen and D. Wu, "A review of hybrid wave-tidal energy conversion technology," *Ocean Eng.*, vol. 303, Jul. 2024, Art. no. 117684.
- [17] X. Zhang, L. Zhang, Y. Yuan, and Q. Zhai, "Life cycle assessment on wave and tidal energy systems: A review of current methodological practice," *Int. J. Environ. Res. Public Health*, vol. 17, no. 5, p. 1604, Mar. 2020.
- [18] A. Uihlein and D. Magagna, "Wave and tidal current energy—A review of the current state of research beyond technology," *Renew. Sustain. Energy Rev.*, vol. 58, pp. 1070–1081, May 2016.
- [19] Z. Qin, X. Tang, Y.-T. Wu, and S.-K. Lyu, "Advancement of tidal current generation technology in recent years: A review," *Energies*, vol. 15, no. 21, p. 8042, Oct. 2022.
- [20] A. López, J. L. Morán, L. R. Núñez, and J. A. Somolinos, "Study of a cost model of tidal energy farms in early design phases with parametrization and numerical values. Application to a second-generation device," *Renew. Sustain. Energy Rev.*, vol. 117, Jan. 2020, Art. no. 109497.
- [21] N. Vedachalam, S. Muthukrishna Babu, G. A. Ramadass, and M. A. Atmanand, "Review of maturing multi-megawatt power electronic converter technologies and reliability modeling in the light of subsea applications," *Appl. Ocean Res.*, vol. 46, pp. 28–39, Jun. 2014.
- [22] F. Wani and H. Polinder, "A review of tidal current turbine technology: Present and future," in *Proc. Eur. Wave Tidal Energy Conf. (EWTEC)*, 2017, p. 1133.
- [23] P. Qian, B. Feng, H. Liu, X. Tian, Y. Si, and D. Zhang, "Review on configuration and control methods of tidal current turbines," *Renew. Sustain. Energy Rev.*, vol. 108, pp. 125–139, Jul. 2019.
- [24] V. Narayanaswamy and H. Bang-Andreasen, "Challenges in realizing reliable subsea electric power grid for tidal energy farms," *Mar. Technol. Soc. J.*, vol. 47, no. 4, pp. 80–93, Jul. 2013.

- [25] V. Smil, "Power density primer: Understanding the spatial dimension of the unfolding transition to renewable electricity generation (Part I—Definitions)," *Atlantic*, vol. 26, p. 2019, May 2010.
- [26] T. El Tawil, J. F. Charpentier, and M. Benbouzid, "Tidal energy site characterization for marine turbine optimal installation: Case of the ouessant Island in France," *Int. J. Mar. Energy*, vol. 18, pp. 57–64, Jun. 2017.
- [27] S. P. Neill, A. Angeloudis, P. E. Robins, I. Walkington, S. L. Ward, I. Masters, M. J. Lewis, M. Piano, A. Avdis, M. D. Piggott, G. Aggidis, P. Evans, T. A. A. Adcock, A. Židonis, R. Ahmadian, and R. Falconer, "Tidal range energy resource and optimization—Past perspectives and future challenges," *Renew. Energy*, vol. 127, pp. 763–778, Nov. 2018.
- [28] A. Roy, F. Auger, F. Dupriez-Robin, S. Bourguet, and Q. T. Tran, "Electrical power supply of remote maritime areas: A review of hybrid systems based on marine renewable energies," *Energies*, vol. 11, no. 7, p. 1904, Jul. 2018.
- [29] *Ocean power generation in the Sustainable Development Scenario, 2000–2030*, Int. Energy Agency (IEA), Paris, France, 2020. [Online]. Available: <https://www.iea.org/data-and-statistics/charts/ocean-power-generation-in-the-sustainable-development-scenario-2000-2030>
- [30] A. Mason, "Marine energy electrical architecture, report 1: Landscape map and literature review," Offshore Renew. Energy (ORE) Catapult, Glasgow, U.K., Tech. Rep. PN000083-LRT-006, Sep. 2015. Accessed: Dec. 28, 2024. [Online]. Available: <https://ore.catapult.org.uk/?orecatapultreports-marine-energy-electrical-architecture-report-1-landscape-map-literature-review>
- [31] *Annual Report 2022: Ocean Energy Systems*, Int. Energy Agency, Ocean Energy Systems (IEA-OES), Paris, France, 2023. Accessed: Mar. 8, 2025. [Online]. Available: <https://www.ocean-energy-systems.org/publications/oes-annual-reports/annual-report-2022/>
- [32] *OES Annual Report 2023*, International Energy Agency, Ocean Energy Systems, Paris, France, 2024. Accessed: Mar. 31, 2025. [Online]. Available: <https://www.ocean-energy-systems.org/publications/oes-annual-reports/document/oes-annual-report-2023/>
- [33] *Innovation Outlook: Ocean Energy Technologies*, Int. Renew. Energy Agency (IRENA), Abu Dhabi, UAE, 2020. Accessed: Mar. 28, 2025. [Online]. Available: <https://www.irena.org/publications/2020/Dec/Innovation-Outlook-Ocean-Energy-Technologies>
- [34] X. Wang, H. Li, J. Chen, C. Jiang, and L. Bao, "Research on solidity of horizontal-axis tidal current turbine," *Energies*, vol. 16, no. 8, p. 3467, Apr. 2023.
- [35] B. Gunawan, V. S. Neary, and J. Colby, "Tidal energy site resource assessment in the east river tidal strait, near roosevelt Island, New York, New York," *Renew. Energy*, vol. 71, pp. 509–517, Nov. 2014.
- [36] G. Savidge, D. Ainsworth, S. Bearhop, N. Christen, B. Elsaesser, F. Fortune, R. Inger, R. Kennedy, A. McRobert, K. E. Plummer, D. W. Pritchard, C. E. Sparling, and T. J. T. Whittaker, *Strangford Lough Tidal Turbine, Northern Ireland*. Cham, Switzerland: Springer, 2014, pp. 153–172.
- [37] Tethys Project Sites. (2024). *Strangford Lough Mct Seagen*. [Online]. Available: <https://tethys.pnnl.gov/project-sites/strangford-lough-mct-seagen>
- [38] European Marine Energy Centre (EMEC). (2024). *Openhydro—Our Tidal Clients*. [Online]. Available: <https://www.emec.org.uk/about-us/our-tidal-clients/open-hydro/>
- [39] M. Lewis, S. P. Neill, P. E. Robins, and M. R. Hashemi, "Resource assessment for future generations of tidal-stream energy arrays," *Energy*, vol. 83, pp. 403–415, Apr. 2015.
- [40] L. M. Kangaji, L. Tartibu, and P. N. Bokoro, "Modelling and performance analysis of a tidal current turbine connected to the grid using an inductance (LCL) filter," *Energies*, vol. 16, no. 16, p. 6090, Aug. 2023.
- [41] N. Erdogan, D. B. Murray, J. Giebhardt, M. Wecker, and J. Donegan, "Real-time hardware emulation of a power take-off model for grid-connected tidal energy systems," in *Proc. IEEE Int. Electric Mach. Drives Conf. (IEMDC)*, May 2019, pp. 1368–1372.
- [42] E. Muljadi, A. Wright, V. Gevorgian, J. Donegan, C. Marnagh, and J. McEntee, "Power generation for river and tidal generators," Nat. Renew. Energy Lab. (NREL), Golden, CO, USA, Tech. Rep. NREL/TP-5D00-66097, Jun. 2016, doi: [10.2172/1259805](https://doi.org/10.2172/1259805). [Online]. Available: <https://www.nrel.gov/docs/fy16osti/66097.pdf>
- [43] J. Khan, G. Bhuyan, and A. Moshref. (2009). *Potential Opportunities and Differences Associated With Integration of Ocean Wave and Marine Current Energy Plants in Comparison To Wind Energy*. [Online]. Available: <http://www.iea-oceans.org>
- [44] S. Leighton, "An analysis of the leading tidal energy projects in the United States since 2000," Master's thesis, School Marine Environ. Affairs, Univ. Washington, Seattle, WA, USA, 2024.
- [45] B. Polagye and R. Bedard, *System Level Design, Performance, Cost and Economic Assessment-San Francisco Tidal In-stream Power Plant*, Standard TP-006-SF, EPRI, 2006.
- [46] X. Liu, Z. Chen, Y. Si, P. Qian, H. Wu, L. Cui, and D. Zhang, "A review of tidal current energy resource assessment in China," *Renew. Sustain. Energy Rev.*, vol. 145, Jul. 2021, Art. no. 111012.
- [47] I. Fairley, H. C. M. Smith, B. Robertson, M. Abusara, and I. Masters, "Spatio-temporal variation in wave power and implications for electricity supply," *Renew. Energy*, vol. 114, pp. 154–165, Dec. 2017.
- [48] D. Magaña and A. Uihlein, "Ocean energy development in Europe: Current status and future perspectives," *Int. J. Mar. Energy*, vol. 11, pp. 84–104, Sep. 2015.
- [49] S. P. Neill and M. R. Hashemi, *Fundamentals of Ocean Renewable Energy: Generating Electricity From the Sea*. New York, NY, USA: Academic, 2018.
- [50] M. Santos, F. Salcedo, D. B. Haim, J. Mendia, P. Ricci, J. Villate, J. Khan, D. Leon, S. Arabi, and A. Moshref, "Integrating wave and tidal current power: Case studies through modelling and simulation (2011)," Ph.D. thesis, Int. Energy Agency Implementing Agreement Ocean Energy Syst., Tecnalia, Powertech Labs HMRC, Powertech Labs, Canada, Mar. 2011.
- [51] S. P. Neill, M. R. Hashemi, and M. J. Lewis, "Optimal phasing of the European tidal stream resource using the greedy algorithm with penalty function," *Energy*, vol. 73, pp. 997–1006, Aug. 2014.
- [52] M. Lewis, J. McNaughton, C. Márquez-Dominguez, G. Todeschini, M. Togneri, I. Masters, M. Allmark, T. Stallard, S. Neill, A. Goward-Brown, and P. Robins, "Power variability of tidal-stream energy and implications for electricity supply," *Energy*, vol. 183, pp. 1061–1074, Sep. 2019.
- [53] A. A. Ameri, A. Koita, A. Payman, M. B. Camara, and B. Dakyo, "EMR modelling of tidal turbines integrated into orkney grid," *Electric Power Syst. Res.*, vol. 201, Dec. 2021, Art. no. 107548.
- [54] H. H. H. Aly, "A novel approach for harmonic tidal currents constitutions forecasting using hybrid intelligent models based on clustering methodologies," *Renew. Energy*, vol. 147, pp. 1554–1564, Mar. 2020.
- [55] A. Roy, F. Auger, F. Dupriez-Robin, S. Bourguet, and Q. T. Tran, "A multi-level demand-side management algorithm for offgrid multi-source systems," *Energy*, vol. 191, Jan. 2020, Art. no. 116536.
- [56] R. Seshu Kumar, L. Phani Raghav, D. Koteswara Raju, and A. R. Singh, "Impact of multiple demand side management programs on the optimal operation of grid-connected microgrids," *Appl. Energy*, vol. 301, Nov. 2021, Art. no. 117466.
- [57] A. Roy, F. Auger, S. Bourguet, F. Dupriez-Robin, and Q. T. Tran, "Benefits of demand side management strategies for an island supplied by marine renewable energies," in *Proc. 7th Int. Conf. Renew. Energy Res. Appl. (ICRERA)*, Oct. 2018, pp. 474–481.
- [58] M. R. Barakat, B. Tala-Ighil, H. Gualous, and D. Hissel, "JADE-based multi-agent decentralized energy management system of a hybrid marine-hydrogen power generation system," in *Proc. ELECTRIMACS*, 2020, pp. 245–257.
- [59] M. Trabelsi, S. Molina, J. F. Charpentier, F. Scullier, and E. Nicolas, "Joint coordination of optimal power management and energy storage system sizing for a full-scale marine current turbine considering microgrid integration constraint," *J. Energy Storage*, vol. 52, Aug. 2022, Art. no. 104792.
- [60] A. Kumar, S. Ghosh, S. Das, A. K. Singh, and N. K. Singh, "ANFIS-based control for low-voltage ride-through enhancement of PMSG tidal turbine," in *Proc. IEEE Students Conf. Eng. Syst. (SCES)*, Jul. 2022, pp. 1–6.
- [61] L. Mackie, D. Coles, M. Piggott, and A. Angeloudis, "The potential for tidal range energy systems to provide continuous power: A U.K. case study," *J. Mar. Sci. Eng.*, vol. 8, no. 10, p. 780, Oct. 2020.
- [62] M. Ashglaf, C. Nichita, and J. Raharjaona, "Hybrid wind-tidal energy systems-literature review," in *Proc. Francophone Multidisciplinary Colloq. Mater., Environ. Electron.*, 2017, pp. 59–71.
- [63] S. P. Neill, M. R. Hashemi, and M. J. Lewis, "Tidal energy leasing and tidal phasing," *Renew. Energy*, vol. 85, pp. 580–587, Jan. 2016.
- [64] N. Majidi Nasab, J. Kilby, and L. Bakhtiyarfard, "Case study of a hybrid wind and tidal turbines system with a microgrid for power supply to a remote off-grid community in New Zealand," *Energies*, vol. 14, no. 12, p. 3636, Jun. 2021.

- [65] M. J. Beam, B. L. Kline, B. E. Elbing, W. Straka, A. A. Fontaine, M. Lawson, Y. Li, R. Thresher, and M. Previsic, "Marine hydrokinetic turbine power-take-off design for optimal performance and low impact on cost-of-energy," in *Proc. Int. Conf. Offshore Mech. Arctic Eng.*, Jun. 2013, pp. 1–8.
- [66] A. Vazquez and G. Iglesias, "Capital costs in tidal stream energy projects—A spatial approach," *Energy*, vol. 107, pp. 215–226, Jul. 2016.
- [67] A. Mason, R. Driver, S. Hay, and R. Hodges, "Marine energy electrical architecture, report 3: Optimum electrical array architectures," Offshore Renew. Energy (ORE) Catapult, Glasgow, U.K., Tech. Rep. PN000083-LRT-008, Sep. 2015. [Online]. Available: <https://ore.catapult.org.uk/?orecatapultreports=marine-energy-electrical-architecture-report-3-optimum-electrical-array-architectures>
- [68] MeyGen, *Lessons Learnt From Meygen Phase 1a: Full Report*, BP Marine Environ. Res. Ltd (ABPmer), Southampton, U.K., May 2017. Accessed: Oct. 28, 2025.
- [69] G. Brandenburg, "Understanding the impact of ocean energy converter types on subsea cables," DeRegt Cables, Delft, The Netherlands, Tech. Rep., Jun. 2023. Accessed: Aug. 24, 2025. [Online]. Available: <https://www.deregtcables.com/blog/understanding-the-impact-of-ocean-energy-converter-types-on-subsea-cables>
- [70] B. C. Cerik and L. Huang, "Recent advances in mechanical analysis and design of dynamic power cables for floating offshore wind turbines," *Ocean Eng.*, vol. 311, Nov. 2024, Art. no. 118810.
- [71] Schottel Hydro, *Cost-Effective Power From Currents*, SCHOTTEL HYDRO GmbH, Spay, Germany, Nov. 2014. Accessed: Aug. 24, 2025. [Online]. Available: [https://s3-eu-west-1.amazonaws.com/assets-sustainablemarine-com/downloads/SCHOTTEL\\_HYDRO\\_Instream\\_Energy.pdf](https://s3-eu-west-1.amazonaws.com/assets-sustainablemarine-com/downloads/SCHOTTEL_HYDRO_Instream_Energy.pdf)
- [72] M. J. Syed and J. Goggins, "Explanation artificial intelligence-based condition monitoring for tidal energy turbines," *AIP Conf. Proc.*, vol. 2919, Mar. 2024, Art. no. 140001.
- [73] G. Li and W. Zhu, "A review on up-to-date gearbox technologies and maintenance of tidal current energy converters," *Energies*, vol. 15, no. 23, p. 9236, Dec. 2022.
- [74] V. S. Neary, M. Lawson, M. Previsic, A. Copping, K. C. Hallett, A. Labonte, J. Rieks, and D. Murray, "Methodology for design and economic analysis of marine energy conversion (MEC) technologies," Sandia Nat. Laboratories, Albuquerque, NM, USA, Tech. Rep. SAND2014-3558C; 517033, 2014. Accessed: Mar. 28, 2025. [Online]. Available: <https://www.osti.gov/biblio/1143279>
- [75] V. S. Neary, P. H. Kobos, D. S. Jenne, and Y.-H. Yu, "Levelized cost of energy for marine energy conversion (MEC) technologies," Dept. Sandia National Lab. (SNL-NM), Albuquerque, NM, USA, Tech. Rep. SAND2016-8298C; 646891, Aug. 2016. [Online]. Available: <https://www.osti.gov/biblio/1378253>
- [76] *Projected Costs of Generating Electricity*, Int. Energy Agency (IEA), Paris, France, 2015. Accessed: Mar. 28, 2025. [Online]. Available: <https://www.iea.org/reports/projected-costs-of-generating-electricity-2015>
- [77] A. Vazquez and G. Iglesias, "LCOE (levelised cost of energy) mapping: A new geospatial tool for tidal stream energy," *Energy*, vol. 91, pp. 192–201, Nov. 2015.
- [78] A. de Andres, A. MacGillivray, O. Roberts, R. Guanache, and H. Jeffrey, "Beyond LCOE: A study of ocean energy technology development and deployment attractiveness," *Sustain. Energy Technol. Assessments*, vol. 19, pp. 1–16, Feb. 2017.
- [79] M. A. Almoghayer, D. K. Woolf, S. Kerr, and G. Davies, "Integration of tidal energy into an island energy system—A case study of orkney islands," *Energy*, vol. 242, Mar. 2022, Art. no. 122547.
- [80] F. Harcourt, A. Angeloudis, and M. D. Piggott, "Utilising the flexible generation potential of tidal range power plants to optimise economic value," *Appl. Energy*, vol. 237, pp. 873–884, Mar. 2019.
- [81] Z. L. Goss, D. S. Coles, and M. D. Piggott, "Identifying economically viable tidal sites within the alderney race through optimization of levelized cost of energy," *Phil. Trans. Roy. Soc. A, Math., Phys. Eng. Sci.*, vol. 378, no. 2178, Aug. 2020, Art. no. 20190500.
- [82] M. B. R. Topper, S. S. Olson, and J. D. Roberts, "On the benefits of negative hydrodynamic interactions in small tidal energy arrays," *Appl. Energy*, vol. 297, Sep. 2021, Art. no. 117091.
- [83] V. Khare, C. Khare, S. Nema, and P. Baredar, *Tidal Energy Systems: Design, Optimization and Control*. Amsterdam, The Netherlands: Elsevier, 2018.
- [84] Z. Zhou, S. Ben Elghali, M. Benbouzid, Y. Amirat, E. Elbouchikhi, and G. Feld, "Tidal stream turbine control: An active disturbance rejection control approach," *Ocean Eng.*, vol. 202, Apr. 2020, Art. no. 107190.
- [85] A. P. Thurlbeck and Y. Cao, "An online peak shaving controller for optimized power-electronic converter lifetimes in turbine array generation systems," *IEEE Trans. Energy Convers.*, vol. 38, no. 2, pp. 1325–1337, Jun. 2023.
- [86] D. Lande-Sudall, T. Stallard, and P. Stansby, "Co-located deployment of offshore wind turbines with tidal stream turbine arrays for improved cost of electricity generation," *Renew. Sustain. Energy Rev.*, vol. 104, pp. 492–503, Apr. 2019.
- [87] N. M. Nasab, J. Kilby, and L. Bakhtiyaryfarid, "Analysis and design of monopile foundations for offshore wind and tidal turbine structures," *Water*, vol. 14, no. 21, p. 3555, Nov. 2022.
- [88] S. Tao, Q. Xu, A. E. Feijóo-Lorenzo, G. Zheng, and J. Zhou, "Optimal layout of a co-located wind/tidal current farm considering forbidden zones," *Energy*, vol. 228, Aug. 2021, Art. no. 120570.
- [89] J. Cohen, M. Kane, A. Marriott, F. Ollivierre, and K. Govertsen, "Economic controls co-design of hybrid microgrids with tidal/PV generation and lithium ion/flow battery storage," 2021, *arXiv:2102.05197*.
- [90] B. K. Talukdar, B. C. Deka, and A. K. Goswami, "Reliability analysis of an active distribution network integrated with solar, wind and tidal energy sources," *Int. Trans. Electr. Energy Syst.*, vol. 31, no. 12, p. 13201, Dec. 2021.
- [91] D. W. Cunningham, E. P. Carlson, J. S. Manser, and I. C. Kizilyalli, "Impacts of wide band gap power electronics on photovoltaic system design," *IEEE J. Photovolt.*, vol. 10, no. 1, pp. 213–218, Jan. 2020.
- [92] J. He, T. Zhao, X. Jing, and N. A. O. Demerdash, "Application of wide bandgap devices in renewable energy systems—Benefits and challenges," in *Proc. Int. Conf. Renew. Energy Res. Appl. (ICRERA)*, Oct. 2014, pp. 749–754.
- [93] B. K. Bose, *Power Electronics in Renewable Energy Systems and Smart Grid: Technology and Applications*. Hoboken, NJ, USA: Wiley, 2019.
- [94] P. Kala and S. Arora, "A comprehensive study of classical and hybrid multilevel inverter topologies for renewable energy applications," *Renew. Sustain. Energy Rev.*, vol. 76, pp. 905–931, Sep. 2017.
- [95] S. Song, W. Shi, Y. K. Demirel, and M. Atlar, "The effect of biofouling on the tidal turbine performance," in *Proc. Appl. Energy Symp.*, 2019, pp. 1–10.
- [96] Z. Goss, D. Coles, and M. Piggott, "Economic analysis of tidal stream turbine arrays: A review," 2021, *arXiv:2105.04718*.
- [97] J. Orme, I. Masters, and R. Griffiths, "Investigation of the effect of biofouling on the efficiency of marine current turbines," in *Proc. MAREC*, 2001, pp. 91–99.
- [98] M. Calvário, L. Sutherland, and C. Guedes Soares, "A review of the applications composite materials in wave and tidal energy devices," in *Natural Artif. Fiber-Reinforced Composites Renew. Sources. Develop. Maritime Transp. Harvesting Sea Resources, Proc. 17th Int. Congr. Int. Maritime Assoc. Medit.*, 2017, pp. 1–7.
- [99] E. Quaranta and P. Davies, "Emerging and innovative materials for hydropower engineering applications: Turbines, bearings, sealing, dams and waterways, and ocean power," *Engineering*, vol. 8, pp. 148–158, Jan. 2022.
- [100] A. K. Sleiti, "Tidal power technology review with potential applications in Gulf stream," *Renew. Sustain. Energy Rev.*, vol. 69, pp. 435–441, Mar. 2017.
- [101] Y. Li and C. Ning, "Latest research progress of marine microbiological corrosion and bio-fouling, and new approaches of marine anti-corrosion and anti-fouling," *Bioactive Mater.*, vol. 4, pp. 189–195, Dec. 2019.
- [102] H. Jia, X. Yang, Q.-Q. Kong, L.-J. Xie, Q.-G. Guo, G. Song, L.-L. Liang, J.-P. Chen, Y. Li, and C.-M. Chen, "Free-standing, anti-corrosion, super flexible graphene oxide/silver nanowire thin films for ultra-wideband electromagnetic interference shielding," *J. Mater. Chem. A*, vol. 9, no. 2, pp. 1180–1191, 2021.
- [103] W.-H. Lam and A. Bhatia, "Folding tidal turbine as an innovative concept toward the new era of turbines," *Renew. Sustain. Energy Rev.*, vol. 28, pp. 463–473, Dec. 2013.
- [104] S. S. Band, P. T. Ghazvinei, K. B. Wan Yusof, M. H. Ahmadi, N. Nabipour, and K.-W. Chau, "Evaluation of the accuracy of soft computing learning algorithms in performance prediction of accuracy of tidal turbine," *Energy Sci. Eng.*, vol. 9, no. 5, pp. 633–644, May 2021.
- [105] E. Segura, R. Morales, and J. A. Somolinos, "Increasing the competitiveness of tidal systems by means of the improvement of installation and maintenance maneuvers in first generation tidal energy converters—An economic argumentation," *Energies*, vol. 12, no. 13, p. 2464, Jun. 2019.

- [106] T. Blackmore, L. E. Myers, and A. S. Bahaj, "Effects of turbulence on tidal turbines: Implications to performance, blade loads, and condition monitoring," *Int. J. Mar. Energy*, vol. 14, pp. 1–26, Jun. 2016.
- [107] A. Mériçaud and J. V. Ringwood, "Condition-based maintenance methods for marine renewable energy," *Renew. Sustain. Energy Rev.*, vol. 66, pp. 53–78, Dec. 2016.
- [108] F. Ewing, P. R. Thies, J. K. Shek, and C. Bittencourt, "A physics-based prognostics approach for tidal turbines," in *Proc. IEEE Int. Conf. Prognostics Health Manage. (ICPHM)*, Jun. 2019, pp. 1–7.
- [109] F. Elasha, D. Mba, M. Togneri, I. Masters, and J. A. Teixeira, "A hybrid prognostic methodology for tidal turbine gearboxes," *Renew. Energy*, vol. 114, pp. 1051–1061, Dec. 2017.
- [110] A. Kavousi-Fard and W. Su, "A combined prognostic model based on machine learning for tidal current prediction," *IEEE Trans. Geosci. Remote Sens.*, vol. 55, no. 6, pp. 3108–3114, Jun. 2017.
- [111] P. L. Fraenkel, "Marine current turbines: Moving from experimental test rigs to a commercial technology," in *Proc. Int. Conf. Offshore Mech. Arctic Eng.*, Jan. 2007, pp. 579–588.
- [112] S. Walker and P. R. Thies, "A review of component and system reliability in tidal turbine deployments," *Renew. Sustain. Energy Rev.*, vol. 151, Nov. 2021, Art. no. 111495.
- [113] J. Khan and R. Ahshan, "Detailed time-domain water-to-wire model of a generic tidal current turbine," in *Proc. 6th IEEE Int. Energy Conf. (ENERGYCon)*, Sep. 2020, pp. 429–433.
- [114] M. Barakat, B. Tala-Ighil, H. Chaoui, H. Gualous, and D. Hissel, "Energy management of a hybrid tidal turbine-hydrogen micro-grid: Losses minimization strategy," *Fuel Cells*, vol. 20, no. 3, pp. 342–350, Jun. 2020.
- [115] A. Aktaş and Y. Kırççek, "A novel optimal energy management strategy for offshore wind/marine current/battery/ultracapacitor hybrid renewable energy system," *Energy*, vol. 199, May 2020, Art. no. 117425.
- [116] Y. Belkhier, A. Achour, F. Hamoudi, N. Ullah, and B. Mendil, "Robust energy-based nonlinear observer and voltage control for grid-connected permanent magnet synchronous generator in the tidal energy conversion system," *Int. J. Energy Res.*, vol. 45, no. 9, pp. 13250–13268, Jul. 2021.
- [117] D. Singh, A. Zhou, A. Muneeb, A. B. Mirza, and F. Luo, "Modeling and performance enhancement of grid tied tidal energy system with fractional order integral based incremental conductance," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Oct. 2023, pp. 685–691.
- [118] G. Mademlis, Y. Liu, P. Chen, and E. Singhroy, "Design of maximum power point tracking for dynamic power response of tidal undersea kite systems," *IEEE Trans. Ind. Appl.*, vol. 56, no. 2, pp. 2048–2060, Mar. 2020.
- [119] A. G. Abo-Khalil and A. S. Alghamdi, "MPPT of permanent magnet synchronous generator in tidal energy systems using support vector regression," *Sustainability*, vol. 13, no. 4, p. 2223, Feb. 2021.
- [120] F. H. Gandoman, A. Ahmadi, A. M. Sharaf, P. Siano, J. Pou, B. Hredzak, and V. G. Agelidis, "Review of FACTS technologies and applications for power quality in smart grids with renewable energy systems," *Renew. Sustain. Energy Rev.*, vol. 82, pp. 502–514, Feb. 2018.
- [121] D. Singh, A. Wasay, K. Choksi, and F. Luo, "Modeling and performance enhancement of tidal energy based seaport microgrid for shipboard loads using DSTATCOM," in *Proc. IEEE Electric Ship Technol. Symp. (ESTS)*, Aug. 2023, pp. 469–476.
- [122] E. Hossain, M. R. Tür, S. Padmanaban, S. Ay, and I. Khan, "Analysis and mitigation of power quality issues in distributed generation systems using custom power devices," *IEEE Access*, vol. 6, pp. 16816–16833, 2018.
- [123] M. L. Rahman, S. Oka, and Y. Shirai, "Hybrid power generation system using offshore-wind turbine and tidal turbine for power fluctuation compensation (HOT-PC)," *IEEE Trans. Sustain. Energy*, vol. 1, no. 2, pp. 92–98, Jul. 2010.
- [124] M. F. Zia, M. Nasir, E. Elbouchikhi, M. Benbouzid, J. C. Vasquez, and J. M. Guerrero, "Energy management system for a hybrid PV-wind-tidal-battery-based islanded DC microgrid: Modeling and experimental validation," *Renew. Sustain. Energy Rev.*, vol. 159, May 2022, Art. no. 112093.
- [125] Y.-J. Gu, H.-W. Liu, W. Li, Y.-G. Lin, and Y.-J. Li, "Integrated design and implementation of 120-kW horizontal-axis tidal current energy conversion system," *Ocean Eng.*, vol. 158, pp. 338–349, Jun. 2018.
- [126] A. Blavette, D. O'Sullivan, M. Egan, and A. Lewis, "Grid compliance of ocean energy converters: Control strategies and recommendations," in *Proc. 9th Eur. Wave Tidal Energy Conf.*, Southampton, France, 2011, pp. 1–11. [Online]. Available: [https://hal.science/hal-01265988/file/Blavette-Grid\\_Compliance\\_of\\_Ocean\\_Energy\\_Converters\\_Revised-EWTEC2011.pdf](https://hal.science/hal-01265988/file/Blavette-Grid_Compliance_of_Ocean_Energy_Converters_Revised-EWTEC2011.pdf)
- [127] M. S. Soliman, Y. Belkhier, N. Ullah, A. Achour, Y. M. Alharbi, A. A. Al Alahmadi, H. Abeida, and Y. S. H. Khraisat, "Supervisory energy management of a hybrid battery/PV/tidal/wind sources integrated in DC-microgrid energy storage system," *Energy Rep.*, vol. 7, pp. 7728–7740, Nov. 2021.
- [128] S. B. Chabane, M. Alami, M. Fiacchini, R. Riah, T. Kovaltchouk, and S. Bacha, "Electricity grid connection of a tidal farm: An active power control framework constrained to grid code requirements," *IEEE Trans. Sustain. Energy*, vol. 9, no. 4, pp. 1948–1956, Oct. 2018.
- [129] P. S. Kundur and O. P. Malik, *Power System Stability and Control*. New York, NY, USA: McGraw-Hill, 2022.
- [130] A. Zhang, M. Cheng, W. Yang, Q. Li, and J. Ekanayake, "Adaptive black-box equivalent modeling of multiple marine micro-grids interconnected through subsea cables," *IEEE Access*, vol. 6, pp. 75988–75996, 2018.
- [131] H. H. H. Aly, "Dynamic modeling and control of the tidal current turbine using DFIG and DDPMSG for power system stability analysis," *Int. J. Electr. Power Energy Syst.*, vol. 83, pp. 525–540, Dec. 2016.
- [132] J. Khan, "Equivalent time-domain water-to-wire model of a generic tidal current turbine," in *Proc. IEEE Power Energy Soc. Gen. Meeting (PESGM)*, Jul. 2021, pp. 1–5.
- [133] D. O'Sullivan, D. Mollaghan, A. Blavette, and R. Alcorn, "Dynamic characteristics of wave and tidal energy converters & a recommended structure for development of a generic model for grid connection," Ph.D. thesis, Hydraulics & Maritime Res. Centre, Univ. College Cork, Ocean Energy Syst.-Implementing Agreement (OES-IA), Int. Energy, Cork, Ireland, Jul. 2010.
- [134] A. M. Othman, "Enhancement of tidal generators by superconducting energy storage and jaya-based sliding-mode controller," *Int. J. Energy Res.*, vol. 44, no. 14, pp. 11658–11675, Nov. 2020.
- [135] Y. Belkhier, A. Achour, N. Ullah, R. N. Shaw, S. Farooq, A. Ullah, and A. N. Alzaed, "Intelligent energy-based modified super twisting algorithm and fractional order PID control for performance improvement of PMSG dedicated to tidal power system," *IEEE Access*, vol. 9, pp. 57414–57425, 2021.
- [136] Y. Belkhier, A. Achour, R. N. Shaw, N. Ullah, M. S. Chowdhury, and K. Techato, "Fuzzy supervisory passivity-based high order-sliding mode control approach for tidal turbine-based permanent magnet synchronous generator conversion system," *Actuators*, vol. 10, no. 5, p. 92, Apr. 2021.
- [137] S. Mehta and P. Basak, "A comprehensive review on control techniques for stability improvement in microgrids," *Int. Trans. Electr. Energy Syst.*, vol. 31, no. 4, p. 12822, Apr. 2021.
- [138] A. Mohanty, M. Viswavandya, P. K. Ray, T. K. Panigrahi, and S. Mohanty, "Stability and optimisation of direct drive permanent magnet synchronous generator based tidal turbine," *Vacuum*, vol. 166, pp. 341–350, Aug. 2019.
- [139] A. Mohanty, M. Viswavandya, P. K. Ray, and S. Mohanty, "Reactive power control and optimisation of hybrid off shore tidal turbine with system uncertainties," *J. Ocean Eng. Sci.*, vol. 1, no. 4, pp. 256–267, Dec. 2016.
- [140] A. Kumar and G. Shankar, "Dynamic stability enhancement of TCSC-based tidal power generation using quasi-oppositional harmony search algorithm," *IET Gener., Transmiss. Distribution*, vol. 12, no. 10, pp. 2288–2298, May 2018.
- [141] A. Testa, S. De, and T. Scimone, "Analysis of a VRB energy storage system for a tidal turbine generator," in *Proc. 13th Eur. Conf. Power Electron. Appl.*, Sep. 2009, pp. 1–10.
- [142] K. Singh and Zaheeruddin, "Enhancement of frequency regulation in tidal turbine power plant using virtual inertia from capacitive energy storage system," *J. Energy Storage*, vol. 35, Mar. 2021, Art. no. 102332.
- [143] L. Wang, J.-Y. Yu, and Y.-T. Chen, "Dynamic stability improvement of an integrated offshore wind and marine-current farm using a flywheel energy-storage system," *IET Renew. Power Gener.*, vol. 5, no. 5, pp. 387–396, Sep. 2011.
- [144] S. K. Salman, J. Gibb, and I. Macdonald, "Integration of tidal power based-electrical plant into a grid," in *Proc. 43rd Int. Universities Power Eng. Conf.*, Sep. 2008, pp. 1–4.
- [145] R. Dashti, G. R. Ghanbari, H. R. Shaker, and H. Mirshekani, "Transient analysis of tidal power plant connected to network when faced with symmetrical and unsymmetrical faults," in *Proc. 7th Int. Conf. Electr. Electron. Eng. (ICEEE)*, Apr. 2020, pp. 165–169.
- [146] K. Omkar, K. B. Karthikeyan, R. Srimathi, N. Venkatesan, E. J. Avital, A. Samad, and S. H. Rhee, "A performance analysis of tidal turbine conversion system based on control strategies," *Energy Proc.*, vol. 160, pp. 526–533, Feb. 2019.

- [147] S. Toumi, E. Elbouchikhi, M. Benbouzid, and Y. Amirat, "Grid fault-resilient control of a pmsg-based tidal stream turbine," *J. Electr. Syst.*, vol. 16, no. 4, pp. 429–447, 2020.
- [148] J. J. Justo, F. Mwasilu, J. Lee, and J.-W. Jung, "AC-microgrids versus DC-microgrids with distributed energy resources: A review," *Renew. Sustain. Energy Rev.*, vol. 24, pp. 387–405, Aug. 2013.
- [149] P. Basak, S. Chowdhury, S. Halder nee Dey, and S. P. Chowdhury, "A literature review on integration of distributed energy resources in the perspective of control, protection and stability of microgrid," *Renew. Sustain. Energy Rev.*, vol. 16, no. 8, pp. 5545–5556, Oct. 2012.
- [150] F. Aminifar, S. Teimourzadeh, A. Shahsavari, M. Savaghebi, and M. S. Golsorkhi, "Machine learning for protection of distribution networks and power electronics-interfaced systems," *Electr. J.*, vol. 34, no. 1, Jan. 2021, Art. no. 106886.
- [151] X. Wu, J. Liu, Y. Men, B. Chen, and X. Lu, "Optimal energy storage system and smart switch placement in dynamic microgrids with applications to marine energy integration," *IEEE Trans. Sustain. Energy*, vol. 14, no. 2, pp. 1205–1216, Apr. 2023.
- [152] S. Toumi, E. Elbouchikhi, Y. Amirat, M. Benbouzid, and G. Feld, "Magnet failure-resilient control of a direct-drive tidal turbine," *Ocean Eng.*, vol. 187, Sep. 2019, Art. no. 106207.
- [153] X. Yan, R. Norman, and M. A. Elgendy, "Fault tolerant control design for a tidal current turbine generation system," in *Proc. 30th Int. Ocean Polar Eng. Conf.*, Oct. 2020, Paper ISOPE-I-20-1146.
- [154] J. Zhang, A. Houari, A. Seck, L. Moreau, and M. Machmoum, "Fault tolerant control of a double stator permanent magnet generator in tidal current energy system," in *Proc. IEEE Int. Conf. Ind. Technol. (ICIT)*, Mar. 2016, pp. 419–424.
- [155] M. Benbouzid, Y. Amirat, and E. Elbouchikhi, *Marine Tidal and Wave Energy Converters: Technologies, Conversions, Grid Interface, Fault Detection, and Fault-Tolerant Control*. Basel, Switzerland: MDPI, 2020.
- [156] Y. Tao, Y. Wang, Q. Lin, and W. Li, "Design and simulation of a bidirectional DC circuit breaker," in *Proc. IECON 46th Annu. Conf. IEEE Ind. Electron. Soc.*, Oct. 2020, pp. 3439–3444.
- [157] V. Shanmugapriya, S. Vidyasagar, and K. Vijayakumar, "Recent developments in AC and DC microgrids: Systematic evaluation of protection schemes," *Int. J. Renew. Energy Res. (IJRER)*, vol. 11, no. 4, pp. 1850–1870, 2021.
- [158] Z. Ayubu, J.-Y. Kim, J.-Y. Yu, S.-M. Song, and I.-D. Kim, "Novel bidirectional DC solid-state circuit breaker with operating duty capability," *IEEE Trans. Ind. Electron.*, vol. 68, no. 10, pp. 9104–9113, Oct. 2021.
- [159] F. R. Yu, P. Zhang, W. Xiao, and P. Choudhury, "Communication systems for grid integration of renewable energy resources," *IEEE Netw.*, vol. 25, no. 5, pp. 22–29, Sep. 2011.
- [160] H. F. Habib, T. Youssef, M. H. Cintuglu, and O. A. Mohammed, "Multi-agent-based technique for fault location, isolation, and service restoration," *IEEE Trans. Ind. Appl.*, vol. 53, no. 3, pp. 1841–1851, May 2017.
- [161] K. S. Ratnam, K. Palanisamy, and G. Yang, "Future low-inertia power systems: Requirements, issues, and solutions—A review," *Renew. Sustain. Energy Rev.*, vol. 124, May 2020, Art. no. 109773.
- [162] A. Kumar and G. Shankar, "Design and implementation of variable inertia and droop controls on tidal power generator," in *Proc. 9th Int. Conf. Power Energy Syst. (ICPES)*, Dec. 2019, pp. 1–6.
- [163] A. M. Othman and A. A. El-Fergany, "Adaptive virtual-inertia control and chicken swarm optimizer for frequency stability in power-grids penetrated by renewable energy sources," *Neural Comput. Appl.*, vol. 33, no. 7, pp. 2905–2918, Apr. 2021.
- [164] V. Trovato, S. H. Tindemans, and G. Strbac, "Demand response contribution to effective inertia for system security in the GB 2020 gone green scenario," in *Proc. IEEE PES ISGT Eur.*, Oct. 2013, pp. 1–5.
- [165] M. Nedd, C. Booth, and K. Bell, "Potential solutions to the challenges of low inertia power systems with a case study concerning synchronous condensers," in *Proc. 52nd Int. Universities Power Eng. Conf. (UPEC)*, Aug. 2017, pp. 1–6.
- [166] D. Stenzel and R. Witzmann, "Estimation of the inertia constant of demand in European regions considering daily and seasonal variations based on statistical information," in *Proc. IEEE/PES Transmiss. Distribution Conf. Expo. (T&D)*, Apr. 2022, pp. 1–5.
- [167] M. H. Khooban and M. Gheisarnejad, "Islanded microgrid frequency regulations concerning the integration of tidal power units: Real-time implementation," *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 67, no. 6, pp. 1099–1103, Jun. 2020.
- [168] M. H. Khooban, "An optimal non-integer model predictive virtual inertia control in inverter-based modern AC power grids-based V2G technology," *IEEE Trans. Energy Convers.*, vol. 36, no. 2, pp. 1336–1346, Jun. 2021.
- [169] B. She, F. Li, H. Cui, J. Wang, Q. Zhang, and R. Bo, "Virtual inertia scheduling for power systems with high penetration of inverter-based resources," 2022, *arXiv:2209.06677*.
- [170] R. Smith, "System operability framework 2016," Nat. Grid Electr. Syst. Operator, London, U.K., Tech. Rep. 8589937803-SOF, Nov. 2016.
- [171] M. Fregelius, "An experimental approach to energy storage based synthetic inertia and fast frequency regulation for grid balancing," Ph.D. thesis, Disciplinary Domain Sci. Technol., Dept. Elect. Eng., Electr. (Hydropower), Acta Universitatis Upsaliensis, Uppsala Univ., Uppsala, Sweden, 2022.
- [172] M. Fregelius, "An experimental approach on linear synthetic inertia," Ph.D. thesis, Dept. Electrical Eng., Uppsala Univ., Uppsala, Sweden, 2021.
- [173] M. B. Anwar, M. S. El Moursi, and W. Xiao, "Dispatching and frequency control strategies for marine current turbines based on doubly fed induction generator," *IEEE Trans. Sustain. Energy*, vol. 7, no. 1, pp. 262–270, Jan. 2016.
- [174] M. G. Simões, F. A. Farret, H. Khajeh, M. Shahparasti, and H. Laaksonen, "Future renewable energy communities based flexible power systems," *Appl. Sci.*, vol. 12, no. 1, p. 121, Dec. 2021.
- [175] H.-T. Pham, J.-M. Bourgeot, and M. Benbouzid, "Power smoothing control and low-voltage ride-through enhancement of a 5-phase PMSG-based marine tidal turbine using a supercapacitor energy storage system," in *Proc. 43rd Annu. Conf. IEEE Ind. Electron. Soc.*, Oct. 2017, pp. 8323–8328.
- [176] A. Kumar and G. Shankar, "Load frequency control assessment of tidal power plant and capacitive energy storage systems supported microgrid," *IET Gener., Transmiss. Distribution*, vol. 14, no. 7, pp. 1279–1291, Apr. 2020.
- [177] K. Singh and Y. Arya, "Tidal turbine support in microgrid frequency regulation through novel cascade fuzzy-FOPID droop in de-loaded region," *ISA Trans.*, vol. 133, pp. 218–232, Feb. 2023.
- [178] Y. Du, Y. Men, X. Lu, J. Liu, F. Qiu, and B. Chen, "Coastal community resiliency enhancement using marine hydrokinetic (MHK) resources and networked microgrids," Argonne Nat. Lab. (ANL), Argonne, IL, USA, Tech. Rep. ANL/ESD-20/13; 165365, Nov. 2020, doi: 10.2172/1767164. [Online]. Available: <https://www.osti.gov/biblio/1767164>
- [179] M. S. Ortmann, V. Maryama, L. J. Camurça, L. C. Gili, D. L. Suarez-Solano, D. Dantas, G. Finamor, V. L. da Silva, L. Munaretto, A. Ruseleler, A. G. Andreta, R. F. Coelho, and M. L. Heldwein, "Architecture, components and operation of an experimental hybrid AC/DC smart microgrid," in *Proc. IEEE 8th Int. Symp. Power Electron. Distrib. Gener. Syst. (PEDG)*, Apr. 2017, pp. 1–8.
- [180] S. Bala, J. Pan, G. Barlow, G. Brown, and S. Ebner, "Power conversion systems for tidal power arrays," in *Proc. IEEE 5th Int. Symp. Power Electron. Distrib. Gener. Syst. (PEDG)*, Jun. 2014, pp. 1–7.
- [181] M. C. Sousounis, "Electro-mechanical modelling of tidal arrays," Ph.D. thesis, Dept. Elect. Eng., Univ. Edinburgh, Edinburgh, U.K., 2018.
- [182] M. C. Sousounis, J. K. H. Shek, and M. A. Mueller, "Filter design for cable overvoltage and power loss minimization in a tidal energy system with onshore converters," *IEEE Trans. Sustain. Energy*, vol. 7, no. 1, pp. 400–408, Jan. 2016.
- [183] M. C. Sousounis, J. K. H. Shek, and M. A. Mueller, "Modelling, control and frequency domain analysis of a tidal current conversion system with onshore converters," *IET Renew. Power Gener.*, vol. 10, no. 2, pp. 158–165, Feb. 2016.
- [184] M. Kuschke and K. Strunz, "Transient cable overvoltage calculation and filter design: Application to onshore converter station for hydrokinetic energy harvesting," *IEEE Trans. Power Del.*, vol. 28, no. 3, pp. 1322–1329, Jul. 2013.
- [185] K. Rajashekara, H. S. Krishnamoorthy, and B. S. Naik, "Electrification of subsea systems: Requirements and challenges in power distribution and conversion," *CPSS Trans. Power Electron. Appl.*, vol. 2, no. 4, pp. 259–266, Dec. 2017.
- [186] R. Itiki, S. G. Di Santo, C. Itiki, M. Manjrekar, and B. H. Chowdhury, "A comprehensive review and proposed architecture for offshore power system," *Int. J. Electr. Power Energy Syst.*, vol. 111, pp. 79–92, Oct. 2019.

- [187] R. N. Fard and E. Tedeschi, "Integration of distributed energy resources into offshore and subsea grids," *CPSS Trans. Power Electron. Appl.*, vol. 3, no. 1, pp. 36–45, Mar. 2018.
- [188] S. Reynolds, A. Kiprakis, and M. Abusara, "Speed control of multiple tidal turbines connected to a shared onshore converter," in *Proc. 13th Eur. Wave Tidal Energy Conf.*, 2019, p. 1228.
- [189] M. Andresen, J. Kuprat, V. Raveendran, J. Falck, and M. Liserre, "Active thermal control for delaying maintenance of power electronics converters," *Chin. J. Electr. Eng.*, vol. 4, no. 3, pp. 13–20, Sep. 2018.
- [190] L. P. Perera, M. M. Machado, A. Valland, and D. A. P. Manguinho, "Failure intensity of offshore power plants under varying maintenance policies," *Eng. Failure Anal.*, vol. 97, pp. 434–453, Mar. 2019.
- [191] S. Peyghami, Z. Wang, and F. Blaabjerg, "Reliability modeling of power electronic converters: A general approach," in *Proc. 20th Workshop Control Model. Power Electron. (COMPEL)*, Jun. 2019, pp. 1–7.
- [192] Z. Chen, "Power electronic converter systems for direct drive renewable energy applications," in *Electrical Drives for Direct Drive Renewable Energy Systems*, 2013, pp. 106–135.
- [193] F. Wani, U. Shipurkar, J. Dong, H. Polinder, A. Jarquin-Laguna, K. Mostafa, and G. Lavidas, "Lifetime analysis of IGBT power modules in passively cooled tidal turbine converters," *Energies*, vol. 13, no. 8, p. 1875, Apr. 2020.
- [194] Z. Ni, X. Lyu, O. P. Yadav, B. N. Singh, S. Zheng, and D. Cao, "Overview of real-time lifetime prediction and extension for SiC power converters," *IEEE Trans. Power Electron.*, vol. 35, no. 8, pp. 7765–7794, Aug. 2020.
- [195] S. Rahimpour, H. Tarzamani, N. V. Kurdkandi, O. Husev, D. Vinnikov, and F. Tahami, "An overview of lifetime management of power electronic converters," *IEEE Access*, vol. 10, pp. 109688–109711, 2022.
- [196] S. Pu, F. Yang, B. T. Vankayalapati, and B. Akin, "Aging mechanisms and accelerated lifetime tests for SiC MOSFETs: An overview," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 10, no. 1, pp. 1232–1254, Feb. 2022.
- [197] V. Raveendran, M. Andresen, and M. Liserre, "Improving onboard converter reliability for more electric aircraft with lifetime-based control," *IEEE Trans. Ind. Electron.*, vol. 66, no. 7, pp. 5787–5796, Jul. 2019.
- [198] F. Gonzalez-Hernando, J. San-Sebastian, A. Garcia-Bediaga, M. Arias, F. Iannuzzo, and F. Blaabjerg, "Wear-out condition monitoring of IGBT and MOSFET power modules in inverter operation," *IEEE Trans. Ind. Appl.*, vol. 55, no. 6, pp. 6184–6192, Nov. 2019.
- [199] M. Andresen, M. Liserre, and G. Buticchi, "Review of active thermal and lifetime control techniques for power electronic modules," in *Proc. 16th Eur. Conf. Power Electron. Appl.*, Aug. 2014, pp. 1–10.
- [200] U.-M. Choi, F. Blaabjerg, S. Jørgensen, S. Munk-Nielsen, and B. Rannestad, "Reliability improvement of power converters by means of condition monitoring of IGBT modules," *IEEE Trans. Power Electron.*, vol. 32, no. 10, pp. 7990–7997, Oct. 2017.
- [201] A. Hanif, S. Das, and F. Khan, "Active power cycling and condition monitoring of IGBT power modules using reflectometry," in *Proc. IEEE Appl. Power Electron. Conf. Expo. (APEC)*, Mar. 2018, pp. 2827–2833.
- [202] S. S. Manohar, A. Sahoo, A. Subramaniam, and S. K. Panda, "Condition monitoring of power electronic converters in power plants—A review," in *Proc. 20th Int. Conf. Electr. Mach. Syst. (ICEMS)*, 2017, pp. 1–5.
- [203] V. Narayanaswamy, "A review of thermal and humidity management needs and feasible solutions for next generation subsea electric systems," *Underwater Technol.*, vol. 32, no. 2, pp. 129–143, Jul. 2014.
- [204] L. A. Militão, C. D. Fernandes, D. D. Santos, D. Machado, M. L. Heldwein, C. R. Rambo, A. K. D. Silva, and J. R. Barbosa, "A novel cooling geometry for subsea variable speed drives," *Appl. Thermal Eng.*, vol. 185, Feb. 2020, Art. no. 116483.
- [205] F. Wani, U. Shipurkar, J. Dong, and H. Polinder, "Thermal cycling in converter IGBT modules with different cooling systems in pitch- and active stall-controlled tidal turbines," *Energies*, vol. 14, no. 20, p. 6457, Oct. 2021.
- [206] T. Kilgore, M. Tariquzzaman, and Y. Cao, "Thermal management of SiC MOSFETs within hydrokinetic applications," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Mar. 2022, pp. 1–8.
- [207] F. Wani, U. Shipurkar, J. Dong, and H. Polinder, "A study on passive cooling in subsea power electronics," *IEEE Access*, vol. 6, pp. 67543–67554, 2018.
- [208] K. Górecki and K. Posobkiewicz, "Cooling systems of power semiconductor devices—A review," *Energies*, vol. 15, no. 13, p. 4566, Jun. 2022.
- [209] L. Wang, J. He, T. Han, and T. Zhao, "Finite control set model predictive control with secondary problem formulation for power loss and thermal stress reductions," *IEEE Trans. Ind. Appl.*, vol. 56, no. 4, pp. 4028–4039, Jul. 2020.
- [210] L. Wang, T. Zhao, and J. He, "Centralized thermal stress oriented dispatch strategy for paralleled grid-connected inverters considering mission profiles," *IEEE Open J. Power Electron.*, vol. 2, pp. 368–382, 2021.
- [211] Y. Qi, K. Ma, and S. Xia, "Active thermal control with optimal phase angle under stall condition of machine drive inverter," *IEEE Trans. Power Electron.*, vol. 37, no. 9, pp. 10128–10132, Sep. 2022.
- [212] F. Di Napoli, A. Magnani, M. Coppola, P. Guerriero, V. D'Alessandro, L. Codecasa, P. Tricoli, and S. Daliento, "On-line junction temperature monitoring of switching devices with dynamic compact thermal models extracted with model order reduction," *Energies*, vol. 10, no. 2, p. 189, Feb. 2017.
- [213] J. Kuprat, Y. Pascal, and M. Liserre, "Real-time thermal characterization of power semiconductors using a PSO-based digital twin approach," in *Proc. 24th Eur. Conf. Power Electron. Appl. (EPE ECCE Europe)*, Sep. 2022, pp. P.1–P.8.
- [214] P. Górecki, "Electrothermal averaged model of a diode-IGBT switch for a fast analysis of DC-DC converters," *IEEE Trans. Power Electron.*, vol. 37, no. 11, pp. 13003–13013, Nov. 2022.
- [215] T. Laneryd, T. Gradinger, H. Lendenmann, E. Virtanen, T. Wagner, and T. Koivuluoma, "Pressure compensated subsea electrical system," U.S. Patent 10 244 650, Mar. 26, 2019.
- [216] T. Saha, A. C. Bagchi, and R. A. Zane, "Analysis and design of an LCL-T resonant DC-DC converter for underwater power supply," *IEEE Trans. Power Electron.*, vol. 36, no. 6, pp. 6725–6737, Jun. 2021.
- [217] S. Ingebrigtsen, S. Vatland, J. Pretlove, and H. Nesheim, "ABB subsea power JIP—Going the distance," in *Proc. Offshore Technol. Conf. OnePetro*, May 2019, Paper D031S041R002.
- [218] S. Sudhindra, L. Ramesh, and A. A. Balandin, "Graphene thermal interface materials—state-of-the-art and application prospects," *IEEE Open J. Nanotechnol.*, vol. 3, pp. 169–181, 2022.
- [219] G. Langer, M. Leitgeb, J. Nicolics, M. Unger, H. Hoschopf, and F. P. Wenzl, "Advanced thermal management solutions on PCBs for high power applications," *J. Microelectron. Electron. Packag.*, vol. 11, no. 3, pp. 104–114, Jul. 2014.
- [220] A. Albarbar and C. Batunlu, *Thermal Analysis of Power Electronic Devices Used in Renewable Energy Systems*. Cham, Switzerland: Springer, 2018.
- [221] F. Deng, Y. Lu, C. Liu, Q. Heng, Q. Yu, and J. Zhao, "Overview on submodule topologies, modeling, modulation, control schemes, fault diagnosis, and tolerant control strategies of modular multilevel converters," *Chin. J. Electr. Eng.*, vol. 6, no. 1, pp. 1–21, Mar. 2020.
- [222] C. Xiao, Z. Liu, T. Zhang, and X. Zhang, "Deep learning method for fault detection of wind turbine converter," *Appl. Sci.*, vol. 11, no. 3, p. 1280, Jan. 2021.
- [223] P. Paret, D. Finegan, and S. Narumanchi, "Artificial intelligence for power electronics in electric vehicles: Challenges and opportunities," *J. Electron. Packag.*, vol. 145, no. 3, Sep. 2023, Art. no. 034501.
- [224] M. R. M. K. Puthiyapurayil, M. N. Nasirudeen, Y. A. Saywan, M. W. Ahmad, and H. Malik, "A review of open-circuit switch fault diagnostic methods for neutral point clamped inverter," *Electronics*, vol. 11, no. 19, p. 3169, Oct. 2022.
- [225] J. Poon, P. Jain, C. Spanos, S. K. Panda, and S. R. Sanders, "Fault prognosis for power electronics systems using adaptive parameter identification," *IEEE Trans. Ind. Appl.*, vol. 53, no. 3, pp. 2862–2870, May 2017.
- [226] S. Ahmadi, P. Poure, D. A. Khaburi, and S. Saadate, "A real-time fault-tolerant control approach to ensure the resiliency of a self-healing multilevel converter," *Energies*, vol. 15, no. 13, p. 4721, Jun. 2022.
- [227] T. Li and L. Parsa, "Design, control, and analysis of a fault-tolerant soft-switching DC-DC converter for high-power high-voltage applications," *IEEE Trans. Power Electron.*, vol. 33, no. 2, pp. 1094–1104, Feb. 2018.
- [228] N. Vedachalam, A. Umapathy, and G. A. Ramadass, "Fault-tolerant design approach for reliable offshore multi-megawatt variable frequency converters," *J. Ocean Eng. Sci.*, vol. 1, no. 3, pp. 226–237, Sep. 2016.
- [229] L. M. Halabi, I. M. Alsofyani, and K.-B. Lee, "Multi open-/short-circuit fault-tolerance using modified SVM technique for three-level HANPC converters," *IEEE Trans. Power Electron.*, vol. 36, no. 12, pp. 13621–13633, Dec. 2021.

- [230] R. Pittini and M. Hernes, "Pressure-tolerant power electronics for deep and ultradeep water," *Oil Gas Facilities*, vol. 1, no. 1, pp. 47–52, Feb. 2012.
- [231] G. Rødal and D. Peftitsis, "Design challenges of a SiC-based MVDC power supply for deep-sea applications," in *Proc. 10th Int. Conf. Power Electron. ECCE Asia*, May 2019, pp. 2368–2375.
- [232] B. O. Vishwanath, N. Vedachalam, P. Muthuvel, K. Jayanthi, and G. A. Ramadass, "Pressure-tolerant electronics and discharge performance of pressure-compensated lead acid batteries under hyperbaric conditions," *Mar. Technol. Soc. J.*, vol. 52, no. 5, pp. 110–117, Sep. 2018.
- [233] J. O. Estima, N. M. A. Freire, and A. J. M. Cardoso, "Recent advances in fault diagnosis by Park's vector approach," in *Proc. IEEE Workshop Electr. Mach. Design, Control Diagnosis (WEMDCD)*, Mar. 2013, pp. 279–288.
- [234] A. V. Rocha, D. F. Melo, T. A. Carvalho Maia, V. N. Ferreira, and B. J. Cardoso Filho, "IoT-based degradation management for self-healing power converters," in *Proc. IEEE Appl. Power Electron. Conf. Expo. (APEC)*, Mar. 2019, pp. 2802–2809.
- [235] O. H. Abu-Rub, A. Y. Fard, M. F. Umar, M. Hosseinzadehtaher, and M. B. Shadmands, "Towards intelligent power electronics-dominated grid via machine learning techniques," *IEEE Power Electron. Mag.*, vol. 8, no. 1, pp. 28–38, Mar. 2021.
- [236] M. Musallam and C. M. Johnson, "Real-time compact thermal models for health management of power electronics," *IEEE Trans. Power Electron.*, vol. 25, no. 6, pp. 1416–1425, Jun. 2010.
- [237] M. Milton, C. De La O, H. L. Ginn, and A. Benigni, "Controller-embeddable probabilistic real-time digital twins for power electronic converter diagnostics," *IEEE Trans. Power Electron.*, vol. 35, no. 9, pp. 9850–9864, Sep. 2020.
- [238] Y. Peng, S. Zhao, and H. Wang, "A digital twin based estimation method for health indicators of DC–DC converters," *IEEE Trans. Power Electron.*, vol. 36, no. 2, pp. 2105–2118, Feb. 2021.
- [239] S. Chen, S. Wang, P. Wen, and S. Zhao, "Digital twin for degradation parameters identification of DC–DC converters based on Bayesian optimization," in *Proc. IEEE Int. Conf. Prognostics Health Manage. (ICPHM)*, Jun. 2021, pp. 1–9.
- [240] K. Choksi, A. B. Mirza, A. Zhou, D. Singh, M. Hijikata, and F. Luo, "Self-evolving digital twin-based online health monitoring of multiphase boost converters," *IEEE Trans. Power Electron.*, vol. 38, no. 12, pp. 16100–16117, Dec. 2023.
- [241] H. H. Aly, F. M. Alhaddad, and M. E. El-Hawary, "A proposed adaptive intelligent controllers for tidal currents turbine driving DDMSG for improving the output power generated," in *Proc. IEEE Electr. Power Energy Conf. (EPEC)*, Oct. 2019, pp. 1–4.
- [242] M. Abdelatef Mostafa, E. A. El-Hay, and M. M. ELkholy, "Recent trends in wind energy conversion system with grid integration based on soft computing methods: Comprehensive review, comparisons and insights," *Arch. Comput. Methods Eng.*, vol. 30, no. 3, pp. 1439–1478, Apr. 2023.
- [243] J. Burhanudin, A. S. A. Hasim, A. M. Ishak, J. Burhanudin, and S. M. F. B. S. M. Dardin, "A review of power electronics for nearshore wave energy converter applications," *IEEE Access*, vol. 10, pp. 16670–16680, 2022.
- [244] S. Zhang, "Comparison of diode rectifier and active-front-end for synchronous generators supplying DC loads for maritime applications," in *Proc. Int. Aegean Conf. Electr. Mach. Power Electron. (ACEMP) Int. Conf. Optim. Electr. Electron. Equip. (OPTIM)*, Sep. 2021, pp. 259–264.
- [245] F. Wahid, "Analysis of a wave power system with passive and active rectification," Master thesis, Dept. Elect. Eng., Uppsala Univ., Uppsala, Sweden, 2020. [Online]. Available: <https://uu.diva-portal.org/smash/record.jsf?pid=diva2:1512397>
- [246] E. Muljadi, V. Gevorgian, A. Wright, J. Donegan, C. Marnagh, and J. McEntee, "Electrical power conversion of river and tidal power generator," in *Proc. North Amer. Power Symp. (NAPS)*, Sep. 2016, pp. 1–6.
- [247] E. Armoudli, A. Mohseni, A. Sheykhi, and K. Javaherdeh, "A case study of energy harvesting by dynamic tidal power in the Persian Gulf," in *Proc. Iranian Conf. Renew. Energy Distrib. Gener. (ICREDG)*, Jun. 2019, pp. 1–6.
- [248] S. Seo, J. Kim, E. Muljadi, R. M. Nelms, and H. Moeljanto, "Holistic design of small-scale oscillating water column in stand-alone DC microgrid," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Oct. 2022, pp. 1–8.
- [249] W. M. H. Nassar, "Design and analysis of LVDC offshore microgrids for improving electric infrastructure of multi-use platforms," Ph.D. thesis, Dept. Electron. Elect. Eng., Univ. Strathclyde, Glasgow, U.K., 2022. [Online]. Available: <https://ethos.bl.uk/OrderDetails.do?uin=uk.bl.ethos.867507>
- [250] Z. Fang, X. Cai, X. Shi, J. Lyu, R. Yang, and F. Rao, "Diode rectifier-based hybrid high-voltage direct current converter for offshore wind farms," *IET Renew. Power Gener.*, vol. 17, no. 4, pp. 907–919, Mar. 2023.
- [251] A. Nami, J. L. Rodriguez-Amenedo, S. Arnaltes, M. Á. Cardiel-Álvarez, and R. A. Baraciarte, "Frequency control of offshore wind farm with diode-rectifier-based HVdc connection," *IEEE Trans. Energy Convers.*, vol. 35, no. 1, pp. 130–138, Mar. 2020.
- [252] R. Li, L. Yu, L. Xu, and G. P. Adam, "Coordinated control of parallel DR-HVDC and MMC-HVDC systems for offshore wind energy transmission," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 8, no. 3, pp. 2572–2582, Sep. 2020.
- [253] S. Jafarishadeh and M. Farasat, "Modeling and sizing of an undersea energy storage system," *IEEE Trans. Ind. Appl.*, vol. 54, no. 3, pp. 2727–2739, May 2018.
- [254] H. Fang, Y. Tao, S. Zhang, and Z. Xiao, "Design and analysis of bidirectional driven float-type wave power generation system," *J. Modern Power Syst. Clean Energy*, vol. 6, no. 1, pp. 50–60, Jan. 2018.
- [255] A. de la Villa-Jaén, D. E. Montoya-Andrade, and A. García-Santana, "Control strategies for point absorbers considering linear generator copper losses and maximum excursion constraints," *IEEE Trans. Sustain. Energy*, vol. 9, no. 1, pp. 433–442, Jan. 2018.
- [256] A. Ghaedi and M. Mirzadeh, "The impact of tidal height variation on the reliability of barrage-type tidal power plants," *Int. Trans. Electr. Energy Syst.*, vol. 30, no. 9, p. 12477, 2020.
- [257] L. M. Kangaji, K. M. Abo-Al-Ez, and E. F. Orumwense, "Modelling and performance analysis of grid connected PMSG based tidal generation system," in *AIUE Proc. 2nd Energy Human Habitat Conf.*, Jul. 2021, pp. 1–7.
- [258] S. Seo, J. Kim, E. Muljadi, S. Meor-Danial, M. Worthington, and R. Wills, "Reactive power control to mitigate flicker in a tidal and river hydrokinetic power generation," in *Proc. IEEE Power Energy Soc. Gen. Meeting (PESGM)*, Aug. 2019, pp. 1–5.
- [259] A. Benzerdjeb, B. Abed, H. Achache, M. K. Hamidou, and A. M. Gorlov, "Experimental study on blade pitch angle effect on the performance of a three-bladed vertical-axis darrieus hydro turbine," *Int. J. Energy Res.*, vol. 43, no. 6, pp. 2123–2134, May 2019.
- [260] M. R. Barakat, B. Tala-Ighil, H. Chaoui, H. Gualous, Y. Slamani, and D. Hissel, "Energetic macroscopic representation of a marine current turbine system with loss minimization control," *IEEE Trans. Sustain. Energy*, vol. 9, no. 1, pp. 106–117, Jan. 2018.
- [261] M. Liu, W. Li, C. Wang, R. Billinton, and J. Yu, "Reliability evaluation of a tidal power generation system considering tidal current speeds," *IEEE Trans. Power Syst.*, vol. 31, no. 4, pp. 3179–3188, Jul. 2016.
- [262] L. Kangaji, E. Orumwense, and A. Raji, "Improving grid-connected tidal power systems through PWM inverters based on voltage-oriented control," *Int. J. Electr. Eng. Appl. Sci. (IJEAS)*, vol. 7, no. 2, Oct. 2024, Art. no. 004, doi: [10.54554/ijeas.2024.7.02.004](https://doi.org/10.54554/ijeas.2024.7.02.004).
- [263] C. Fjellstedt, M. I. Ullah, J. Forslund, E. Jonasson, I. Temiz, and K. Thomas, "A review of AC and DC collection grids for offshore renewable energy with a qualitative evaluation for marine energy resources," *Energies*, vol. 15, no. 16, p. 5816, Aug. 2022.
- [264] G. Mademlis, "Medium voltage generation system with five-level npc converters for kite tidal power," Master's thesis, Dept. Elect. Eng., Chalmers Univ. Technol., Gothenburg, Sweden, 2019. [Online]. Available: [https://research.chalmers.se/publication/510092/file/510092\\_Fulltext.pdf](https://research.chalmers.se/publication/510092/file/510092_Fulltext.pdf)
- [265] N. Müller, S. Kouro, J. Glaría, and M. Malinowski, "Medium-voltage power converter interface for wave dragon wave energy conversion system," in *Proc. IEEE Energy Convers. Congr. Expo.*, Feb. 2013, pp. 352–358.
- [266] H. M. Zapata, M. A. Perez, and A. Marquez Alcaide, "Control of cascaded multilevel converter for wave energy applications," *Energies*, vol. 16, no. 1, p. 71, Dec. 2022.
- [267] H. M. Zapata and M. A. Pérez, "Modular multilevel converter for a linear generator for wave energy converter," *Energies*, vol. 15, no. 17, p. 6346, Aug. 2022.
- [268] D. Zhang, D. Dong, R. Datta, A. Rockhill, Q. Lei, and L. Garces, "Modular embedded multilevel converter for MV/HVDC applications," *IEEE Trans. Ind. Appl.*, vol. 54, no. 6, pp. 6320–6331, Nov. 2018.

- [269] K. M. Tsang and W. L. Chan, "Direct AC-AC grid interface converter for ocean wave energy system," *Energy Convers. Manage.*, vol. 92, pp. 302–311, Mar. 2015.
- [270] J.-M. Kwon and H. Lee, "Tidal current power generation system with matrix converter," in *Proc. 6th Int. Forum Strategic Technol.*, 2011, pp. 448–451.
- [271] M. Diaz, R. Cárdenas Dobson, E. Ibaceta, A. Mora, M. Urrutia, M. Espinoza, F. Rojas, and P. Wheeler, "An overview of applications of the modular multilevel matrix converter," *Energies*, vol. 13, no. 21, p. 5546, Oct. 2020.
- [272] K. Sinu and G. Ranganathan, "A power electronic converter for tidal turbine generation using DC generators," *Indian J. Public Health Res. Develop.*, vol. 9, no. 3, pp. 410–414, 2018.
- [273] Y. Da and A. Khaligh, "Hybrid offshore wind and tidal turbine energy harvesting system with independently controlled rectifiers," in *Proc. 35th Annu. Conf. IEEE Ind. Electron.*, Nov. 2009, pp. 4577–4582.
- [274] M. R. K. Rachi, S. Cen, M. R. H. Bipu, M. A. Khan, and I. Husain, "Design and development of a multi-port converter for marine microgrid applications," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Jun. 2021, pp. 1184–1190.
- [275] GEPS Techno. (2017). *Le Premier Hybride Marin Combine 4 Sources D'énergies—PH4S*. [Online]. Available: <https://www.geps-techno.com/ph4s/>
- [276] 4C Offshore. (2025). *Savonius Keel & Wind Turbine Darrieus (SKWID)—Japan*. [Online]. Available: [https://www.4coffshore.com/windfarms/savonius-keel-%26-wind-turbine-darrieus-\[skwid\]-japan-jp24.html](https://www.4coffshore.com/windfarms/savonius-keel-%26-wind-turbine-darrieus-[skwid]-japan-jp24.html)
- [277] J. Martínez, R. Guanache, G. Bellotti, C. Cecioni, M. Cantu, G. Franceschi, and R. Suffredini, "Integration of energy converters in multi-use offshore platforms," MERMAID Project, Lyngby, Denmark, Tech. Rep. MERMAID FP7 GA 288710, Deliverable D3.4, v1.1, Dec. 2015.
- [278] Hann-Ocean Industries Ltd. (2017). *HexiFloat Hybrid Marine Platform*. [Online]. Available: <http://www.hann-ocean.com/index.php/products/hexifloat.html>
- [279] H. Zhang, X. Cao, Z. Zhou, and N. Zhang, "Experimental investigation on hydrodynamic response and motion suppression of a floating wind-wave-tidal hybrid system under freak waves," *Renew. Energy*, vol. 256, Jan. 2025, Art. no. 123944. [Online]. Available: <https://doi.org/10.1016/j.renene.2025.123944>
- [280] (2024). *Wide Bandgap Semiconductors (SiC/GaN)—Infineon Technologies—Infineon.Com*. [Online]. Available: <https://www.infineon.com/cms/en/product/technology/wide-bandgap-semiconductors-sic-gan/>
- [281] G. Mademlis, "Inverter design for sic-based electric drive systems with optimal redundant states control of space vector modulation," Ph.D. thesis, Dept. Elect. Eng., Division Electr. Power Eng., Chalmers Univ. Technol., Gothenburg, Sweden, Mar. 2021.
- [282] A. Darwish and G. A. Aggidis, "A review on power electronic topologies and control for wave energy converters," *Energies*, vol. 15, no. 23, p. 9174, Dec. 2022.
- [283] S. Tiwari, T. Undeland, O. M. Midtgård, and R. Nilsen, "SiC MOSFETs for offshore wind applications," *J. Phys., Conf. Ser.*, vol. 1104, Oct. 2018, Art. no. 012032.
- [284] C. Frid, E. Andonegi, J. Depestele, A. Judd, D. Rihan, S. I. Rogers, and E. Kenchington, "The environmental interactions of tidal and wave energy generation devices," *Environ. Impact Assessment Rev.*, vol. 32, no. 1, pp. 133–139, Jan. 2012.
- [285] K. Sukanuma, *Wide Bandgap Power Semiconductor Packaging: Materials, Components, and Reliability*. Sawston, U.K.: Woodhead Publishing, 2018.
- [286] S. Qazi, P. Venugopal, G. Rietveld, T. B. Soeiro, U. Shipurkar, A. Grasman, A. J. Watson, and P. Wheeler, "Powering maritime: Challenges and prospects in ship electrification," *IEEE Electrific. Mag.*, vol. 11, no. 2, pp. 74–87, Jun. 2023.
- [287] S. Vatland, E. Thibaut, and H. Lendenmann, "ABB subsea technology-power for a new energy future," in *Proc. Offshore Technol. Conf.*, May 2020, p. 11.
- [288] S.-E. Chen, R.-Y. Yang, G.-K. Wu, and C.-C. Wu, "A piezoelectric wave-energy converter equipped with a geared-linkage-based frequency up-conversion mechanism," *Sensors*, vol. 21, no. 1, p. 204, Dec. 2020.
- [289] X. Wang, Z. Yang, B. Wang, W. Chen, G. Zhang, J. Zhang, J. Fan, and P. Liu, "Effect of epoxy resin addition on properties and corrosion behavior of sintered joints in power modules serviced offshore," *J. Mater. Res. Technol.*, vol. 25, pp. 6593–6612, Jul. 2023.
- [290] S. A. Navarrete, M. Parragué, N. Osiadacz, F. Rojas, J. Bonicelli, M. Fernández, C. Arboleda-Baena, R. Finke, and S. Baldanzi, "Susceptibility of different materials and antifouling coating to macrofouling organisms in a high wave-energy environment," *J. Ocean Technol.*, vol. 15, no. 1, pp. 72–91, 2020.
- [291] K. Choudhury, "Thermal modelling of power semiconductor modules in power electronic applications," Ph.D. thesis, Dept. Eng. Sci., Univ. Oxford, Oxford, U.K., 2021.
- [292] S. Jones-Jackson, R. Rodriguez, and A. Emadi, "Jet impingement cooling in power electronics for electrified automotive transportation: Current status and future trends," *IEEE Trans. Power Electron.*, vol. 36, no. 9, pp. 10420–10435, Sep. 2021.



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