TOPICAL REVIEW

Offshore Horizons: HVDC Wind Farms-Exploring Techno-Economic Dimensions

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ABSTRACT High Voltage Direct Current (HVDC) technology is a cornerstone of efficient Offshore Wind Farm (OWF) power transmission. This review examines the integration of HVDC technology in OWFs, considering collection and transmission aspects. The analysis is structured around four key dimensions: economic considerations, connection topologies, converter designs, and technical modeling. It begins with an in-depth economic analysis, evaluating cost-effectiveness, reliability, and market dynamics, focusing on investment, operational costs, and lifecycle expenses. Building on this foundation, the review explores various collection and transmission architectures, highlighting their technical and economical trade-offs, and evaluates power converter designs for efficiency, reliability, and offshore adaptability. Finally, advanced modeling and simulation techniques are reviewed to optimize system performance, enhance reliability, and balance computational efficiency. Throughout each of the four sections, economic and technical constraints are considered together. This helps to improve understanding of how systems can be designed in a way that meets the constraints of both fields and to enhance the feasibility on both dimensions. These insights provide a holistic framework for sustainable and economically viable Offshore Wind Energy (OWE) integration, offering practical guidance for developers and grid operators involved in the planning, deployment, and operation of HVDC-enabled offshore wind systems.

INDEX TERMS Offshore wind energy, HVDC, economic consideration, collection and transmission architectures, power converter design, technical modeling.

I. INTRODUCTION

In recent years, the global energy landscape has witnessed a remarkable surge in renewable energy deployment, particularly in Offshore Wind Power (OWP) generation. Offshore Wind Farms (OWFs), due to their vast potential and proximity to populous regions, have emerged as the cornerstone of sustainable energy strategies. OWFs are at a critical stage in their implementation as a technology. Fig. 1, based on

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data from the Department of Energy (DOE), illustrates the current geographic distribution of offshore wind capacity, highlighting the countries of northern Europe and eastern Asia as leaders in deployment [1]. In recent decades, there has been an exponential increase in offshore wind capacity development, as shown in Fig. 2. Globally, the constructed OWF capacity is expected to surpass 150 gigawatts (GW) by 2027, up 480% since 2020 [2].

China and the United Kingdom have led the world in investment in offshore wind. They have 36 GW and 16 GW of installed OWF capacity, respectively, demonstrating
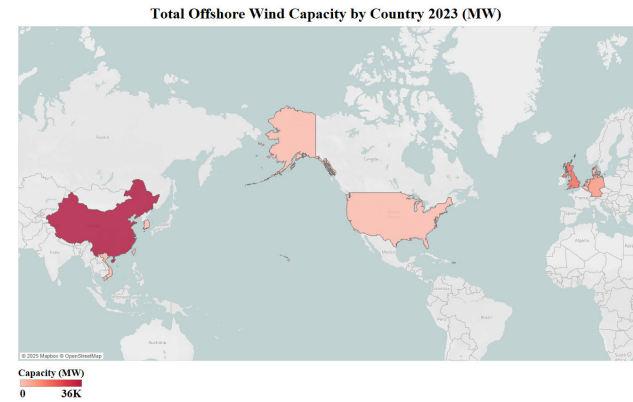
FIGURE 1. Capacity of OWF constructed as of 2023 according to DOE [1].
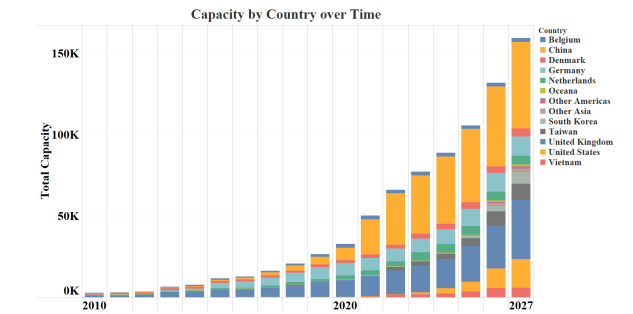

FIGURE 2. Total capacity (MW) of OWF by Country by Year according to DOE.

significant early movement in the space. The DOE recently found that 144 GW of OWF capacity had positive economic potential by 2027 in the United States alone [3], and that expected annual average cost reductions of 5% are likely to significantly increase the economic viability of the technology [4]. Table 1 uses data from Global Energy Monitor [2] and information provided by 4C Wind [5] and local wind farms to provide a description of global wind farms up to 2022 that are greater than 500 MW. The characteristics of the farms are provided in terms of substations, number of turbines, architectures, and type of system.

However, the successful integration of these offshore wind resources into existing power systems presents a complex challenge that requires a thorough understanding of both technological and economic aspects [6]. One of the most prominent advances in this field is the use of High Voltage Direct Current (HVDC) technology, which has the potential to revolutionize the way electricity is harnessed and transmitted from wind-rich marine environments to energy-demanding onshore areas [7]. The integration of HVDC technology with OWF marks a significant advancement, offering several advantages over traditional High Voltage Alternating Current (HVAC) transmission systems [8]. The ability of HVDC to efficiently transmit large amounts of power over long distances makes it a promising solution for delivering reliable and cost-effective energy [9].

As HVDC-based OWFs become increasingly pivotal in the global energy landscape, it becomes increasingly crucial to optimize their performance, reliability, and cost-effectiveness. Achieving this optimization requires a comprehensive understanding of key factors, including a technical and economic analysis of the system. This review seeks to explore these critical elements in detail, emphasizing their significance within the Offshore Wind Energy (OWE) sector.

The economic viability of HVDC systems for OWFs is a pivotal aspect of feasibility analysis [6]. A comprehensive economic evaluation, including factors such as initial investment, operational expenses, maintenance costs, and lifecycle assessments, is crucial to balancing technological advancements with financial feasibility. These economic considerations are intrinsically linked to technical decisions, as both impact the overall cost-effectiveness and reliability of the system.

The choice of connection topology exemplifies this interdependence. Configurations such as point-to-point, multiterminal, All-DC or hybrid systems significantly influence power collection and transmission efficiency, stability, and loss mitigation [10], [11]. Each topology comes with distinct economic and technical trade-offs, affecting infrastructure costs, power flow control, and grid stability - key components in optimizing both performance and financial returns. Converter design is another keystone of HVDC systems that directly affects their efficiency, reliability, and adaptabity to offshore environments. The selection between Voltage Source Converters (VSCs), Line-Commutated Converters (LCCs), and DC-DC converters carries substantial economic and technical implications [12], [13]. These converters determine the scalability and flexibility of the system, influencing not only the upfront costs but also the operational efficiency and maintenance requirements.

Technical modeling further bridges economic and technical analysis [14], [15]. Accurate simulations, control strategies, and performance models optimize system design and operational reliability while enabling cost-effective planning. These models are essential to predict dynamic behaviors, minimize transmission losses, and ensure seamless grid integration [16]. By combining technical insights with economic evaluations, modeling ensures that HVDC OWFs deliver sustainable and financially viable energy solutions. This interconnected approach underscores the need for holistic analysis, where economic and technical factors are jointly considered to maximize the efficiency, reliability, and cost-effectiveness of HVDC systems for OWFs.

Table 2 offers a comprehensive comparison of various research papers and evaluates their contributions in these four main dimensions to the best of the author's knowledge. The table provides a clear overview of the focus areas addressed in the existing literature, highlighting both strengths and gaps. Recent studies such as [13], [17], [18], and [19] review and compare various power converter architectures used in OWF integration. For example, [13] discusses converter topologies in HVDC systems for OWFs and provides a detailed analysis of the Modular Multilevel Converter (MMC) and its operational states.

TABLE 1. Wind farms over 500 MW in operation worldwide.

Project Name	Year	Power Rating (MW)	Type of System	Number of Turbines	Substation	Cable Length to Shore	Cable Details	Architecture
Beatrice	2019	588	HVAC	84	-	70 km	Two composite bundles (970 m and 1920 m)	Star
East Anglia	2020	714	HVDC	102	66 /220 kV	87 km	Two transmission cables	-
Greater Gabbard	2012	504	HVAC	140	132/33 kV (Offshore)	22.5 km	3 phase 18/30(36) kV power core	-
Gwynt Y Mor	2015	576	HVAC	160	Two 33 kV and 132 kV (Offshore)	20 km	-	Star
Hornsea 2	2022	1300	HVDC	165	-	120 km	-	-
Hornsea 1	2019	1200	HVDC	174	-	120 km	-	-
London Array	2013	630	HVAC	175	Two 33 kV	54 km	Three copper core conductors	Radial
Moray East	2022	950	HVAC	100	Three (Offshore)	22 km	-	Radial
Triton Knoll	2022	857	HVAC	90	-	57 km	220 kV HVAC	-
Walney	2018	659	HVAC	87	-	44 km	-	Point-to-point
Kriegers Flak	2021	605	HVDC	72	-	44 km	-	MTDC
Gemini	2017	600	HVAC	130	Two offshore high voltage substations	110 km	230 kV alternating current	Star
Guangdong Jieyang Shenquan 2	2023	502	HVAC	50	220 kV offshore booster station	22 km	220 kV export cables & 66 kV inter-array cables	-
Guangdong Shan-wei Jiazi 1	2022	503.1	HVAC	78	One 500 kV	25 km	-	-
Guangdong Yangjiang Qingzhou Iii	2022	500.6	HVAC	30	-	142 km	75 km of 220 kV & 142 km of 35 kV XLPE subsea cables	-
Guangdong Zhan-jiang Xuwen	2020	608.65	HVAC	25	-	27.5 km	-	-
Shandong Bozhong A	2022	501	HVAC	60	-	20 km	-	Star
Yunlin	2021	640	HVAC	80	Two substations (4 x 66/161-kV each)	270 km	-	-

Similarly, [17] offers a comprehensive review of HVDC converter architectures used in both research and real-world OWF projects, exploring how advanced HVDC topologies can overcome offshore challenges by improving efficiency, reducing converter size and weight, and enhancing reliability. In [18], a comparison of Diode Rectifier Unit (DRU)-based HVDC with other HVDC systems is presented, focusing on control, initialization solutions and fault management, along with future research directions. Reference [19] evaluates Multilevel Converters (MLCs) in VSC-based HVDC systems, highlighting their potential to improve efficiency, performance, and reliability for OWF integration.

In another key study, [20] compares eight offshore wind power transmission schemes based on economic viability, reliability, and technological maturity, recommending accelerated development of HVDC and Low Frequency AC (LFAC) technologies for grid-following and grid-forming OWFs. Reference [21] further provides an extensive review of HVDC transmission topologies, converter technologies, and control strategies for OWFs, highlighting their role in enhancing system reliability and fault ride-through capabilities.

Several papers focus on the economic analysis of OWF integration technologies. For instance, [22], [23], [24], [25] present detailed economic analyses that explore the financial viability and technical performance of HVAC,

HVDC, and LFAC technologies, emphasizing factors such as Levelized Cost of Energy (LCOE), cost optimization, and transmission distance. These analyses are crucial for strategic decision-making in selecting the most suitable technologies for OWF collection and grid integration. Similarly, [26], [27], [28] provide valuable insights into the economic benefits of different HVDC connection strategies for OWFs, promoting efficient and cost-effective offshore transmission solutions.

In [29], the author evaluates four different offshore wind power DC collection topologies using the Universal Generating Function technique, offering a reliable and economic assessment from both technical and economical perspectives. Additionally, [30] conducts a comparative economic analysis of LFAC, HVDC, and HVAC systems, determining the most cost-effective transmission solution based on capital costs, converter topologies, and transmission capacities. Reference [31] compares Medium Voltage DC (MVDC) and HVAC systems for different OWF topologies through an integrated techno-economic analysis, focusing on energy efficiency, CAPEX, OPEX, and LCOE, using case studies to emphasize the role of connection topologies in improving OWF reliability and economics.

Further expanding on the economic and technical dimensions, [32] offers insights for stakeholders on the trajectory of technology development and market dynamics by comparing HVDC and HVAC systems across complex technical and economic factors through a practical case study. Similarly, [33] comprehensively evaluates various grid connection technologies for large OWFs, considering transmission systems, fault ride-through strategies, and economic feasibility. Focusing on collection, [34] reviews OWF electrical collection systems, categorizing them into AC, DC, and LFAC systems, with a focus on cost reduction, improved energy efficiency, and enhanced reliability. This work highlights the importance of DC-DC converters and novel protection systems, while underscoring the potential of LFAC and DC systems to reduce platform sizes and optimize system design. However, the paper could benefit from deeper insights into the technical modeling.

On the other hand, [35] provide a comprehensive review of OWF HVDC systems, focusing on advanced converter topologies like hybrid MMC, Alternate Arm Converters (AAC), and Diode Rectifiers (DR). The work emphasizes key operational aspects such as control strategies, stability analysis, and fault protection, with a particular focus on future research directions involving system evaluation methods and the role of advanced semiconductor materials for greater efficiency. However, a more detailed economic analysis could further enhance the paper's insights.

Despite the existing body of research, a notable gap persists in the form of a lack of studies that comprehensively address all four critical dimensions; economic analysis, connection topology, converter design, and technical modeling in a single review. This paper aims to bridge that gap by providing the examination of these key dimensions, offering a more integrated understanding of their interactions and mutual

influences. By adopting this holistic approach, the paper seeks to guide the effective optimization and implementation of HVDC technology in OWE projects.

A. CONTRIBUTION OF THE PAPER
This paper reviews the existing research, innovations, and methodologies relevant to the economical analysis, connection topology, converter design, and technical modeling within the realm of HVDC OWFs.

- **Economic Analysis:** This article examines the economic aspects of HVAC vs. HVDC architectures emphasizing cost factors, reliability and discounting to bridge economic and technical perspectives, identify gaps, and improve techno-economic analysis for offshore wind integration.
- **Connection Architectures:** The paper evaluates collection grid configurations for HVDC transmission including emerging architectures. The anlysis consider reliability, control, scalability, and cost implications to economic and technical performance.
- **Converter Designs:** It examines various converter topologies, including Voltage Source Converters (VSCs), Line Commutated Converters (LCCs), and DC-DC converters, analyzing their efficiency, reliability, and adaptability for offshore wind farm integration across both collection and transmission systems.
- **Technical Modeling:** Simulation and modeling techniques are reviewed to optimize performance, balance computational efficiency, and support decision-making by predicting operational behaviors and system reliability for OFW system as a whole.

By analyzing these multifaceted parameters, this review aims to provide a comprehensive framework that aids in informed decision-making and fosters the advancement of sustainable and economically viable OWE systems.

B. ORGANIZATION OF THE PAPER
The rest of the paper is organized as follows: Section II begins with a comprehensive economic analysis, focusing on the costs associated with HVDC and HVAC connections and economic considerations for reliability. Section III delves into OWF connection architectures, thoroughly examining collection and transmission architectures. It also includes a techno-economic analysis for both collection and transmission architectures, followed by a discussion of grid connection challenges. Section IV explores power converter topologies, addressing both AC-DC and DC-DC converters and their suitability for HVDC based OWE collection and transmission. Section V focuses on modeling techniques, highlighting the challenges in OWF modeling, the trade-offs between dynamics and efficiency, and the use of analytical approaches in both time-domain and frequency-domain analyses. This section also identifies key research gaps and areas for further exploration. Section VI covers ongoing

TABLE 2. Summary of recent review articles.

Ref	Converter Design	Connection Topology	Technical Modeling	Economic Analysis
[13]	✓	✗	✗	✗
[17]	✓	✗	✗	✗
[18]	✓	✗	✗	✗
[19]	✓	✗	✗	✗
[20]	✗	✓	✗	✗
[21]	✓	✓	✗	✗
[22]	✗	✗	✗	✓
[23]	✗	✗	✗	✓
[24]	✗	✗	✗	✓
[25]	✗	✗	✗	✓
[26]	✗	✓	✗	✓
[27]	✗	✓	✗	✓
[28]	✗	✓	✗	✓
[29]	✗	✓	✗	✓
[30]	✓	✗	✗	✓
[31]	✗	✓	✗	✓
[32]	✓	✓	✗	✓
[33]	✓	✓	✗	✓
[35]	✓	✓	✓	✗
[34]	✓	✓	✗	✓

FIGURE 3. LCOE for different system types, power ratings, and interest rates.

research and the future scope of OWF technologies, while Section VII provides the paper's conclusions, summarizing the key findings and insights.
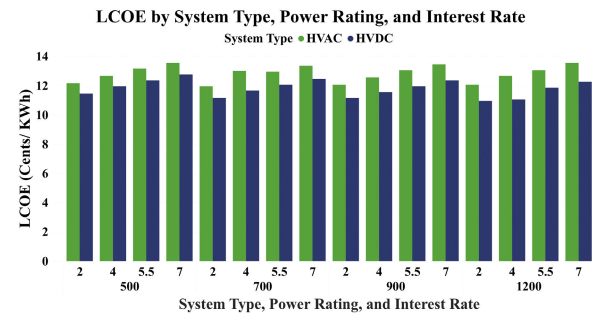
II. ECONOMIC ANALYSIS

A. COSTS RELATED TO CONNECTIONS

The cost structure for OWF differs significantly between HVDC and HVAC. Between the two, HVDC maintains the highest fixed cost but the lowest variable cost. The low variable costs are mainly due to the low line losses and the lower cost of lines [22], [36]. The cost differential for one system over the other in OWF depends on the line length, the discount rate used, and the cost estimation technique.

The literature traditionally estimates the impacts of costs through discounted payback periods, LCOE, or Internal Rate of Return (IRR), with LCOE consistently being the most popular. Substantial prior work has examined the breakeven point between transmission technologies for OWF. Recent work places the breakeven point around 150 kilometers (93 miles) [25] for a 300 MW system; however, recent advances in HVDC converters have brought costs down significantly in the past decade. Due to these changes, estimates of the breakeven point have been halved since 2010 [37].

As a cost estimation method, LCOE represents the average minimum price at which electricity generated by a resource must be sold to make building the resource viable [31]. LCOE provides the same project selections as net present value and focuses on the economic viability from the producer's perspective. LCOE can be calculated by dividing

the discounted sum of investment expenditures I_t, operations expenditures M_t, and fuel expenditures F_t by the discounted sum of electricity generated E_t.

$$LCOE = \frac{\sum_{t=1}^{T} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_t}{(1+r)^t}} \quad (1)$$

Fig. 3 shows the LCOE for HVDC and HVAC for power ratings at different baseline interest rates. To create the figure, the CREST LCOE calculator from the National Renewable Energy Laboratory (NREL) [38] was used in conjunction with the estimates for the cost of the system from Table 4 based on [30].

The baseline interest rate used to create Fig. 3 is the interest rate for construction financing. The interest rates for reserves and long-term debt were adjusted based on this baseline interest rate. The costs related to capital that vary with the size of the wind farm were adjusted for larger OWFs. The HVAC system capacity factor was adjusted to a value of 3.3% from the HVDC system's capacity factor to reflect line losses. A 150-kilometer distance was used to compare the systems. A standard retirement time of 20 years is used. These numbers are highly stylized and therefore should be treated as estimates with high variance and more value for comparison across system types than estimation of real-world LCOE.

Fig. 4 isolates the impact of increases in interest rates on system LCOE by holding the power rating constant at 1200 MW. Fig. 5 shows the LCOE by distance for the different types of system for a 1200 MW system at varying lengths from shore at 2% interest. Note that the breakeven distance in terms of LCOE is shorter than the breakeven distance based only on capital costs (shown later in Fig. 7). This is because the LCOE calculation accounts for line losses $\sim 3.3\%$ lower for HVDC systems than for HVAC systems, which leads to higher discounted revenues over the system's lifecycle.

It should be noted that HVDC is more economical at all interest rates, but the difference between costs decreases as interest rates rise. This reduction in relative advantage is due to the increasing importance of fixed costs and the decreasing value of discounted future revenues as interest rates increase. Rising interest rates also cause a change in the
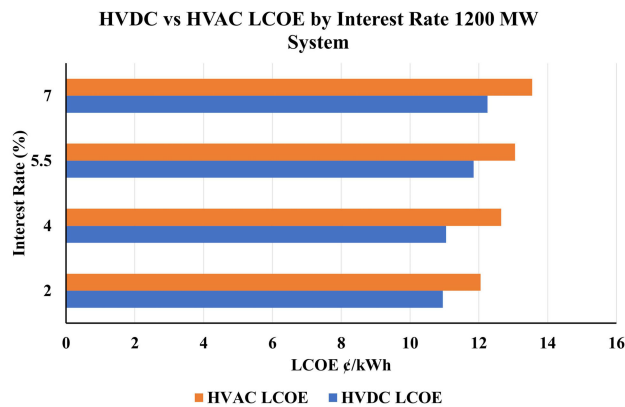
FIGURE 4. LCOE by interest rate and system type for 1200 MW system.
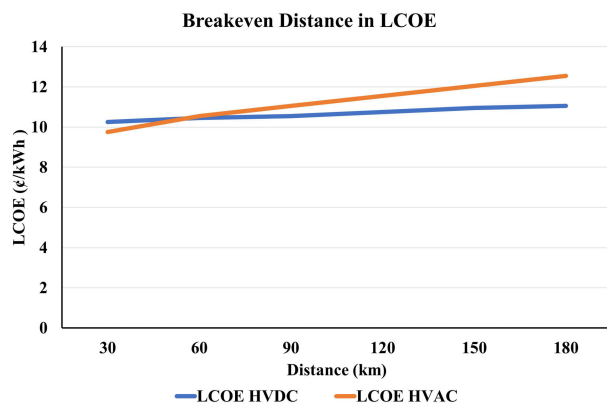

FIGURE 5. LCOE for different system types by interest rate for 1200 MW system.

most economical power rating as a result of the increase in the value of fixed costs and line losses.

The dramatically increased costs with higher interest rates show the impact of rising rates on OWF investment. The increase in LCOE helps explain the significant cancellation of OWF farms following increases in interest rates in recent years. At low interest rates of 2%, 1200 MW HVDC systems are significantly cheaper than 1200 MW HVAC systems. This advantage becomes smaller as interest rates rise.

On the other side of a cost-benefit balance sheet, LACE (Levelized Avoided Cost of Energy) is a metric commonly used to complement LCOE. LACE provides the generator's value to the market as a whole or the increase in consumer surplus for the aggregate market [39]. When LACE exceeds LCOE, there is a net surplus and the resource will be net economically viable.

LCOE and LACE differ dramatically geographically, and NREL provides a map of the differences through the State and Local Planning for Energy (SLOPE) [40]. In 2020, the median offshore wind LCOE was 86 dollars per MWh, with the 2024 maximum at 126 dollars per MWh in Washington and a minimum of 72 on the Great Lakes in Ohio. In 2018, the most recent year on record, NREL put the highest LACE

TABLE 3. Cost of component by system for set size in million dollars.

System	Cost of Component	
Component	HVDC (M$)	HVAC (M$)
Substation	24-45	10-45
Cable	0.6/km	1.5/km
Offshore Platform	73.5	24
Onshore Platform	24	24
Cable Installation	215	215
Line Losses % per 1000 km	0.035	0.067

Note: Values are based on data provided in [22, 23, 25, 30, 41]

at 5 cents per KWh in Connecticut and the lowest at 1 cent per KWh in Wisconsin.

There are still substantive challenges to overcome before offshore wind becomes economically competitive at these rates. However, the median LCOE of offshore wind is projected to fall by 35% by 2050, placing it below NREL's LCOE projections for combined cycles and making OWF competitive with most other energy sources. These estimates of LCOE are much higher than the current paper's estimates. Heterogeneity in system scale may help explain these differences, as the systems examined here are much larger and benefit from size compared to the systems currently in place in the United States.

An important area of future research is quantifying uncertainty related to LCOE estimates and finding ways to represent various future paths of revenues and costs. Although this research is in a stage that is developed for much of the techno-economic analysis literature, it is imperative in the case of offshore wind, where uncertainty about the learning curve and technological improvement leads to immense variability in LCOE estimates based on assumptions. Focusing on quantifying uncertainty would allow OWF research to follow the same path as other primary research into techno-economic analysis in other energy sources.

The metrics calculated within the literature often do not consider the impacts of the generators on other resources in the market, and an economical style analysis with an equilibrium model could yield an improved understanding of the fundamental values of changes in consumer welfare, and thus improve the estimation of LACE. The addition of electricity at peak load times proves particularly salient for consideration and can only be distinguished with a model that considers equilibrium effects. Also, because line losses increase at a quadratic rate with utilization, equilibrium impacts have outsized effects on costs.

Table 3 shows how the cost estimate for the OWF components per megawatt varies depending on the chosen type of transmission system. High and low ends of ranges are based on quotes from papers within the literatures [22], [23], [25], [30], and [41].

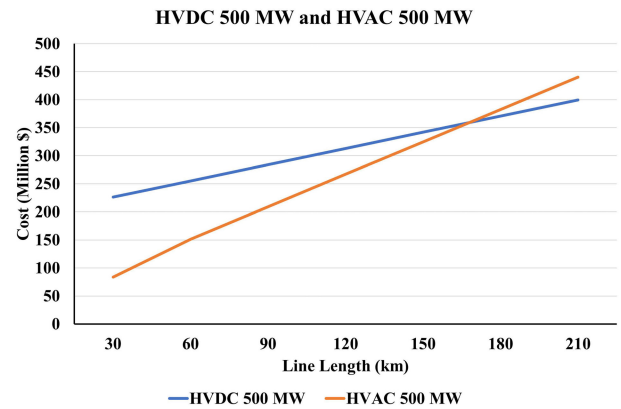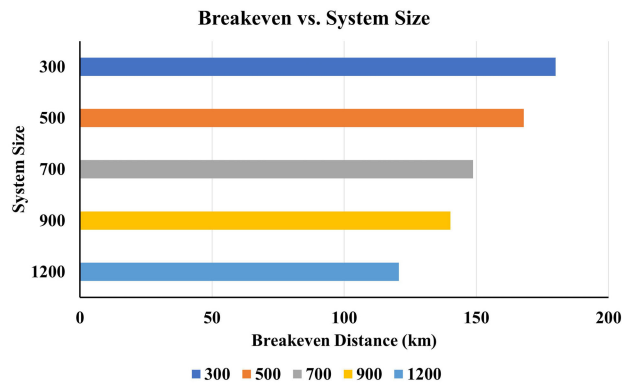**TABLE 4.** Cost of system in million dollars by size and line length.

Power Rating (MW)	Line Length (km)	System Cost	
		HVDC (M$)	HVAC (M$)
300	30	142	54
	90	196	147
	150	248	232
	210	299	315
500	30	226	94
	90	284	151
	150	342	267
	210	400	382
700	30	370	125
	90	349	208
	150	421	487
	210	493	607
900	30	398	204
	90	441	273
	150	527	485
	210	613	696
1200	30	538	251
	90	568	370
	150	662	660
	210	757	950

Note: Values are based on data provided in [30]

FIGURE 6. Breakeven point for systems of differing ratings without considering life cycle costs.

FIGURE 7. Breakeven point with considerations for different power ratings.

Beyond individual components, two other critical technical dimensions related to the cost-effectiveness of the two technologies are the size and the line length. As OWF has increased in size, and the cost compositions have changed both as a function of size and line length, breakeven analysis using these variables provides increasingly valuable information. Table 4 compares the costs of the systems by line length and size in voltage rating using data from the literature [30].

Reference [30] considers three costs in a system: the Cost of the Onshore Platform (OPC), the Costs of the Offshore Platform and Plant (OPPC), and the cost of the cable C_{Cable}. The cost of the cable varies directly proportionately to the number of sets, the length of the line, and the price per kilometer. All cost estimates were taken from the appendix to [30]. These costs differ by line length l and system size S_N according to [30].

The values presented in Table 3 and Table 4 remain unadjusted for inflation to align with the original sources and ensure consistency. Since inflation impacts various cost components at different rates, applying adjustments would require assumptions that may not always be fully substantiated by available data. Recent studies [69], [70] highlight cost increases in offshore wind projects due to supply chain challenges and market dynamics since 2020, while strategic long-term planning has been recognized as a key factor in mitigating these costs. Additionally, [71] provides

a structured approach for incorporating inflation adjustments into techno-economic analyses, offering a framework to enhance the accuracy and depth of cost evaluations.

The impact of interest rate risk on the cost of investment in OWF systems has yet to be considered as most papers assume the interest rate throughout life or do not consider line losses in breakeven analysis. However, the discount rate increases with rising interest rates, and the breakeven point between technologies changes, as shown above. Considering the impacts of different interest rates on the lowest-cost technology would allow for a more realistic estimation of the breakeven distance.

Fig. 6 below shows the breakeven distance using approximate cost data from [30] to plot the breakeven point by system rating and is followed by Fig. 7. Fig. 7 directly compares the approximated breakeven point by system rating. The breakeven point decreases uniformly because of economies of scale. The variable costs of cables increase substantially faster for HVDC than for HVAC.

The tradeoffs between HVDC and HVAC in offshore wind represent an essential consideration in developing OWF. However, offshore wind faces many headwinds beyond those related to the transmission system. Table 5 describes some

TABLE 5. Economic challenges to offshore wind industry.

Main Challenge		Mitigation Strategy	References
Long-term Financing	Capital Intensive	− Subsidies for wind energy development − Renewable Portfolio Standards − Feed-in tariffs	[42, 43]
	Cost and Revenue Uncertainty	− Contracts for Differences − Long-term electricity price modeling − Power purchase agreements − Inflation Adjustments	[44]–[46]
Missing Money Problem	Low Revenues for Baseload Generators	− Capacity market redesign − Convex hull pricing	[47]–[49]
	Increased Ramping by Dispatchable Resources	− Improved cold start efficiency − Diversified portfolios (fossil and renewable)	[50]–[52]
	Price Variability	− Demand response − Energy storage systems (ESS) − Long-distance transmission	[53]–[55]
Sustainable Supply Chain	Waste of Wind Turbines	− Turbine recycling − Reduced metal intensity	[56, 57]
	Securing Metals for Turbine Production	− Development of mineral sources − Supply chain transparency	[58, 59]
Intermittency	Non-dispatchability	− Coordination with ESS − Black-start natural gas cooperation − Capacity market redesign	[53, 60, 61]
Concept to Industry	Initial Investments	− Public-private partnerships − Loans via DOE programs − Government contracts (e.g., Executive Order 14057)	[62]–[64]
	Workforce Development	− Education funding − Project pipelines to retain knowledge	[65]–[67]
Political Support	Uncertain Technology Funding	− Long-term funding guarantees − Resilience to leadership changes	[67, 68]

of the challenges opposing the development and integration of offshore wind systems and potential mitigation strategies. Long-term financing proves a perennial challenge for any significant offshore wind system due to the highly uncertain nature of the revenue stream and the highly variable cost of infrastructure projects [42], [43], [44], [45], [46].

Contracts for differences and renewable portfolio standards have gone a long way toward improving financing outcomes. Offshore wind penetration– like all renewables penetration– has the potential to exacerbate the missing money problem for base load and cause reliability challenges or price increases [47], [48], [49], [50], [51], [52], [53], [54], [55]. Work toward improved capacity markets and convex hull pricing can help ensure funding for traditional generation. A sustainable supply chain remains essential for offshore wind as wind farm development

is highly dependent on metals, and metals procurement is not without geopolitical risks and environmental costs [58], [59].

The intermittency problem further poses challenges for grid planners, as does the issue of reliability and resilience to outages [53], [60], [61], [72]. Finally, like any technology, offshore wind faces a learning curve as it transitions toward not just technological but commercial maturity. This will require initial support for workforce development and investments and could be challenged by the uncertainty of political environments related to funding and environmental policy [62], [63], [64], [65], [66], [67], [68]. Ultimately, all these challenges, though complex, are solvable and demonstrate the significant value of future collaboration between engineering and economic analysis.

TABLE 6. Failure likelihood by component.

System Component	Reliability Measure		
	P(Failure)	DT (hrs)	DT per Year
Generator	0.01-0.1	NA	NA
Transformer	0.0108-0.03	1440-4320	15.552-1296
AC Breaker	0.0015-0.025	NA	NA
DC Breaker	0.0033-0.025	240	0.792-6
AC/DC Converter	0.1	NA	NA
DC/DC Converter	0.014-0.613	NA	NA
Full Power Converter	0.05-0.2	720	36-144
DC Cables	0.0706	1440	101.67
AC Cables	0.0001-0.008/km	2160	0.216-17.28

B. ECONOMIC CONSIDERATIONS FOR RELIABILITY

Reliability creates another dimension of distinction between technologies. In the literature, there is a consensus that HVAC has the highest reliability, followed by VSC-HVDC and LCC-HVDC, with work being performed to improve reliability across all system types. DC/DC and DC/AC converters have significantly higher probabilities of failure than other components and also create outages of the entire generator rather than a specific cluster [29].
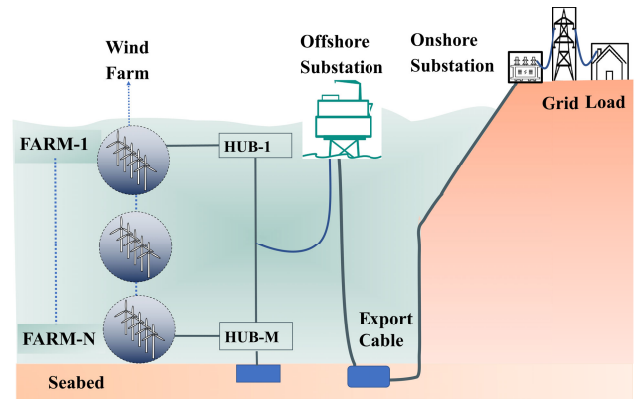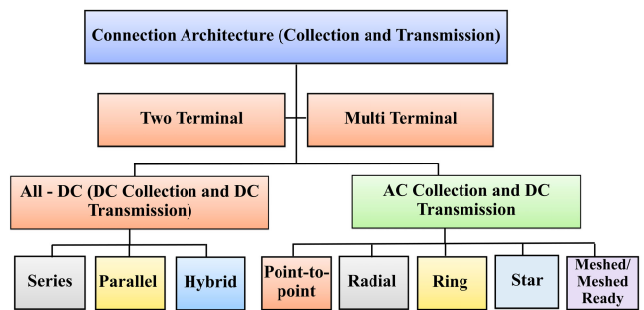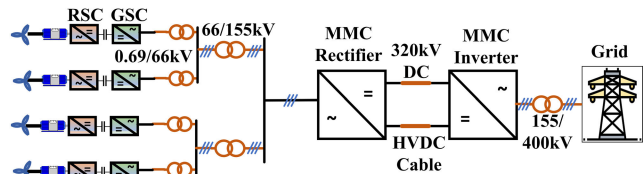
Based on estimates from the literatures [?], [17], [29], [34], [73]db@andbib:33, Table 6 provides the likelihood of failure for different components within the OWF system, as well as the average Down Time (DT) for those components in an outage, and the yearly expected maintenance time of the components.

Typical models of reliability of OWF utilize assumed independent Poisson likelihood functions for individual components to perform Monte-Carlo simulations of the likelihood of total failure rather than an individual cluster. Most of these models do not consider potential external variables and potential dependence in the distributions of failures of multiple components.

The prior literature has not taken into account market considerations related to reliability. While the likelihood of failure of different components and the time to repair these components is determined, a valuation has not yet been put on the cost of downtime either for the generator or for the system as a whole. Further research could focus on quantifying average revenue losses from reliability failures and the associated costs to the grid system over the lifetime of the OWF. Developing a comprehensive revenue model would enable a more accurate determination of the breakeven point between HVDC and HVAC systems, considering the varying levels of reliability that research indicates directly influence costs.

III. OWF CONNECTION ARCHITECTURES

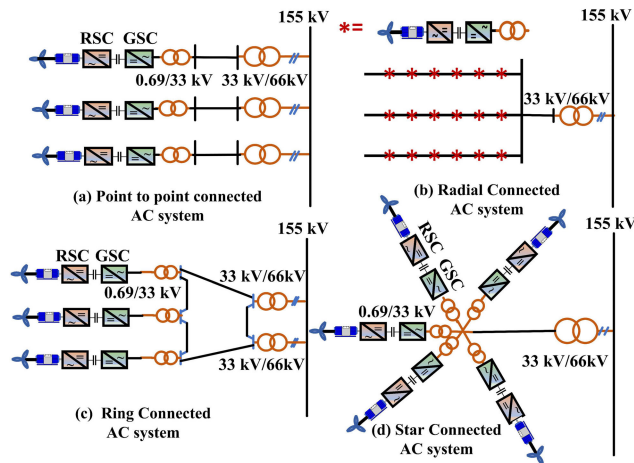The efficient gathering and transmission of power from OWFs constitute a critical aspect influencing their overall

FIGURE 8. Connection layout of grid-tied offshore wind farm.

FIGURE 9. Classification of connection topology.

FIGURE 10. Schematic of grid-tied HVDC offshore wind farm.

performance and economic viability. Fig. 8 illustrates the comprehensive connection layout of the OWFs, representing all the electrical components that connect the wind turbine output to the onshore power grid. This includes generating units, power electronic converters, transformers, inter-turbine cables, transmission cables, and switch gears. This electrical infrastructure operates through two primary sections that define the power transfer networks [74]. The first section, known as the collection system, interconnects the wind turbines within the OWFs. Meanwhile, the second section, the transmission system, plays a pivotal role by establishing the vital link between the offshore and the onshore grid, often operating at elevated voltage levels.

Offshore wind turbines generate electricity individually, and the generated power must be collected and aggregated prior to transmission. Collection systems, often consisting of subsea cables, gather the electricity from multiple turbines within an array and transmit it towards a central point [75]. Reference [34] addresses the related research on different

TABLE 7. Comparison of AC collection grid architectures.

Aspect	Point-to-Point	Radial	Ring	Star
Topology	− Direct connection to a central substation	− Single path linear structure	− Circular loop with multiple interconnections	− Multiple units connected to a central hub
Redundancy & Reliability	− Limited	− Limited	− Moderate	− High
	− Single fault disrupts the connected unit	− Fault affects down-stream units	− Faults in one segment may not impact the loop	− Centralized hub reduces fault impacts
Control	− Simplified voltage control at the sub-station	− Easy control with possible voltage drops along the path	− Partial voltage control through loop paths	− Centralized, robust voltage control
Scalability	− Low; significant adjustments needed	− Limited; requires new connections	− Moderate via loop paths	− Highly scalable; units easily added to the hub
Complexity & Cost	− Simple design; lower initial cost	− Simple design; added cost for voltage & reliability	− Moderate due to loop setup	− High, but better redundancy
Suitability	− Best for small systems with limited growth	−For small to medium systems	− Ideal for medium install-ations with room for expansion	− Best for large, complex, or expanding systems

FIGURE 11. AC collection architecture.

FIGURE 12. DC series collection architecture.

OWF collection systems and explores their operational characteristics and challenges.

The architecture of the collection grid can be either AC or DC based on the type of energy source and the location of the offshore farm [8], [76]. Reference [77] provides a technical and economic comparative analysis between DC and AC collection systems for OWFs, highlighting that while DC systems offer size and weight reductions, they face higher costs and losses compared to AC systems due to the need for DC protection devices and converters.

In this review paper, our primary focus revolves around various collection architectures designed for HVDC transmission in OWFs. Fig. 9 presents potential connection architectures for OWFs, such as AC collection combined with DC transmission and all DC-based systems. Meanwhile,
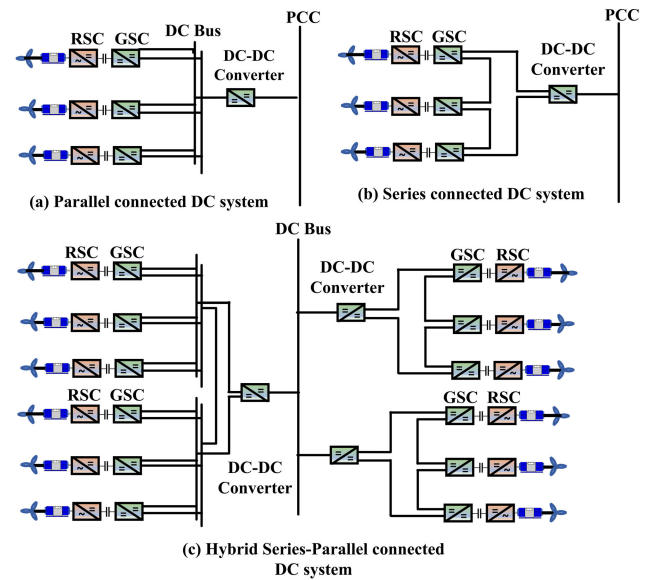
Fig. 10 provides a general schematic of a grid-connected HVDC OWF, highlighting the voltage ratings at key points throughout the system.

A. AC COLLECTION ARCHITECTURE

In AC collection grids, the electrical power generated by OWF devices is stepped up to a higher voltage level for efficient transmission to onshore substations [9]. AC grids offer several benefits, including mature technology, high efficiency, and seamless integration with existing electrical networks [78], [79]. Depending on the size of the wind

farm and its distance from the shore, different topologies are employed to optimize power collection and ensure system reliability. Each topology presents specific advantages and limitations, tailored to suit particular wind farm layouts and their proximity to the coast [34]. Fig. 11 provides an overview of various AC collection-based topologies utilized in HVDC transmission systems.

1) POINT-TO-POINT
The point-to-point topology consists of direct connections between individual offshore energy generation units and the shore, with each unit independently linked through its transmission cable [80]. Although this design offers simplicity in both implementation and operation, it requires many individual cables, leading to higher installation and maintenance costs. As a result, it is not well suited for large-scale wind farms. Furthermore, the point-to-point configuration lacks the flexibility to facilitate power exchange between multiple areas or regions, limiting its adaptability to interconnected systems [81].

2) RADIAL
The radial topology uses a ''daisy-chain'' configuration, where the cable capacity increases progressively after each connected unit. This design minimizes costs by requiring fewer cables and simpler infrastructure. However, it is vulnerable to single-point failures, compromising system reliability. To connect multiple units, hubs, junctions, or low-/medium-voltage transformers are typically used [73].

3) RING
The ring topology interconnects units through looping cables, creating a circular arrangement [12]. Although the ring design adds complexity and higher costs due to the need for additional switches and cabling, it significantly enhances reliability. In the event of a fault, the two-way power flow within the loop ensures continued operation, making it more robust than a radial system [8].

4) STAR
In the star topology, units are grouped and connected to a central hub using cables of similar ratings, with the collected power transmitted to shore through higher-rated cables [82]. This design simplifies the connection process and allows individual control of each turbine. However, a hub failure can impact all connected turbines, reducing the reliability of the system. While the star topology can be cost-effective for smaller-scale systems, both cost and complexity increase for larger systems due to the central hub's location and associated infrastructure. A similar cluster-based architecture is described in [17].

Table 7 offers a detailed comparison of different AC collection grid architectures. It evaluates their performance across several key parameters, including redundancy, reliability, voltage levels, transmission distance, complexity, cost,

scalability, and adaptability for seamless integration with offshore wind systems.

B. LIMITATIONS OF AC COLLECTION GRIDS
AC grids, known for their mature technology, high efficiency, and seamless integration, have long served as the backbone of onshore and offshore power transmission. However, integrating large-scale OWFs into AC grids presents unique challenges due to the fluctuating power output, extended transmission distances, and complex synchronization requirements with onshore grids. These factors amplify critical issues such as voltage instability, harmonic distortions, and reactive power management, which are crucial to maintaining reliable grid operations [75], [125], [126]. Table 8 lists the challenges and their mitigation strategies.

In offshore environments, AC collection grids encounter additional technical and operational challenges stemming from the reactive nature of AC power. Long transmission distances introduce capacitive effects in submarine cables, leading to a reactive power imbalance. Shunt reactors and Static Synchronous Compensators (STATCOMs) are deployed to manage these effects. While effective, these approaches increase system complexity and operational costs [127].

Voltage regulation becomes more difficult as the transmission distance increases, requiring additional equipment to maintain stability [128]. Furthermore, power converters and switching operations in AC systems generate harmonics, which demands sophisticated filtering solutions to ensure that power quality is not compromised [129]. These technical hurdles make the design, operation, and maintenance of AC systems for OWFs more complex and expensive.

Moreover, a key limitation of AC collection systems is the large size and footprint required for offshore substations, further complicating their deployment and scalability [34]. AC substations need bulky components such as transformers, reactors, switchgear, and harmonic filters to manage voltage levels and reactive power [130]. This increases the weight of offshore platforms, making construction and installation costly and logistically challenging. The platforms must not only support heavy equipment, but also withstand harsh marine conditions, further raising the cost and limits the scalability of the infrastructure. Furthermore, as OWFs increase in size and move farther from shore, the economic and logistical challenges of AC systems become even more pronounced [33].

C. TRANSITION FROM AC TO DC COLLECTION SYSTEMS
To address the limitations of AC systems, research has increasingly emphasized the development of DC collection grids and All-DC systems for OWFs [9]. DC systems offer several advantages over AC infrastructure, particularly for long-distance, high-capacity power transmission [131]. One of the most notable benefits is the elimination of reactive

TABLE 8. Integration challenges of OWFs.

Main Challenge		Mitigation Strategy	References
Power Quality	Harmonic Distortion	−Use of active/passive filters −Advanced Control Algorithms	[83]–[85]
	Voltage Unbalance	−Dynamic voltage balancing techniques	[86]
	Voltage Sag, Swell, Flickers	−Use of FACTS devices − Dynamic VAR compensators − Power conditioning systems.	[87, 88]
Stability	Voltage Stability	−Reactive power compensation −Advanced Control Techniques −Turbine converters with reactive power control	[89]
	Frequency Stability	−De-loading by Variable Speed Wind Turbine −Capacitor energy storage in VSC-HVDC −Coordinated Frequency Control of OWF & VSC-HVDC	[90]
	Fault Ride-Through Capability (LVRT/HVRT)	−Implement LVRT and HVRT schemes in wind turbines & HVDC converters	[91]
Fault Diagnosis & Protection	Offshore Converter Protection	− Use of advanced protection systems & fault detection technologies	[92]–[95]
	Short-Circuit Current Limitation	−Use of superconducting fault current limiters −Adaptive relays; precise fault detection and response	[96]–[98]
Inertia	System Inertia Reduction	−Use of synthetic inertia from wind turbine control −ESS-based inertia emulation −Virtual synchronous machines to mimic inertia	[99]–[101]
Ancillary Service Provision	Frequency Regulation	− Battery Energy Storage Systems (BESS) − Synthetic inertia for fast frequency response − Advanced control algorithms	[102]–[104]
	Voltage & Reactive Power Control	−Use of FACTS devices (STATCOM, SVC) −Wind turbine converters with reactive power support	[105]–[108]
	Provision of Reserve Power	−Novel large-scale ESS −Coordinated operation with other RES	[109]–[112]
	Black Start Capability	−Implement black start capability in ESS −Specific turbines designed for black start operations −Coordinated black-start strategy	[113]–[116]
Converter Sizing & Efficiency	Converter Weight and Volume	−Use of modular multilevel converters (MMC) −Advanced materials to reduce size and weight −Novel collection systems	[117]–[120]
	Converter Losses	−Use of high-efficiency semiconductor technologies (e.g., SiC or GaN) −Advanced converter topologies for lower losses	[121, 122]
Grid Code Compliance	Compliance with Grid Codes	−Adaptive control schemes to meet diverse grid codes −Ensuring LVRT/HVRT capabilities	[123, 124]

power compensation, as DC transmission does not involve reactive power [132]. This allows for the removal of large transformers, reactors, and compensation devices, resulting in smaller, lighter substations with a reduced physical and environmental footprint [120].

DC systems also simplify grid integration by reducing the number of conversion stages and minimizing harmonic distortion [85]. In an All-DC setup, wind turbines generate DC power directly, which can be transmitted to the shore without need for AC / DC conversion at the wind farm level,

improving efficiency and reliability [133]. With fewer components required for voltage and power quality management, DC grids reduce operational complexity and maintenance needs, making them more suitable for large-scale offshore installations.

In summary, while AC grids have been the cornerstone of power infrastructure, their limitations in offshore applications have accelerated the shift toward DC collection grids and HVDC systems. DC systems provide a promising solution to address the challenges of power quality, reactive power

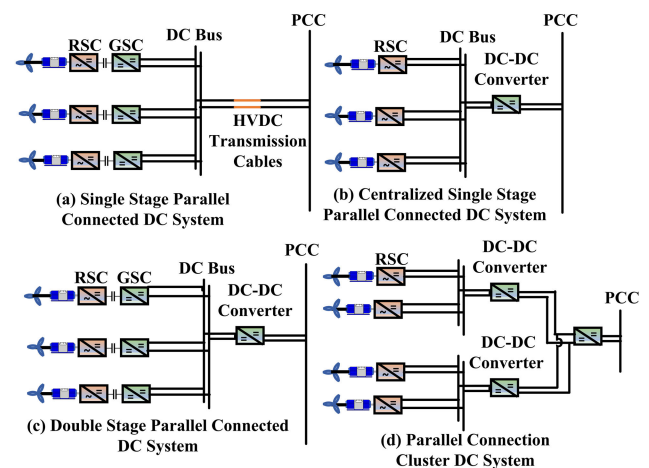**TABLE 9.** Comparison of DC collection grid architectures.

Aspects	Parallel DC Collection Grid	Series DC Collection Grid	Series-Parallel DC Collection Grid
Redundancy & Reliability	− High redundancy within branches − Faults in one branch do not affect others	− Vulnerable to single-point failure − Complex fault detection and protection	− Moderate redundancy; faults do not disrupt entire system − Better fault isolation and protection
Voltage Level & Transmission	− Common voltage level − For short-range transmission	− Aggregated voltage − Ideal for long-distance offshore transmission	− Moderate voltage aggregation − Suitable for mid-range transmission
Complexity & Cost	− Simple design, easier installation − Higher cost due to multiple converters & extensive cabling	− Complex voltage and insulation management − Lower cost by eliminating offshore substations and reducing cabling	− Moderate complexity and cost − Balanced between series and parallel designs
Scalability	− Easily scaled for smaller installations	− Challenging due to voltage management	− Balanced scalability for medium-sized systems
Suitability	− Ideal for near-shore installations requiring redundancy & simplicity	− Best for long-distance offshore, high-power demand installations	− Suitable for medium-sized OWFs with balanced performance and cost

management, and infrastructure size associated with AC grids. As OWFs grow in scale and distance from shore, All-DC architectures are likely to play a critical role in ensuring efficient, reliable, and sustainable energy transmission.

D. DC COLLECTION GRID

Recently, the work has shifted to analyzing the potential consequences of DC collection systems across technical and economic domains. This section explores various potential DC collection grid topologies for OWE integration. It is important to highlight that commercial DC grids within offshore farms remain relatively uncommon, particularly for large, remote installations where HVDC transmission to shore is the standard. Despite the growing interest in DC grids, the internal collection networks of most offshore farms still predominantly rely on AC technologies.

Reference [134] examines the cost-effectiveness of DC wind farm collectors and finds that modeling assumptions dramatically impact the optimal choice of OWF configuration. Standard parallel wind farms have the lowest technological risk and have the most significant potential for early implementation. At the same time, series and series-parallel systems outperformed in terms of costs, but had significant limitations in reliability. References [77] and [131] reviewed configurations of DC collection grids for OWFs, including the generator systems, the power electronics converter topologies, and the control and protection methods. Reference [135] presents a technical and economic comparison between conventional AC and four proposed DC topologies for Offshore Wind Power Plants (OWPPs). Using Horn's Rev wind farm as a case study, the analysis shows that DC OWPPs have capital costs comparable to AC systems and lower energy losses, making them a potential option

FIGURE 13. DC parallel collection architecture.

for future installations. DC collection grids can be broadly classified into three main topologies: parallel, series, and hybrid (series-parallel) configurations [75], [136] (Fig. 12).

1) PARALLEL DC COLLECTION GRIDS

Parallel DC collection grids resemble AC radial topologies but with added redundancy through double-sided ring setups. One fundamental design connects energy converters directly to an onshore inverter via a feeder cable [80], [137]. More complex designs involve multiple feeder strings attached to a passive offshore point, offering fault tolerance redundancy and increasing the system's reliability [33], [138]. This approach suits large farm systems but may incorporate offshore hubs for greater distances, albeit with increased complexity and cost [120]. Fig. 13 depicts various DC Parallel collection architectures for HVDC-OSW Power.

2) SERIES DC COLLECTION GRIDS

In series DC collection topology, energy converters are connected in series to achieve high voltage DC transmission, providing cost-effective long-distance transmission without the need for HVDC offshore platforms. In [139], a DC wind farm design with series-connected wind turbines based on diode bridge rectifiers and partial power processing converters (PPPCs) has been developed. However, insulation coordination and the strong power-voltage coupling between series-connected WTs present significant technical challenges, particularly for the final power converter in the string [33]. Alternative solutions include series-connected offshore farm concepts with AC/AC conversion, high-frequency transformers, and passive diode rectification, particularly useful for high-power-rated energy converters [140], [141]. Another key drawback of series-connected turbines is their low resilience; a fault in one of them will shut down entire connected turbines [75]. Fig. 14 represents different architectures based on DC Series collection for HVDC transmission.

3) SERIES-PARALLEL COLLECTION GRIDS

In [142], a DC series–parallel wind farm is proposed as an alternative to AC wind farms. It eliminates the need for offshore transmission platforms by directly raising the string voltage to the transmission level without further transformation [143]. Hence, reducing footprint and cost compared to the AC collection system and traditional DC alternatives, the study by [144] examines power curtailment losses in DC series-parallel wind farms, focusing on voltage issues in MVDC converters caused by wind speed variations. A 200 MW case study highlights the need for appropriate voltage tolerance levels to minimize annual energy losses. Reference [145] explores the series-parallel wind farm topology, highlighting its cost and efficiency advantages over pure DC systems, and proposes a global control strategy to address voltage imbalances among turbines. The approach, validated in a 300 MW wind farm simulation, ensures safe operation and maximum power point tracking with active support from the onshore converter. Table 9 gives a comparative analysis of all three DC collection architectures.

Although DC systems address many issues inherent to AC infrastructure, they bring their own set of challenges. Offshore DC substations must be compact and efficient, and the infrastructure required for HVDC systems is more expensive and complex than traditional AC systems. Installation of underwater cables, substations, and grid connection points involves high capital costs and can have significant environmental impacts, necessitating thorough regulatory approvals and environmental assessments. Coordination among stakeholders is essential to optimize resource use and minimize ecological disturbances, especially when multiple wind farms share substations and transmission lines [146].

Managing harmonics and resonance is crucial for HVDC-connected wind farms, as discussed in [85]. Although
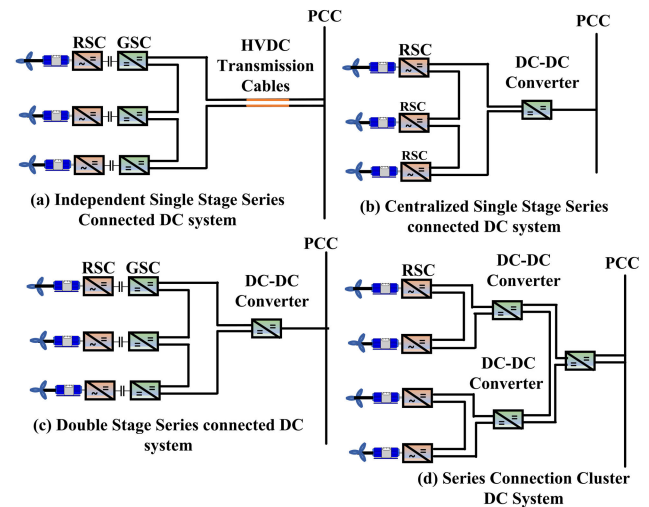

FIGURE 14. DC series collection architecture.

HVDC systems generate minimal harmonics, total harmonic distortion may exceed acceptable limits if early mitigation measures, such as high-pass filters, are not employed. HVDC systems are well-suited for long-distance, high-capacity transmission, but they introduce new challenges, including the need for compact and lightweight offshore converters. Research into innovative power electronic converter topologies is ongoing, with solutions such as centralized Voltage Source Converters (VSCs), diode rectifiers, series-connected turbine converters, and DC transformers being explored to enhance system performance [17].

E. EMERGING TRENDS IN ARCHITECTURES

To address the size and weight challenges of an offshore converter, a high voltage diode rectifier (DR) is suggested [17], [33]. However, coordinating turbines in the offshore AC grid and achieving MPPT pose hurdles. Hence, variants with auxiliary devices such as Aux-MMC and Aux-STATCOM are used [147]. Another promising architecture proposed is the mesh-connected architecture, in which there is always more than one path between any two points (Fig. 15). When a fault occurs, these alternate routes can quickly redirect power flows, minimizing the loss of input in connected AC grids. The AC collector system transitioned to a mesh connection from parallel, significantly bolstering reliability on the collector side [148]. This alteration promotes a more robust and fault-tolerant configuration. Mesh-ready designs are engineered to enable future grid meshing by incorporating modular and adaptable components, providing scalability and resilience for evolving energy systems. In line with these advances, New York requires mesh-ready designs to support its renewable energy transition and enhance grid reliability [149].

The Multi-Terminal Direct Current (MTDC) connection is another promising solution to seamlessly integrate multi-use offshore platforms into continental grids, as shown in Fig. 16.

TABLE 10. HVDC offshore connection topologies comparison.

HVDC Offshore Connection Topologies	Advantages	Limitations	Feasibility	Reliability	Cost	Complexity
Parallel AC Collection System with HVDC Transmission [152]	— Higher voltage/power transmission — Longer distances from shore	— Reactive power compensation — Lower reliability	*****	***	***	**
Mesh-Connected AC Collection System with HVDC Transmission [153]	— Enhanced system reliability — Improved redundancy	— Infrastructure cost — Complex structure	****	****	****	****
Multi-Terminal DC Collection Grid with Mesh HVDC Transmission [154]	— Higher reliability; continued power transfer under cable failure	— Infrastructure cost — Complex	****	*****	*****	****
Parallel DC Collection with Medium-Frequency Transformer Embedded HVDC Transmission [155]	— Reduced offshore converter station footprint & weight	— Initial cost & transformer technology	** Under Research	***	****	***
Series DC Collection System with HVDC Transmission [29, 156]	— Reduced infrastructure requirements — Elimination of offshore substations	— Voltage maintenance — Reliability concerns	** Under Research	**	***	***

TABLE 11. Cost of cable for collection and transmission architecture.

Cable	Type	Voltage (kV)	Diameter (mm^2)	Ampere (A)	mΩ/km	Transmission Loss (kW/km)
Low	AC	110	1000	1283	16.8	27.65
Medium	AC	220	1600	1644	10.5	28.37
High	AC	500	800	1192	21	29.84
1	DC	150	1200	1375	14	26.47
2	DC	200	1600	1640	10.5	28.24
3	DC	250	1200	1375	14	26.46
4	DC	250	2500	2145	6.72	30.92
5	DC	320	800	1095	21	25.18
6	DC	320	2500	2145	6.72	30.92

This approach aims to efficiently leverage offshore resources, improve energy efficiency, and unify diverse functions such as renewable energy generation and aquaculture within a single platform. In [150], an MTDC connection is proposed to integrate offshore multi-use platforms into continental grids. Reference [151] presents a comprehensive method for minimizing transmission power loss in mesh and radial MTDC networks.

Table 10 compares potential HVDC offshore connection topologies, assessing their advantages, limitations, feasibility, reliability, cost, and complexity to comprehensively understand the trade-offs involved and their suitability for offshore wind integration.

F. ECONOMIC ANALYSIS FOR CONNECTION ARCHITECTURE

Economic analysis of connection architectures is critical for optimizing the cost-effectiveness of OWFs, as it directly impacts both capital expenditures (e.g., cabling and substations) and operational costs (e.g., transmission losses and maintenance). For a 500 MW reference wind farm comprising 50 turbines (10 MW each) spaced 1,000 meters apart, this study evaluates inter-array cabling layouts: radial, ring, branched, star, and mesh, as depicted in Fig. 17. Such analyses are essential to identify configurations that minimize energy losses and infrastructure costs, thus improving the overall economic viability of OWFs [27], [37].
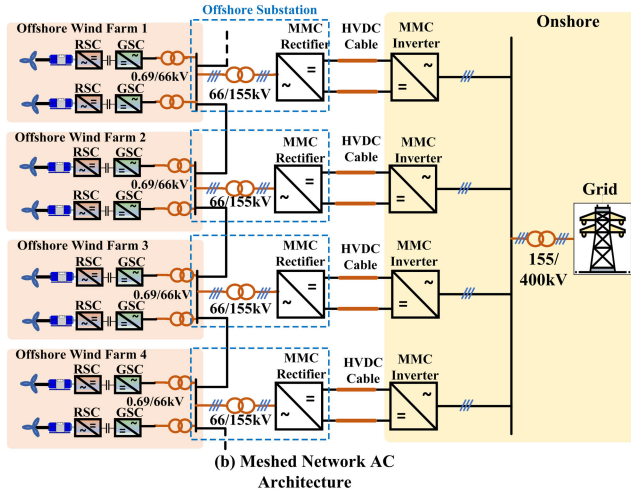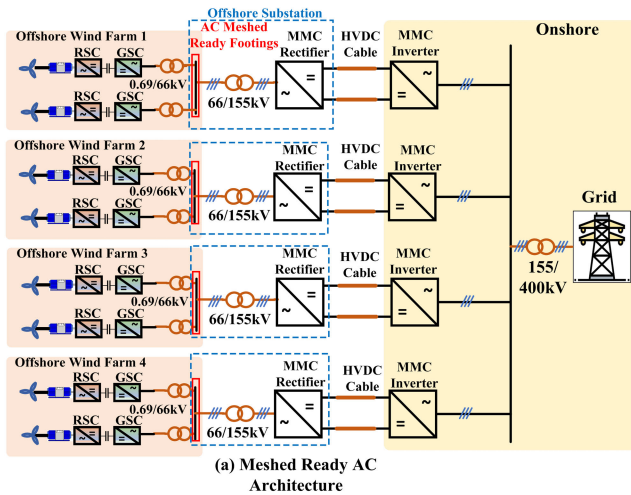
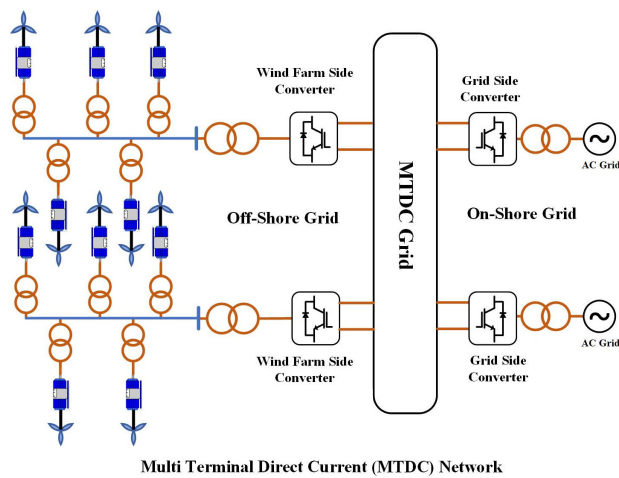**FIGURE 15.** Meshed AC architecture for offshore wind farm [149].

FIGURE 16. Multi terminal direct current (MTDC) network.

Each layout presents unique connectivity patterns that impact redundancy, reliability, and overall cost. The economic cost of the architecture is primarily determined by the chosen cable, which, in turn, is selected based on the required
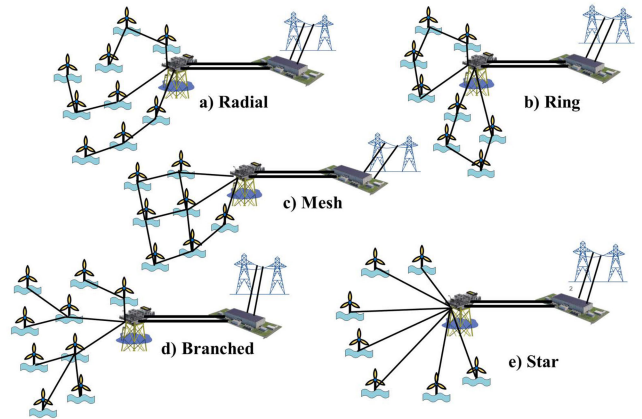

FIGURE 17. Collection architecture techno-economic analysis.
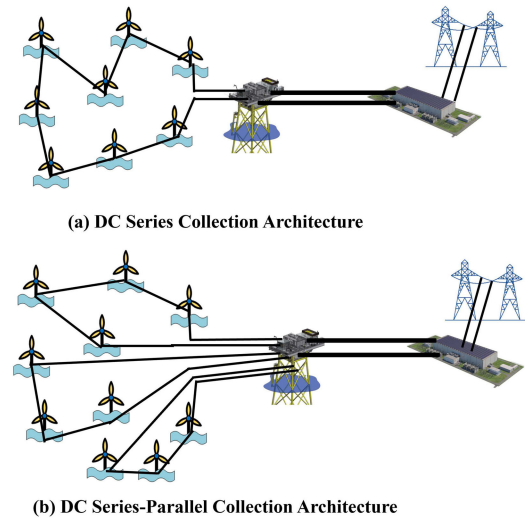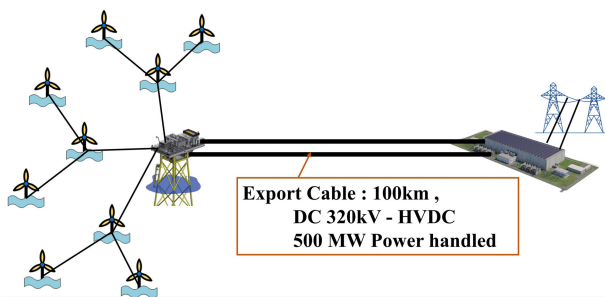

FIGURE 18. DC series collection architecture techno-economic analysis.

current-carrying capacity. This capacity is influenced by the total power transmission needs and the voltage rating of the wind turbine's grid-side converter. Within the selected architecture, the configuration and number of wind turbines in a string define each string's total power transmission capacity. It is also essential to incorporate a safety margin for the cable's current-carrying capacity to accommodate potential fault currents. Three distinct AC cable types and six DC cable types have been selected for a streamlined comparison of the different architectures, as presented in Table 11. These cable types are utilized across both collection and transmission architectures [30]. Copper serves as the conductor material in the cores of subsea cables, and consequently the cable resistance per kilometer is determined based on the resistivity of copper (standard resistivities of 1.68×10^{-8} Ω m at 20 °C) [157].

Table 12 presents a comprehensive analysis of inter-array cable lengths, transmission losses, and reliability for different collection architectures. This includes details on power, current, and cable costs, providing an evaluation of the
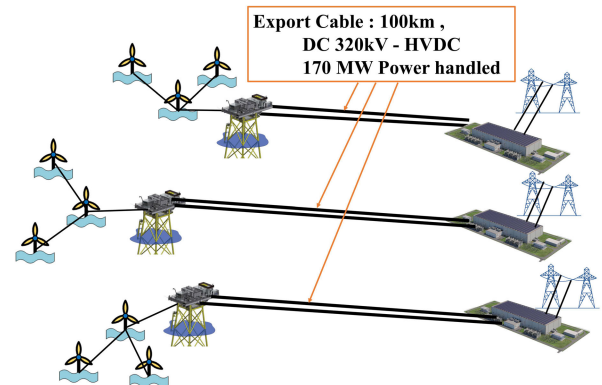
TABLE 12. Cost of cable for ac collection architecture.

Architecture	Total Estimated Inter-Array Cable Length (km)	Cable Used	Total Power per String (MW)	Cable Cost (k$ / km)	Calculated Cable Cost (M$)	Calculated Power Loss (MW)	Reliability
Radial	50	Low	50	1070	53.5	1.38	*
	50	Medium	50	1926	96.3	1.41	*
	50	High	50	2208	110.4	1.49	*
Ring	55	Low	100	1070	58.9	1.52	***
	55	Medium	100	1926	105.9	1.56	***
	55	High	100	2208	121.44	1.64	***
Branched	50	Low	50	1070	53.5	1.38	**
	50	Medium	50	1926	96.3	1.42	**
	50	High	50	2208	110.4	1.49	**
Star	100	Low	10	1070	107	2.76	**
	100	Medium	10	1926	192.6	2.82	**
	100	High	10	2208	220.8	2.98	**
Mesh	120	Low	50	1070	128.4	3.32	****
	120	Medium	50	1926	231.1	3.41	****
	120	High	50	2208	128.4	3.58	****

FIGURE 19. Single point transmission architecture.

FIGURE 20. Multi-terminal grid design point to point transmission architecture.

infrastructure and financial requirements for each architecture. The total length of each architecture is estimated by considering its complexity and redundancy, providing insights into how various architectural choices influence the overall cost.

The radial architecture connects wind turbines in series, with 10 strings of 5 turbines each, resulting in a total cable length of approximately 50 km and transmitting 50 MW of power per string. The ring architecture enhances connectivity by combining two radial strings with an additional 1 km cable, forming a ring with a total cable length of 55 km and transmitting 100 MW of power per ring. The branched architecture consists of 10 branches, each 5 km long, with 5 turbines per branch, totaling 50 km of cable and transmitting 50 MW of power per branch. In the star architecture, each turbine is directly connected to a central substation, averaging 2 km of cable per turbine, with a total

cable length of 100 km and supporting 10 MW of power per turbine for reliable transmission. The mesh architecture interconnects each turbine to two or three neighbors, forming a network with an estimated total cable length of 120 km, capable of transmitting 50 MW of power while offering enhanced redundancy and reliability.

The analysis reveals that mesh architecture offers the highest reliability due to multiple power dispatch pathways, albeit at a higher cost. In contrast, ring architecture provides a balanced option with two dispatch pathways, ensuring reliability and cost efficiency. An additional analysis of the DC series, DC series-parallel (Fig. 18), and DC parallel architectures (comparable to the radial configuration shown in Fig. 17(a)) is conducted and summarized in Table 13.

TABLE 13. Cost of cable for DC series, parallel, and series-parallel collection architecture.

Architecture	Estimated Cable Length (km)	Cable Used	Cable Cost k$ per km	Calculated Cable Cost (M$)	Calculated Power Loss (MW)	Reliability
Series	55	1	936	51.48	1.455	*
Parallel	120	1	936	112.32	3.17	***
Series-Parallel	65	1	936	60.84	1.72	**

TABLE 14. Cost of cable for dc transmission architecture.

Architecture	Estimated Cable Length (km)	Cable Used	Sets	Cable Cost (k$ per km)	Calculated Cable Cost (M$)	Calculated Power Loss (kW)	Reliability
Single Point to Point	100	1	3	936	280.8	7,941	*
	100	2	2	1,183	236.6	5,648	*
	100	3	2	1,136	227.2	5,294	*
	100	4	1	1,614	161.4	3,093	*
	100	5	2	1,130	226.0	5,036	*
	100	6	1	1,755	175.5	3,092	*
Multi-Terminal Point to Point	300	1	1	936	280.8	7,941	**
	300	2	1	1,183	354.9	8,472	**
	300	3	1	1,136	340.8	7,941	**
	300	4	1	1,614	484.2	9,278	**
	300	5	1	1,130	339.0	7,554	**
	300	6	1	1,755	526.5	9,276	**
Multi-Terminal Radial	203	1	3	936	570.0	16,119	***
	203	2	2	1,183	480.3	11,466	***
	203	3	2	1,136	461.2	10,746	***
	203	4	1	1,614	327.6	6,278	***
	203	5	2	1,130	458.8	10,223	***
	203	6	1	1,755	356.3	6,277	***
Multi-Terminal Mesh	206	1	3	936	578.4	16,358	****
	206	2	2	1,183	487.4	11,635	****
	206	3	2	1,136	468.0	10,905	****
	206	4	1	1,614	332.5	6,370	****
	206	5	2	1,130	465.6	10,374	****
	206	6	1	1,755	361.5	6,369	****

The results indicate that the parallel architecture offers better reliability due to its inherent redundancy; however, this advantage comes at the cost of increased expenses and higher power losses.

A similar analysis is conducted for transmission architectures, including single point-to-point, multi-terminal point-to-point, multi-terminal radial, and multi-terminal mesh configurations, as illustrated in Fig. 19, Fig. 20, Fig. 21, and Fig. 22. DC export cables, selected based on their power and current-carrying capacity from Table 11, are analyzed in Table 14. This detailed techno-economic analysis compares six export cables for each transmission architecture,

concluding that the multi-terminal mesh architecture provides the highest reliability, though at a slightly higher cost, while the multi-terminal radial architecture offers better reliability at a favorable cost.

IV. POWER CONVERTER TOPOLOGIES

Power electronic converters play a pivotal role in converting power from one electrical form to another, maintaining the stability and quality of power, and ensuring grid compatibility. The technology used for these converters determines the overall efficiency, the response time to grid disturbances, and the performance of the system, making the selection of
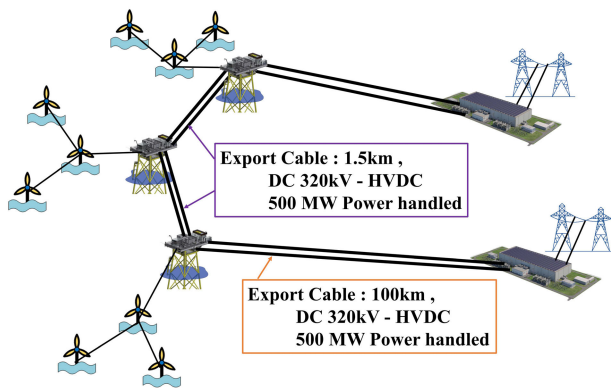
FIGURE 21. Multi-terminal grid design radial transmission architecture.
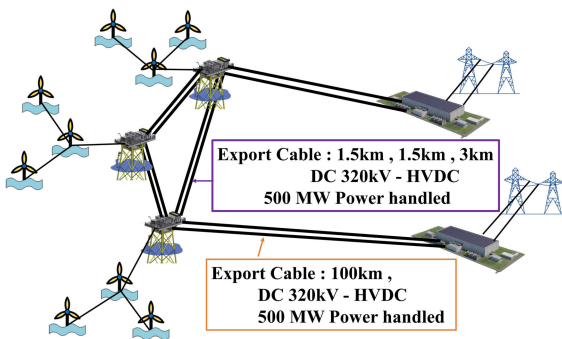

FIGURE 22. Multi-terminal grid design meshed transmission architecture.

converter technology a significant step in the design of the HVDC transmission system [13]. Each converter technology provides unique characteristics and suitability for specific applications [17], [158].

Criteria for selection depend on various factors such as collection architectures, transmission distance, capacity requirements, grid conditions, and cost considerations. The grid side converter is always DC/AC, but based on the output from the wind turbine (AC or DC), the wind turbine side converter can either be AC/DC or DC/DC [94], [159], [160]. Fig. 23 shows the classification of the power electronic converter used for collection and transmission architectures for HVDC applications in OWFs.

A. AC/DC CONVERTERS

AC/DC converters can be categorized based on the type of switches used into (i) Diode Rectifiers (DRs), (ii) Line-Commutated Converters (LCCs),(iii) Voltage Source Converters (VSCs), and (iv) Hybrid Converters.

DRs have applications in low (<1 kV) to medium Voltage (33-66 kV) systems collection and transmission, but they are generally not the preferred choice for HVDC transmission systems associated with OWFs [161]. Due to the variable nature of wind power, the uncontrolled operation of DRs makes them unsuitable for such applications. Furthermore, DRs lack the ability to provide reactive power support, which

is essential for maintaining voltage stability and ensuring grid compliance. Furthermore, they introduce significant harmonic distortions into the electrical system [33].

LCC technology is a well-established solution for HVDC transmission, offering exceptional performance in long-distance, high-capacity power transfer and robust handling of short circuits [162], [163], [164]. However, it faces notable challenges, particularly in reactive power control. LCC requires external compensation devices, such as STATCOMs, due to limitations imposed by the inverter's extinction angle [165]. Compared to the flexible, reactive power control of VSCs, the adaptability of LCC is limited [33], [162], [166], [167].

Furthermore, LCC-HVDC systems are not suitable for weak grids with SCR < 2 due to stability concerns and reliance on strong AC systems for commutation [168]. It is also sensitive to grid disturbances and generates significant harmonic distortions, necessitating complex filtering solutions. Additionally, LCC lacks bidirectional power flow flexibility and is hindered by its large size and weight, making it impractical for OWFs, where space optimization is critical [160], [169]. These limitations highlight the need to carefully evaluate LCC's strengths and weaknesses when considering its application across diverse scenarios.

To overcome the challenges posed by LCC technology, the industry is increasingly shifting toward more advanced solutions such as VSCs, which utilize fully controllable transistors such as IGBTs [163]. VSCs offer bidirectional power flow control, enhance voltage stability through reactive power management, and provide black start capability, making them reliable for HVDC applications [170], [171]. However, the adoption of VSCs has been relatively slow, in part due to the need for additional filters to manage the high voltage (dv/dt) and current (di/dt) slew-rates, which increases costs and complexity [163], [172]. To improve market penetration, VSC systems must address challenges such as switching losses and harmonic distortion [33], [166]. Nonetheless, their adaptability positions them well for future integration into OWFs [162], [173].

The VSCs are classified as (i) Two-level, (ii) Three-level, and (iii) N-level (Multilevel), based on output voltage levels. Two-level VSCs switch between positive and negative DC voltage, making them simple and cost-effective for low voltage collection architectures but limited in HVDC transmission applications. Three-level VSCs like Neutral Point Clamped (NPC) and Active Neutral Point Clamped (ANPC) add a zero voltage level, offering lower harmonic distortion and better efficiency for medium voltage high-power systems [183]. N-level (Multilevel) VSCs, like Cascaded-H Bridge and Modular Multilevel Converter (MMC), generate multiple voltage levels, reducing harmonics and improving efficiency in high-voltage applications. MMCs are favored in offshore wind HVDC transmission systems for their higher efficiency, better control, superior harmonic performance, scalability, and better fault tolerance and reliability in high-voltage settings [184], [185], [186].
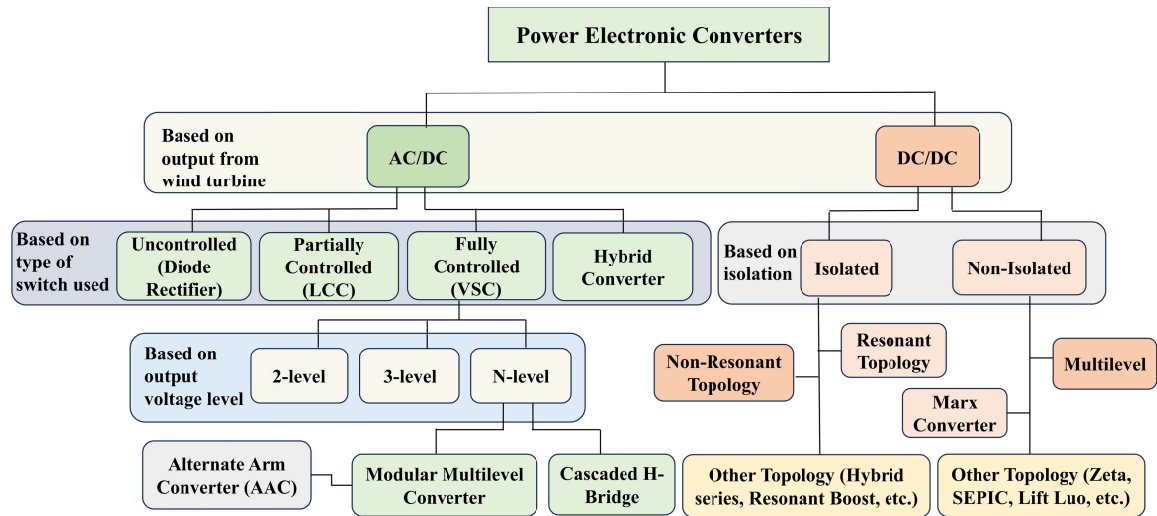
FIGURE 23. Classification of power electronic converters in HVDC in OWF.

TABLE 15. Comparative analysis of AC/DC converters for OSW HVDC.

Converter Type	Line Commuted Converter	Voltage Source Converter	Modular Multilevel Converter	Alternate Arm Modular Converter
Losses	Low switching losses [162]	High switching losses [162, 174]	<1% semiconductor losses [175]	Lower than MMC and VSC [176]
Commutation	External commutation [162]	Self-commutated	Self-commutated	Self-commutated
Reactive Power Compensation	Limited [165, 166]	Flexible [162]	Flexible modes [177]	Offers compensation, enhancing stability [176]
DC - Fault Tolerance	Withstands short circuits [163]	Vulnerable to line faults [163, 178]	Half-bridge SMs lack fault handling [176]	Strong fault tolerance [179, 180]
Power Flow Direction	DC polarity inversion [162]	Bidirectional control [174]	Bidirectional [177, 180]	Bidirectional [180]
Suitability for OSW	Suitable for long-distance transmission [162]	Suitable for both medium voltage DC collection and HVDC transmission [162, 163]	Most suitable for HVDC transmission [181]	Potential alternative for HVDC transmission; still in development [176]
EMI Challenges	Minimal [163]	Requires additional filters [163]	Continuous arm reduces EMI [182]	Lower dv/dt; superior EMI performance [180]
Footprint & Weight	Large volume and high weight [162]	Smaller footprints [28]	Reduced footprint due to modular structure [182]	Smaller footprint and reduced weight [176]

MMC is a promising technology for HVDC transmission, particularly in integrating OWFs [13]. Its modular design enables high voltage levels and low switching frequencies, reducing harmonics and electromagnetic interference (EMI) [175]. MMC independently controls active and reactive power, improving grid stability [187], [188]. Modular redundancy bolsters fault tolerance, ensuring reliability in demanding HVDC conditions [189]. Furthermore, MMC supports bidirectional power flow, which makes it ideal for dynamic energy systems [181]. Although still in development, ongoing research on MMCs continues to focus on enhancing their reliability [175], [181], [190], [191].

Conventional MMC structures are modified for various HVDC applications, including transmission, multi-terminal systems, and tapping applications, among other HVDC uses [192]. The Alternate Arm Modular Converter (AAC), a variation of MMC topology, stands out for its excellent fault-tolerant features [179]. With high reactive power compensation and lower di/dt, AAC ensures superior EMI performance [180]. Additionally, the compact design and

the reduced footprint further increase its suitability for space-limited projects [176]. Although less widely deployed than LCC and VSC, the reliability of AAC in DC fault scenarios positions it as a valuable option in specific HVDC applications [176], [179].

Expanding on this, hybrid converters offer an inventive solution for HVDC transmission in offshore wind applications by integrating the advantages of both VSC and LCC [33], [193]. This hybrid strategy aims to combine the flexibility, control accuracy, and grid-supporting characteristics of VSCs with the high power capacity and efficiency of LCCs. Although the VSC component of the hybrid system can lessen the need for significant filtering and reactive power correction, which are normally associated with LCC systems, the LCC component of the system ensures effective power transmission over long distances, a common requirement for OWFs. Moreover, hybrid converters are more suitable for various offshore locations since they may be customized to maximize performance under certain grid conditions [194], [195]. However, because these sophisticated systems integrate and operate two distinct converter technologies, it is critical to understand the added complexity and potential financial consequences of these setups. Table 15 provides a comprehensive comparative analysis of power electronic converters used in OWPPs connected to HVDC, highlighting key factors such as losses, fault tolerance, power flow capability, and overall suitability.

B. DC/DC CONVERTERS

DC/DC converters play a pivotal role in OWFs by enabling efficient voltage regulation, power flow control, and fault management within DC collection and transmission systems. For the DC collection system, DC/DC converters are required to step up the relatively low voltage from the wind generator's rectifier to a higher voltage suitable for transmission to shore. Additionally, they are vital for future meshed HVDC grids, enabling efficient cross-national sharing of renewable resources and supporting the transition to a low-carbon future. Thus, highly efficient and lightweight high-voltage, high-power DC/DC converters are core components for integrating wind farms into HVDC systems. DC/DC converter topologies can be classified into two types: Isolated and Non-Isolated [196], as shown in Fig. 23.

Fig. 24 gives a glimpse of some of the basic and advanced DC-DC converter topologies which are found in literature [25], [197], [198], [199], [200], [201], [202], [203], [204]. Each of the mentioned topologies further has several variants to enhance the performance of the converter further.

In [25], it is noted that the Full Bridge (FB) converter has average performance due to hard switching, resulting in higher switching losses and necessitating the use of a (lossy) snubber to reduce di/dt during switch-on. The Phase Shift Full Bridge converter exhibits low losses and minimal component stress, but may lose its soft-switching capability under light load conditions, necessitating careful control

system design. The Series Load Resonant (SLR) converter also performs well, but its variable operating frequency can limit the transformer design. On the other hand, the Parallel Load Resonant (PLR) converter performs poorly under part load conditions, making it unsuitable for wind power applications. The Dual Active Bridge (DAB) converter requires a significant number of switching devices, adding complexity and cost to the system. While requiring no transformer, the Thyristor-based Resonant converter boasts comparable efficiency to other topologies. However, it suffers from high peak component stresses and the need for a large AC capacitor bank. In [197], an improved DAB submodule topology is proposed. To prevent rapid discharge of the secondary side capacitor caused by a short circuit, a power electronic switch is connected in series to the secondary side capacitor. The switch is turned off after detecting overcurrent to prevent capacitor discharge.

In [198], a High Ratio DC/DC Converter (HRDC) is proposed, featuring Half-Bridge Submodules (HBSMs), diodes, and thyristors. This design offers high device utilization, efficiency, and cost-effectiveness compared to the Front-to-Front MMC DC/DC (FTF) converter [198], which comprises two MMCs and an internal Full-Power AC transformer. The FTF converter exhibits low submodule utilization, high power loss, and a bulky AC transformer. Additionally, [198] introduces a transformerless Modular Multilevel DC/DC (MMDC) converter composed of a single MMC. However, it suffers from high-amplitude voltage and current waveforms, resulting in high power loss and the need for bulky filters. Reference [198] also presents the Modular Hybrid DC/DC (MHDC) converter, which reduces the number of IGBTs in FBSMs. Furthermore, it proposes the Auto-Transformer DC/DC (AT) converter, which offers higher submodule utilization than the FTF converter due to partial power features. However, this advantage diminishes with a large voltage ratio. The AC transformer in the AT converter bears a substantial DC voltage bias, increasing insulation costs.

Reference [199] provides a comprehensive review of DC/DC converter topologies, encompassing both Isolated and Non-Isolated types. It also proposes a bidirectional Marx converter topology for OWF applications. It employs the Half Bridge (HB) converter for low currents and the FB converter for higher currents. DAB technology facilitates bidirectional power transfer, a capability that is absent in HB and FB configurations. Using a high-frequency transformer reduces transformer weight and soft switching minimizes switching losses, resulting in efficiencies of the order of 95%. However, challenges in multilevel power conversion include the increased required semiconductor switches and complex control to maintain capacitor voltage balance. The Switched Capacitor converter operates by charging and discharging module capacitors in a specific sequence. These topologies switch at high frequencies, but the literature needs to indicate whether switching at low frequencies is feasible.
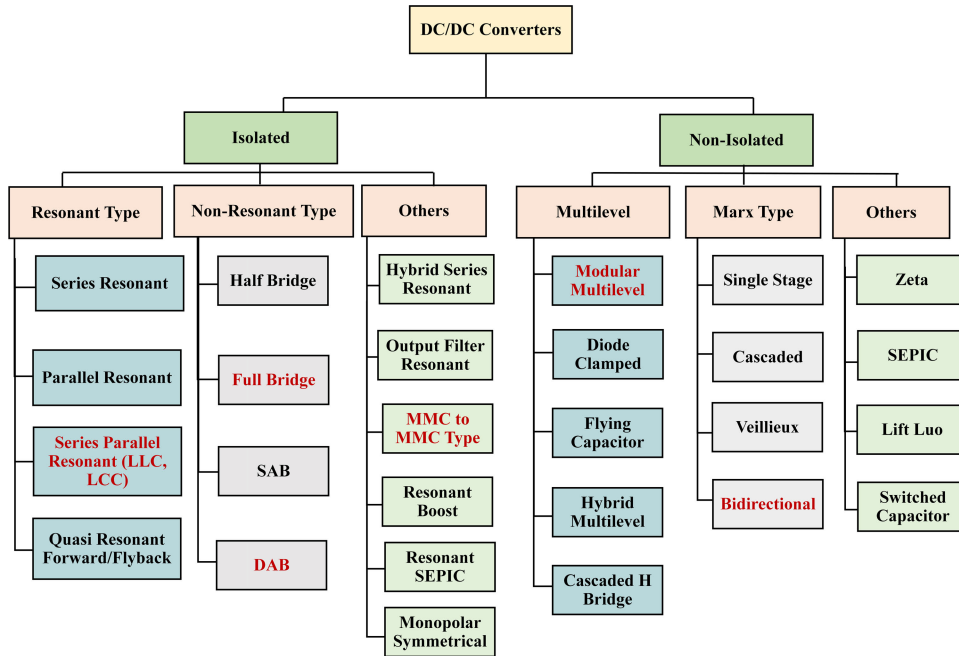
FIGURE 24. DC/DC converter topologies.

Based on the above analysis, some potential candidate topologies for the OWF application are highlighted in red in Fig. 24. The adoption and commercialization will require prototyping and in-depth analysis of converter operation for OWF application, which is beyond the scope of this current study.

C. ECONOMIC CONSIDERATIONS

The offshore substation and platform are major contributing factors to the higher costs of HVDC systems for offshore wind. The need for offshore conversion between current types also contributes heavily to the reliability deficit of HVDC systems. As such, significant work has been done to examine the potential for fully DC systems and DC/DC converters to remove the offshore substation and reduce costs while improving reliability. The early literature in this area considered how power collection systems contributed to the cost of HVDC and postulated that DC/DC systems might reduce costs [205], [206].

Reference [9] furthers the conversation by considering the conditions required for All-DC wind farms to be cost-competitive for MDVC and HVDC. LCOE and sensitivity analysis are performed with findings that converter costs for a DC/DC converter must be 90% lower than a comparable MMC to be economical with 25% reductions in the cost of the DC platform for HVDC compared to only 30% in the DC platform for MVDC. The paper finds that these cost gains can be achieved in the case of MVDC through a 50% reduction in the cost of cable installations. Similarly, [29], [207] perform complete reliability assessments of DC collection systems

and find that a radial topology with a single-plate DC / DC converter is more economical and reliable than alternatives.

Reference [34] reviews various architectures, including fully DC/DC systems, and provides insight into the main challenges in moving toward fully integrated DC collection. Chief among the challenges is the state-of-the-art technology with the need for advanced novel semiconductor devices for robust power conversion, fault tolerance, and grid connection. DC grid collection architectures have the potential to reduce LCOE and address significant challenges for HVDC systems.

Future research should continue to pursue the economic component of All-DC grids for OWF, focusing on evaluating how costs can be brought down while bringing reliability up. Of particular interest is how these grids could be used in synergizing offshore wind and marine energy farms to further reduce the effects of fixed costs [78], [208]. Additionally, improved loss and fault monitoring technologies may improve performance [209].

V. MODELING TECHNIQUE

This section focuses on the challenges associated with the electrical modeling of large-scale OWFs, particularly in capturing complex dynamic and transient behaviors [210]. As VSC-HVDC-connected OWFs become integral to future power systems, their impact on power system dynamics, especially during transient stability scenarios, becomes increasingly significant.

However, this integration introduces complexities in simulation studies due to overlapping dynamic behaviors and uncertainties in selecting suitable modeling techniques,
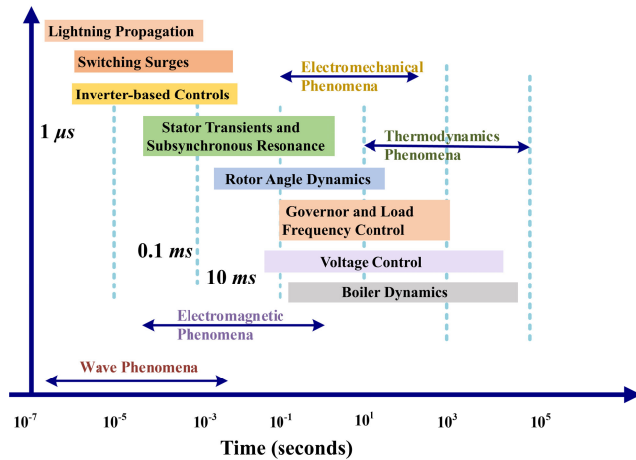
FIGURE 25. Time scales of power system dynamic phenomena [218].

necessitating innovative approaches for more accurate and reliable analyses (Fig. 25) [211], [212].

Modeling wind turbine generation is also beneficial for understanding how to minimize the costs of the wind farm and how the wind farm can contribute to frequency regulation, inertia, and control. Successful bidding into the ancillary services market proves challenging without sufficient impedance and voltage control modeling, and OWF operators decrease their ability to access a valuable potential revenue stream.

Several incidents, including low-frequency oscillations in Texas and China [213], the OWF disruption in England on August 9, 2019, [214], the cascaded trips power outages in South Australia in 2016 and 2018 [215], and the BowWin1 OWF commissioning issue [216] underscore the critical importance of developing advanced modeling techniques for wind farms to ensure grid stability. These events highlight the complexities and vulnerabilities inherent in power networks, necessitating accurate models to effectively anticipate and mitigate instability issues.

Given the dynamic nature of wind energy generation and its interaction with the grid, innovative modeling tools are essential for capturing phenomena such as low-frequency oscillations and harmonic interactions, which may otherwise go undetected, leading to significant operational delays and disruptions [217]. Failure to detect such phenomena during the modeling phase, as seen in the BowWin1 incident, can lead to significant operational setbacks and disruptions.

Therefore, continuous advancements in modeling methodologies are imperative to improve the resilience and dependability of power systems amid the shifting landscape of power converter-based renewable energy integration. Current research is dedicated to developing simulation techniques that strike a balance between accuracy and computational efficiency, with a specific emphasis on effectively controlling and stabilizing power systems experiencing high levels of converter-interfaced generation (CIG) and HVDC penetration, and the consequent reduction in grid inertia.

A. CHALLENGES IN OWF MODELING

OWFs present a unique set of challenges for modeling due to complex environmental conditions and intricate interaction with the grid [219], [220], [221]. OWF modeling faces challenges in capturing complex environmental conditions, integrating with the power grid, predicting energy output, and simulating large-scale wind farm dynamics. One primary challenge is accurately capturing the dynamic behavior of offshore wind turbines and their response to varying wind and ocean conditions. Offshore environments are characterized by high wind speeds, turbulent conditions, and significant wave interactions, which can impact turbine performance and structural integrity [210], [222]. Furthermore, the distance from shore introduces logistical challenges for data collection and monitoring, necessitating sophisticated remote sensing techniques for model validation [223].

Another critical challenge is the integration of OWFs into the main power grid while ensuring stability and reliability. OWFs often operate in close proximity to coastal regions with constrained grid infrastructure, which poses challenges for grid connection and power transmission. Modeling the interaction between OWFs and onshore grid systems requires an accurate representation of power electronics, grid dynamics, and control strategies to prevent instability and grid disturbances [125], [224].

In addition, the variability and intermittency of wind resources present challenges for predicting power output and optimizing energy generation [225]. Offshore wind conditions vary over time, ranging from seconds to seasons, making it challenging to forecast energy production and plan for grid integration accurately. Advanced stochastic modeling techniques and ensemble forecasting methods are needed to account for the inherent uncertainty in wind resources and improve the accuracy of energy yield predictions [226], [227], [228].

Moreover, the increasing scale and complexity of offshore wind projects introduce challenges for modeling and simulation [229]. Large-scale OWFs with hundreds of turbines require computationally intensive modeling approaches to simulate the interactions between individual turbines, wake effects, and overall farm performance [230]. High-fidelity simulation tools, coupled with parallel computing techniques, are essential to capture the spatial and temporal dynamics of OWFs accurately [231], [232]. Addressing these challenges requires interdisciplinary research efforts and the development of advanced modeling techniques tailored to the unique characteristics of OWE systems.

B. CAPTURING DYNAMICS AND EFFICIENCY TRADE-OFFS

Modeling wind turbine generation systems involves addressing complex challenges due to the dynamic nature of modern power systems. Accurate models are essential for representing transient events and high-frequency phenomena associated with power electronics, which are crucial to maintaining system stability and reliability [81]. However,
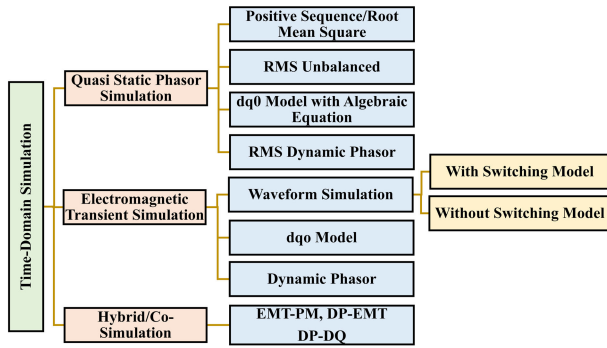
FIGURE 26. Classification of time domain simulation methods.

FIGURE 27. Classification of frequency domain simulation methods.

capturing these intricate dynamics introduces computational challenges, requiring advanced modeling techniques to accurately reflect fast-changing behaviors without overwhelming computational resources [233].

These systems evolve rapidly, demanding simulations that can keep up with real-time changes while still providing meaningful results [234]. Ensuring computational efficiency is therefore critical to managing this complexity without compromising the accuracy required for reliable system operation. An additional challenge lies in selecting the appropriate level of model detail [235]. The optimal level of abstraction depends on factors such as the specific phenomena under study, simulation time constraints, and the system's overall complexity. Although more detailed models can offer greater accuracy, they also increase computational demands. Striking the right balance between model precision and efficiency ensures that simulations remain practical, enabling insightful analysis while avoiding unnecessary computational overhead [15].

C. ANALYTICAL APPROACHES: TIME-DOMAIN AND FREQUENCY-DOMAIN ANALYSIS

Modeling of OWF requires a comprehensive analytical approach that incorporates both time-domain and frequency-domain analysis to accurately represent dynamic behaviors, grid interactions, and energy conversion processes in varying operating conditions. Reference [35] provides a comparative analysis of time domain and frequency domain modeling techniques and their applications in stability analysis of HVDC OWFs.

Time-domain analysis is preferred for assessing component interactions and system stability, yet increasing complexity from power-electronic integration poses challenges. Frequency domain impedance modeling offers advantages such as wideband oscillation study, closed-box device modeling, combined impedance analysis, and multi-frequency instability study.

Table 16 gives a brief literature survey of various modeling techniques used for HVDC OWFs along with examples of models used in the economic domain. Reference [233]
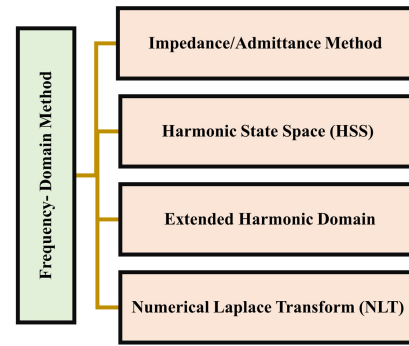
compares modeling accuracy and computational performance of modeling in multiple combinations of MMC and OWF models, including the Detailed Model (DM), Detailed Equivalent Circuit Model (DECM), Equivalent Switching Function Model (ESFM), and Average Value Model (AVM) and their limitations. Reference [236] introduces a comprehensive RMS modeling framework for dynamic studies of Doubly Fed Induction Generator (DFIG)-based wind farms in multi-terminal VSC-HVDC grids, offering high fidelity and faster simulations than EMT solutions.

Reference [237] develops an offshore AC side impedance model for MMC-HVDC wind power integration, considering the effects of offshore / offshore stations and DC cables, to analyze the AC-DC system coupling and the impact of the DC system and controller on offshore AC impedance, overcoming deficiencies in harmonic resonance analysis. Reference [238] develops the impedance model and stability analysis for All-DC offshore Permanent Magnet Synchronous Generator (PMSG) wind farms, with simulations validating the model's effectiveness by reproducing time-domain oscillations. Reference [239] investigates the stability of DR-HVDC connected OWFs by developing and validating an impedance model in the dq frame and analyzes the impacts of the DC smoothing reactor and AC filter sizes of the DR-HVDC on system stability using PSCAD/EMTDC simulations. Fig. 26 and Fig. 27 provide a systematic categorization of modeling techniques in both the time and frequency domains applied in simulation studies of systems.

The accuracy of the model depends heavily on the level of detail incorporated into the representation. To ensure precision, non-linearities within the system are addressed through linearization techniques. This approach helps manage the complexities inherent in modeling, but it also highlights that the accuracy of stability predictions is intrinsically linked to the overall model accuracy. Therefore, maintaining high fidelity in model details is crucial for reliable stability analysis.

Several research gaps need to be addressed to improve modeling techniques. One significant area is understanding the impact of frequency coupling on system stability. Additionally, effective addressing non-linearities such as

TABLE 16. Examples of HVDC offshore wind farm models.

Topology	Modeling Techniques	Key Points and Outcome	Reference
VSC-HVDC	MMC and OWF modeling DM, DECM, ESFM, AVM Time Domain Models	− Accuracy vs. computational efficiency for MMC and OWF models. − AVM (OWF) + DECM (MMC) boosts speed with minimal accuracy loss.	[233]
	Time Domain Modeling	− A comprehensive techno-economic comparison of MT-HVDC OWFs. − A semidefinite programming model for optimal economic operation in MT-HVDC systems.	[82, 240]
	RMS modeling	− Introduction of RMS model for MTAC/DC grids for VSC-DFIG WFs. − Flexible and numerically efficient.	[236]
	AC Side Impedance modeling	− AC side impedance model for MMC-HVDC wind integration. − Analysis with different DC system configurations. − Influence of dual closed-loop control indicated.	[237]
All-DC	Impedance modeling	− Harmonic linearization for impedance modeling of All-DC WF with PMSG and LCC-inverter. − Verification through simulation and oscillation analysis.	[238]
DR-HVDC	Impedance Model of Connected OWF	− Investigates DR-HVDC connected OWF stability. − Impedance model in dq frame developed, validated vs. EMT simulations. − DR-HVDC's DC smoothing reactor and AC filter sizes impact system stability.	[239]

PWM and limiters remains a challenge. There is also a need to develop independent models that can adapt to changing conditions within the system. Furthermore, analyzing the interactions between sources and loads and the complexities of impedance networks presents ongoing challenges that require innovative solutions.

D. RESEARCH GAPS AND AREAS FOR EXPLORATION

Electrical modeling is a foundational aspect of designing and operating large-scale HVDC OWFs. Although significant progress has been made in the development of various modeling techniques, ongoing research is essential to address existing gaps and explore new areas of innovation. By advancing electrical modeling techniques, we can ensure offshore wind power's efficient and reliable integration into the global energy grid, contributing to a sustainable energy future. Addressing these challenges reveals several research gaps and areas demanding further exploration in wind turbine generation modeling:

Novel Modeling Methods: Advanced techniques, such as Digital Twin models [241], data-driven modeling [242], and multi-scale modeling [243]; enable real-time monitoring and predictive analysis [244]. These models enhance system performance by providing detailed insights into both component-level behavior and overall system dynamics,

facilitating proactive decision-making and optimization. As the complexity of wind power systems continues to increase, combining these advanced techniques with existing methods will enable more efficient, reliable, and scalable integration of OWE into the global grid.

Efficient Representation of Fast Dynamics: Capturing the rapid dynamics of power electronics remains a challenge due to the high computational demand of such simulations. Advanced techniques such as reduced-order models can help simplify the representation of high-frequency switching without sacrificing accuracy [245]. Such models enable grid operators to simulate fault scenarios quickly and develop appropriate control strategies to ensure system stability.

Co-simulation Techniques: Co-simulation offers a powerful method to integrate different models to capture various aspects of OWF operations [246]. By combining phasor-based grid models with detailed models of converter-interfaced devices, researchers can study interactions between the grid and converters under complex scenarios [247]. This holistic approach is crucial for identifying potential risks and designing robust control schemes for hybrid AC/DC systems.

Full Phasor Model (PM) for CIG Integration: Implementing full PM for studies involving CIG enables a more comprehensive analysis of system stability, protection, and

control [248]. Full PM models offer a valuable framework for designing control strategies, ensuring reliable fault ride-through capabilities, and maintaining grid stability by accurately representing the voltage and current phasors over time.

Integrated Economic Stochastic Optimal Control:

HVDC OWF poses a unique opportunity for economic models of stochastic optimal control and operational bidding behaviors to start [249], [250], [251]. HVDC architectures can potentially provide more parameters for OWF operators, including control over line losses, faster interaction with the grid, and potential for black start capability [252]. As such, work should be done to advance the stochastic optimal control literature to optimize both economic and engineering parameters.

This requires significant advancement in dynamic models that consider large state spaces and choice sets to optimize bidding in both financial and physical markets with power and ancillary services markets. The problem of simultaneously bidding in the day-ahead, inter-day, real-time, and ancillary services markets proves particularly difficult under these, particularly when OWF is colocated with Energy Storage System [253], [254]. Recent developments in reinforcement learning algorithms may have potential in this domain [255].

VI. ONGOING RESEARCH AND FUTURE SCOPE

As offshore wind approaches technological maturity and market saturation, research continues to explore its role in the future energy grid. Four key factors—connection topology, converter design, technical modeling, and economic considerations—are essential in shaping decisions regarding offshore wind adoption.

Challenges and Key Research Areas

- Grid Architecture
  - Scalability, complexity, reliability, suitability, and cost are crucial in selecting grid configurations. Effective load management techniques are required to address the challenges of integrating offshore systems with existing onshore grids.
- Converter Technologies
  - Although earlier VSC systems are well researched, emerging technologies, such as medium-frequency systems, transformer-embedded HVDC, and series DC grids—show promise but need further exploration.
  - Solid-state transformers in HVDC grids and DC-DC converter prototypes must be investigated to improve cost, reliability, and performance.
- Fault Management and Intelligent Protection
  - Reliable and fast fault detection in HVDC offshore systems remains a significant challenge due to weak fault signatures, measurement noise, and the fast-changing dynamics of converter-based grids. There is a growing need for advanced protection

schemes that are adaptive, noise-resilient, and capable of operating under varying system conditions in real time.

- Modeling and Computational Advances
  - Modeling Techniques: Future research should focus on improving the capabilities of dynamics, accuracy, and co-simulation capabilities by integrating phasor models with CIG systems for better stability and control.
  - Algorithm Design: Computational innovations are required to simulate complex models efficiently and improve overall system operations.
- Economic and Market Integration
  - Holistic Market Integration: Offshore wind engineering decisions affect the broader energy market, influencing long-term costs, revenues, and market equilibrium. Transmission infrastructure impacts investment decisions and market entry/exit dynamics, requiring comprehensive study.
  - Interest Rates and Market Design: As rising interest rates challenge project viability, research into new market models—such as comparing the UK and German funding frameworks—is needed to address these risks.
- Reliability and Social Costs
  - Reliability Trade-offs: Future work should explore the cost-benefit trade-offs between enhanced reliability through technical solutions and the associated economic impacts. Rather than focusing on isolated components, a system-wide approach to reliability is essential.
  - Social Costs: Models must incorporate social costs—an aspect often overlooked—as renewable energy displaces fossil fuels.
- Bridging Technical and Economic Analysis: Future research must integrate technical and economic insights by combining architectural choices with long-term impacts on LCOE, construction timelines, and system costs. This holistic approach will help align technical feasibility with economic sustainability, ensuring offshore wind development remains viable and resilient.

VII. CONCLUSION

This review evaluates HVDC technology integration in OWFs, examining economic considerations, connection topologies, converter designs, and technical modeling to optimize the performance and efficiency of collection and transmission systems. It explores the techno-economic aspects of HVDC OWFs, focusing on collection and transmission costs, system reliability, and architecture. It analyzes both LCOE and LACE, along with breakeven distances between HVDC and HVAC systems based on costs and performance. The study highlights how improving HVDC reliability is essential for economic viability and how engineering advancements can address these challenges. The paper reviews global wind farm installation capacity and assesses various collection

and transmission architectures, paying particular attention to emerging designs such as MTDC grids and All-DC systems, which offer improved scalability, efficiency and reliability with reduced footprint for large OWFs.

Furthermore, the article examines the topologies of the power converters, focusing on the role of AC/DC and DC/DC converters. A comparison between LCC and VSC is presented, along with an exploration of emerging technologies such as MMC and AAMC. While VSCs are recognized as the preferred option for medium-voltage DC collection, MMCs demonstrate significant advantages for offshore wind transmission. Additionally, DC/DC converters offer key benefits in terms of reducing system footprint and optimizing costs, as they enable efficient voltage conversion, eliminate the need for bulky offshore transformers, and enhance integration between DC collection grids and HVDC transmission systems.

Modeling offshore wind systems present significant challenges due to complex environmental conditions and the highly variable output of wind farms. The paper explores analytical methods in both the time and frequency domains to maintain the stability of the grid as the penetration of offshore wind increases. The review concludes by outlining key future research directions, including the need to improve system scalability, reduce architectural complexity, and develop next-generation converter technologies tailored with advanced and real-time fault detection and management techniques for offshore applications. It also emphasizes the importance of interdisciplinary collaboration to ensure that technical advancements align with economic and regulatory realities.

As OWFs expand in scale and are deployed farther from shore, grid operators will increasingly rely on complex HVDC architectures for long-distance transmission. This transition demands a clear understanding of HVDC system capabilities, limitations, and their impact on overall grid stability. By applying the insights presented in this review—spanning techno-economic analysis, system design, and modeling approaches—grid planners and operators can make informed decisions that enhance reliability, reduce costs, and support the safe integration of large-scale offshore wind energy. Ultimately, this article offers a comprehensive foundation for building resilient, efficient, and economically viable HVDC-based offshore power systems.

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