IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Date of publication xxxx 00, 0000, date of current version xxxx 00, 0000.

Digital Object Identifier 10.1109/ACCESS.2024.0429000

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

DEEPI SINGH[1], (Student Member, IEEE), DANA GOLDEN[2], GAURAV BHANSALI[1], (Student Member, IEEE), ALI ANWAR[1], (Student Member, IEEE), SHREEPOOJA SINGH[1], (Student Member, IEEE), FANG LUO[1] (Senior Member, IEEE), and YIYI ZHOU[2]

[1]Department of Electrical and Computer Engineering, Stony Brook University, Stony Brook, NY 11790 USA
[2]Department of Economics, Stony Brook University, Stony Brook, NY 11790 USA

Corresponding author: Deepi Singh (e-mail: deepi.singh@stonybrook.edu).

This material is based upon research supported by the Sunrise Phase-2 project under award number 1181547-1 -92424. This material is also based upon work supported by the National Science Foundation under Award No. 2125295 (NRT-HDR: Detecting and Addressing Bias in Data, Humans, and Institutions). Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

ABSTRACT High Voltage Direct Current (HVDC) technology is a cornerstone of efficient Offshore Wind Farm (OWF) power transmission. This review examines HVDC OWF integration through four 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 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 feasibility on both dimensions. These insights provide a holistic framework for sustainable and economically viable offshore wind energy integration.

INDEX TERMS Offshore Wind energy, HVDC, economic consideration, collection and transmission architectures, power converter design, and 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 a cornerstone of sustainable energy strategies. OWFs are at a critical stage in implementation as a technology. Figure 1, based on 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 Figure 2. Globally, the constructed OWF capacity is expected to surpass 150 gigawatts (GW) by 2027, up 480 % since 2020 [2].

China, the United Kingdom, and the United States have led the world in investment in offshore wind. They have 36 GW and 16 GW of OWF installed capacity, respectively, demonstrating 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 and local wind farms to provide a description of global wind farms as of 2022 that are larger than 500 MW. The characteristics of the farms in terms of substations, number of turbines, architectures, and system type are provided.

However, the successful integration of these offshore wind resources into existing power systems presents a complex challenge, demanding a thorough understanding of both technological and economic aspects [5]. One of the most promi-

TABLE 1: Wind farms over 500 MW in Operation Worldwide.

Project Name	Year	Power Rating	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	132/33kV (Offshore)	22.5 km	3 phase 18/30(36) kV power core	-
Gwynt Y Mor	2015	576	HVAC	160	Two 33kV & 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	220kV 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	230kV alternating current	Star
Guangdong Jieyang Shenquan 2	2023	502	HVAC	50	220 kV offshore booster station	22 km	220 kV export cables and the 66 kV inter-array cables	-
Guangdong Shanwei 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 and 142 km of 35 kV XLPE subsea cables	-
Guangdong Zhanjiang 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	-	-

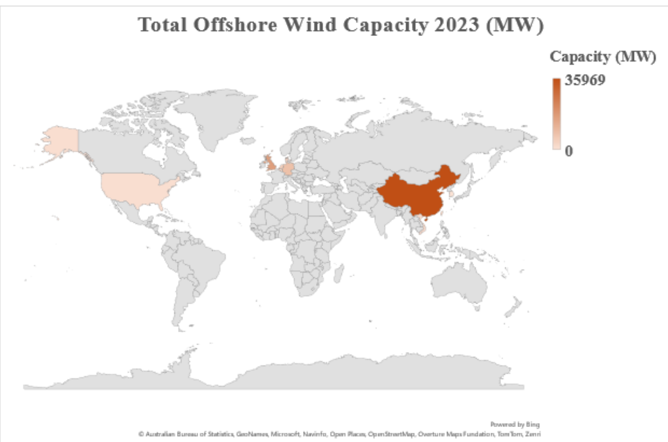


FIGURE 1: Capacity of OWF constructed as of 2023 according to DOE.

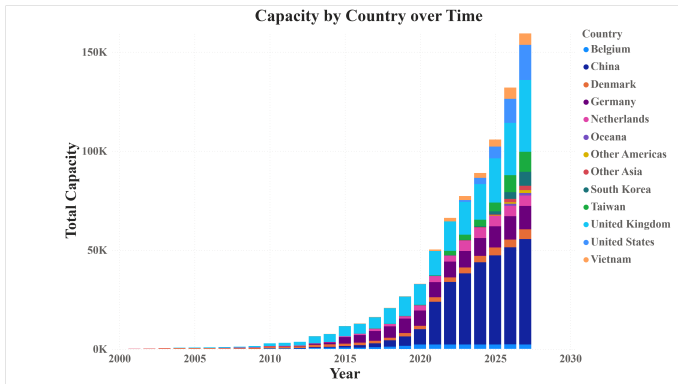


FIGURE 2: Total capacity (MW) of OWF by country by year according to DOE.

nent advancements in this field is the use of High Voltage Direct Current (HVDC) technology, which has the potential to revolutionize how electricity is harnessed and transmitted from wind-rich marine environments to energy-demanding onshore areas [6]. The integration of HVDC technology with OWF marks a significant advancement, offering several advantages over traditional Alternating Current (AC) transmission systems [7]. HVDC's ability to efficiently transmit large amounts of power over long distances makes it a promising solution for delivering reliable and cost-effective energy [8].

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 necessitates a comprehensive understanding of key factors including both technical and economic analysis of system. This review seeks to explore these critical elements in detail, emphasizing their significance within the offshore wind energy sector. The economic viability of HVDC systems for OWFs is a pivotal aspect of feasibility analysis [5]. A comprehensive economic evaluation, including factors such as initial investment, operational expenses, maintenance costs, and lifecycle assessments, is crucial for 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, multi-terminal, All-DC, or hybrid systems significantly influence power transmission efficiency, stability, and loss mitigation [9, 10]. 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 impacting their efficiency, reliability, and adaptability to offshore environments. The selection between Voltage Source Converters (VSCs), Line-Commutated Converters (LCCs), and DC-DC Converters carries substantial economic and technical implications [11, 12]. These converters determine the scalability and flexibility of the system, influencing not only the upfront costs but also operational efficiency and maintenance requirements.

Technical modeling further bridges economic and technical analysis [13, 14]. Accurate simulations, control strategies, and performance models optimize system design and operational reliability while enabling cost-effective planning. These models are essential for predicting dynamic behaviors, minimizing transmission losses, and ensuring seamless grid integration [15]. 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 across these four main dimensions. The table provides a clear overview of the focus areas addressed in the existing literature, highlighting both strengths and gaps.

Recent studies such as [12, 16]–[18] review and compare various power converter architectures used in OWF integration. For instance, [12] discusses converter topologies in HVDC systems for OWFs and provides a detailed analysis of the Modular Multilevel Converter (MMC) and its operational states. Similarly, [16] 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 [17], a comparison of Diode Rectifier Unit (DRU)-based HVDC with other HVDC systems is presented, focusing on control, startup solutions, and fault management, along with future research directions. [18] evaluates multilevel converters (MLCs) in VSC-based HVDC systems, emphasizing their potential to improve efficiency, performance, and reliability for OWF integration.

In another key study, [19] 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. [20] 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, [21]–[24] 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, [25]–[27] provide valuable insights into the economic benefits of different HVDC connection strategies for OWFs, promoting efficient and cost-effective offshore transmission solutions.

In [28], 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 financial perspectives. Additionally, [29] 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. [30] compares 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, [31] 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, [32] comprehensively evaluates various grid connection technologies for large OWFs, considering transmission systems, fault ride-through strategies, and economic feasibility.

Focusing on collection, [33] 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 lacks detailed economic analysis. On the other hand, [34] 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, the paper could benefit from deeper insights into the technical modeling.

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 an in-depth 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 offshore wind energy 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:** It synthesizes the literature on costs, reliability, and discounting, emphasizing integrating economic and technical perspectives to identify gaps and refine the techno-economic analysis.
- **Connection Architectures:** The paper evaluates AC, DC, and emerging configurations, linking their reliability, control, scalability, and cost implications to economic and technical performance.
- **Converter Designs:** It examines diverse converter topologies, such as VSCs, LCCs, and DC-DC converters, assessing their efficiency, reliability, and adaptability for offshore applications.
- **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.

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 offshore wind energy transmission 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. 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 research and the future scope of OWF technologies, while Section VII provides the paper's conclusions, summarizing the key findings and insights.

TABLE 2: Summary of recent review articles

Paper	Converter Design	Connection Topology	Technical Modeling	Economical Analysis
[12]	✓	✗	✗	✗
[16]	✓	✗	✗	✗
[17]	✓	✗	✗	✗
[18]	✓	✗	✗	✗
[19]	✗	✓	✗	✗
[20]	✓	✓	✗	✗
[21]	✗	✗	✗	✓
[22]	✗	✗	✗	✓
[23]	✗	✗	✗	✓
[24]	✗	✗	✗	✓
[25]	✗	✓	✗	✓
[26]	✗	✓	✗	✓
[27]	✗	✓	✗	✓
[28]	✗	✓	✗	✓
[29]	✓	✗	✗	✓
[30]	✗	✓	✗	✓
[31]	✓	✓	✗	✓
[32]	✓	✓	✗	✓
[34]	✓	✓	✓	✗
[33]	✓	✓	✗	✓

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 primarily due to its low line losses and lower cost of lines [21, 35]. The cost differential for one system over the other in OWF depends on the line length, the discount rate utilized, and the cost estimation technique.

The literature traditionally estimates the impacts of costs through discounted payback periods, Levelized Cost of Energy (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 puts the breakeven point around 150 kilometers (93 Miles) [24] for a 300 MW system; however, recent advancements in HVDC converters have brought costs down significantly in the past decade. Because of these changes, estimates of the breakeven point have been halved since 2010 [36].

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 [30]. 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.

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

Figure 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

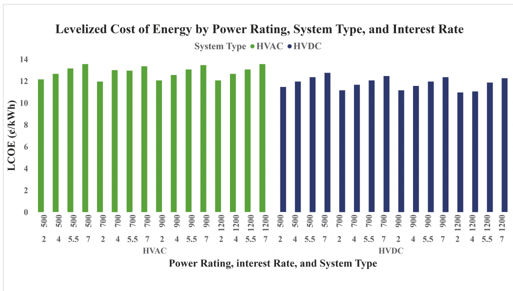


FIGURE 3: LCOE for Different System Types, Power Ratings, and Interest Rates.

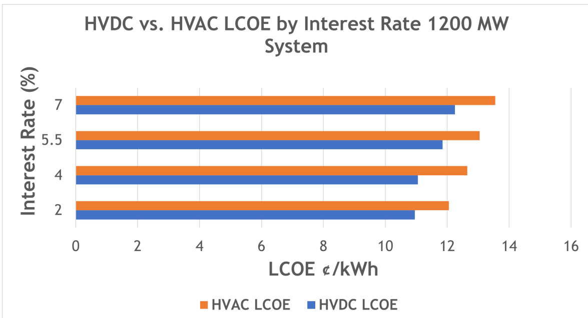


FIGURE 4: LCOE by Interest Rate and System Type for 1200 MW System.

Energy Laboratory (NREL) [37] was used in conjunction with the estimates for system cost from Table 4 based on [29].

The baseline interest rate utilized to create Figure 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's capacity factor was adjusted down 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 time to retirement of 20 years is used. These numbers are highly stylized and thus should be treated as estimates with high variance and more value for comparison across system types than estimation of real-world LCOE.

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

Meanwhile,

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

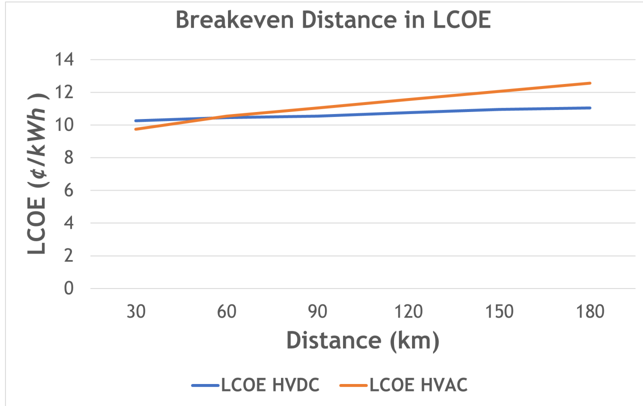


FIGURE 5: LCOE for Different System Types by Interest Rate for 1200 MW System.

value of discounted future revenues as interest rates increase. Rising interest rates also cause a change in the most economical power rating due to 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 increased 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 [38]. When LACE exceeds LCOE, a net surplus exists, and the resource will be net economically viable.

LCOE and LACE differ dramatically geographically, and the National Renewable Energy Lab provides a map of the differences through the State and Local Planning for Energy (SLOPE) [39]. In 2020, the median offshore wind LCOE was 86 dollars per MWh, with the 2024 maximum coming at 126 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 at 5 cents per KWh in Connecticut and the lowest at 1 cent per KWh in Wisconsin. There is still a lengthy distance 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

TABLE 3: Cost of Component by System for Set Size in Million Dollars

System Component	Transmission System HVDC	HVAC
Substation	24-45	10-45
Cable	.6/KM	1.5/KM
Offshore Platform	73.5	24
Onshore Platform	24	24
Cable Installation	215	215
Line Losses % per 1000 KM	.035	.067

TABLE 4: Cost of System in Millions of Dollars by Size and Line Length

Power rating MW	Line Length KM	Transmission System HVDC	HVAC
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

represent various future paths of revenues and costs. While 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 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 literature [21, 22, 24, 29, 40].

Beyond individual components, two other critical technical dimensions related to the cost-effectiveness of the two technologies are size and 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 [29].

[29] considers three costs in a system: the cost of the onshore platform (OPC), the costs of the offshore platform (OPPC), and the cost of the cable C_{Cable}. The cost of the cable varies directly proportionately to the number of sets, line length, and price per kilometer. All cost estimates were taken from the appendix to [29]. These costs differ by line length l and system size S_N as per [29].

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 rises 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.

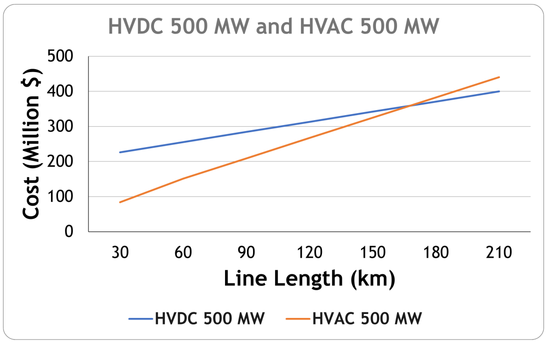


FIGURE 6: Breakeven point for systems of differing ratings without considering life cycle costs.

Figure 6 below shows the breakeven distance using approximate cost data from [29] to plot the breakeven point by system rating and is followed by Figure 7. Figure 7 directly compares the approximated breakeven point by system rating. The breakeven point decreases uniformly because of economies of scale. Variable costs of cables rise substantially faster for HVDC than 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 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

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	[41, 42]
	Cost and Revenue Uncertainty	– Contracts for Differences – Long-term electricity price modeling – Power purchase agreements – Inflation Adjustments	[43]–[45]
Missing Money Problem	Low Revenues for Baseload Generators	– Capacity market redesign – Convex hull pricing	[46]–[48]
	Increased Ramping by Dispatchable Resources	– Improved cold start efficiency – Diversified portfolios (fossil and renewable)	[49]–[51]
	Price Variability	– Demand response – Energy storage systems (ESS) – Long-distance transmission	[52]–[54]
Sustainable Supply Chain	Waste of Wind Turbines	– Turbine recycling – Reduced metal intensity	[55, 56]
	Securing Metals for Turbine Production	– Development of mineral sources – Supply chain transparency	[57, 58]
Intermittency	Non-dispatchability	– Coordination with ESS – Black-start natural gas cooperation – Capacity market redesign	[52, 59, 60]
Concept to Industry	Initial Investments	– Public-private partnerships – Loans via DOE programs – Government contracts (e.g., Executive Order 14057)	[61]–[63]
	Workforce Development	– Education funding – Project pipelines to retain knowledge	[64]–[66]
Political Support	Uncertain Technology Funding	– Long-term funding guarantees – Resilience to leadership changes	[66, 67]

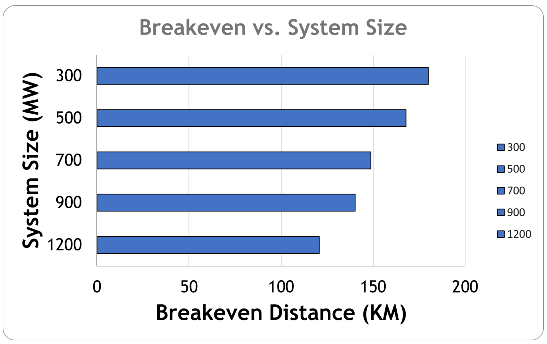


FIGURE 7: Breakeven point with considerations for different power ratings.

nature of the revenue stream and the highly variable cost of infrastructure projects [41]–[45].

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 [46]–[54]. Work towards 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 [57, 58].

The intermittency problem further poses challenges to grid planners, as does the issue of reliability and resilience to outages [52, 59, 60, 68]. Finally, like any technology, offshore wind faces a learning curve as it transitions towards not just technological but commercial maturity. This will require initial support for workforce developments and investments and could be challenged by the uncertainty of political environments related to funding and environmental policy [61]–[67]. Ultimately, all these challenges, though complex, are solvable and demonstrate the significant value of future collaboration between engineering and economic analysis.

B. ECONOMIC CONSIDERATIONS FOR RELIABILITY

Reliability creates another dimension of distinction between technologies. A consensus exists within the literature 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 [28].

Based on literature estimates [16, 28, 32, 33, 69], 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.

TABLE 6: Failure Likelihood by Component

System Component	Reliability Measure		
	P(Failure)	*DT (hrs)*	*DT per Year*
Generator	.01-.1	NA	NA
Transformer	.0108-.03	1440-4320	15.552-1296
AC Breaker	0.0015-0.025	NA	NA
DC Breaker	0.0033-0.025	240	.792-6
AC/DC Converter	.1	NA	NA
DC/DC Converter	.014-.613	NA	NA
Full Power Converter	.05-.2	720	36-144
DC Cables	0.0706	1440	101.67
AC Cables	0.0001-.008/KM	2160	.216-17.28

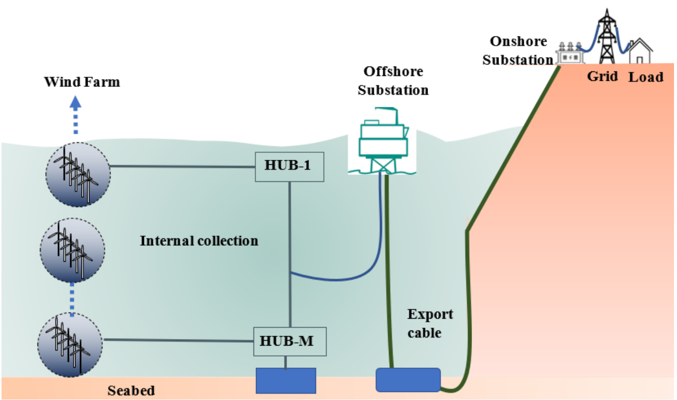


FIGURE 8: Connection Layout of Grid-Tied Offshore Wind Farm.

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. More research could be performed to determine average revenue losses from reliability failures and the cost of reliability failures to the grid system over the lifetime of the OWF. Without such a revenue model, the breakeven point between HVDC and HVAC is likely wrong because research suggests different levels of reliability, which directly impact costs.

III. OWF CONNECTION ARCHITECTURES

The efficient gathering and transmission of power from OWFs constitute a critical aspect influencing their overall performance and economic viability. Figure 8 illustrates the comprehensive connection layout of 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 [70]. 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 before transmission. Collection systems, often comprising subsea cables, gather the electricity from multiple turbines within an array and transmit it towards a central point [71]. [33] addresses the related research on different collection systems for OWFs and explores their operational characteristics and challenges. The collection grid architecture can be either AC or DC based on the type of energy source and the location of the offshore farm [7, 72]. [73] 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 architectures designed for HVDC connection in OWFs. Figure 9 presents potential connection architectures for OWFs, such as AC collection combined with DC transmission and All DC-based systems.

Meanwhile, Figure 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 [8]. AC grids offer several benefits, including mature technology, high efficiency, and seamless integration with existing electrical net-

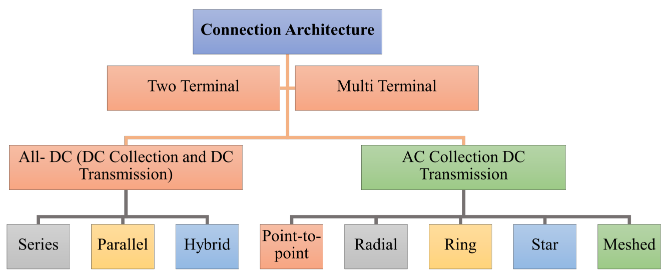


FIGURE 9: Classification of Connection Topology.

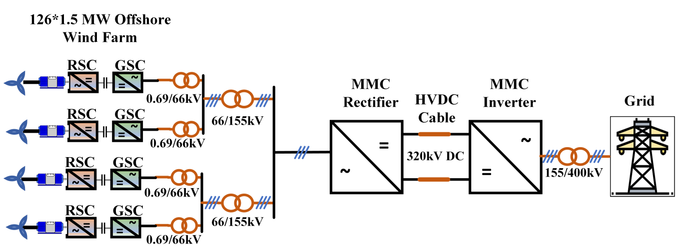


FIGURE 10: Schematic of Grid-Tied HVDC Offshore Wind Farm.

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 – Single fault disrupts the connected unit.	– Limited – Fault affects downstream units.	– Moderate – Faults in one segment may not impact the loop.	– High – Centralized hub reduces fault impacts.
Control	– Simplified voltage control at the substation.	– Easy control with possible voltage drops along the path.	– Partial voltage control through loop paths.	– Centralized, robust voltage control.
Scalability	– Low scalability; significant adjustments needed.	– Limited scalability; requires new connections.	– Moderate scalability via loop paths.	– Highly scalable; units easily added to the hub.
Complexity & Cost	– Simple design; lower initial cost.	– Simple design, costs may rise for voltage & reliability improvements.	– Moderate complexity and cost due to loop setup.	– High complexity and cost, but better redundancy.
Suitability	– Best for small systems with limited growth.	– Suitable for small to medium systems.	– Ideal for medium installations with room for expansion.	– Best for large, complex, or expanding systems.

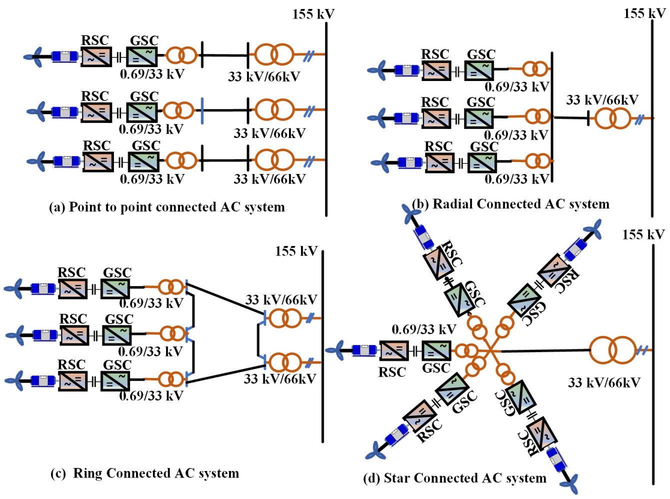


FIGURE 11: AC collection architecture.

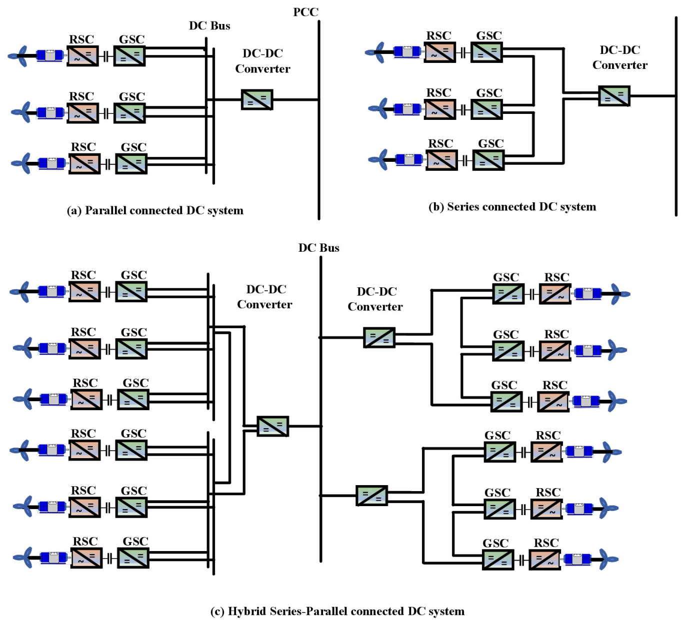


FIGURE 12: DC Series collection architecture.

works [74, 75]. 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 [33]. Figure 11 overviews 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 [76]. While 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. Additionally, the point-to-point configuration lacks the flexibility to facilitate power exchange between multiple areas or regions, limiting its adaptability for interconnected systems [77].

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 [69].

3) Ring

The ring topology interconnects units through looping cables, creating a circular arrangement [11]. While 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 [7].

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 [78]. This design simplifies the connection process and allows individual control of each turbine. However, a hub failure can impact all connected turbines, reducing system reliability. 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 [16].

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 for maintaining reliable grid operations [71, 121, 122]. Table 8 lists a few 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, which lead to 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 [123]. Voltage regulation becomes more difficult as the transmission distance increases, requiring additional equipment to maintain stability [124]. Moreover, power converters and switching operations in AC systems generate harmonics, demanding sophisticated filtering solutions to ensure power quality is not compromised [125]. 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 [33]. AC substations need bulky components such as transformers, reactors, switchgear, and harmonic filters to manage voltage levels and reactive power [126]. 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, which further raises the cost and limits the scalability of the infrastructure. Additionally, as OWFs increase in size and move farther from shore, the economic and logistical challenges of AC systems become even more pronounced [32].

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 fully DC transmission systems for OWFs [8]. DC systems offer several advantages over AC infrastructure, particularly for long-distance, high-capacity power transmission [127]. One of the most notable benefits is eliminating reactive power compensation, as DC transmission does not involve reactive power [128]. This allows for removing large transformers, reactors, and compensation devices, resulting in smaller, lighter substations with a reduced physical and environmental footprint [116].

DC systems also simplify grid integration by reducing the number of conversion stages and minimizing harmonic distortion [81]. In an All-DC setup, wind turbines generate DC power directly, which can be transmitted to shore without needing AC-DC conversion at the wind farm level, improving efficiency and reliability [129]. 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 management, and infrastructure size associated with AC grids. As OWFs grow in scale and distance from shore, All-DC architectures will likely 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 fully DC collection systems across technical and economic domains. This section explores various potential DC collection grid topologies for offshore wind energy integration. It's 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.

[130] 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. [73, 127] reviewed configurations of DC collection grids for OWFs, including the generator systems, the power electronics converter topologies, and the control and protection methods. [131] 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

TABLE 8: Integration Challenges of OWFs

Main Challenge		Mitigation Strategy	References
Power Quality	Harmonic Distortion	–Use of active/passive filters; –Advanced Control Algorithms.	[79]–[81]
	Voltage Unbalance	–Dynamic voltage balancing techniques –Use of FACTS devices	[82]
	Voltage Sag, Swell, Flickers	– Dynamic VAR compensators – Power conditioning systems.	[83, 84]
Stability	Voltage Stability	–Reactive power compensation –Advanced Control Techniques –Wind turbine converters with reactive power control capabilities.	[85]
	Frequency Stability	–De-loading by Variable Speed Wind Turbine –Capacitor energy storage in VSC-HVDC –Coordinated frequency regulation between OWF and VSC-HVDC	[86]
	Fault Ride-Through Capability (LVRT/HVRT)	–Implement LVRT and HVRT schemes in wind turbines and HVDC converters	[87]
Fault Diagnosis and Protection	Offshore Converter Protection	–Use of advanced protection systems and fault detection technologies	[88]–[91]
	Short-Circuit Current Limitation	–Use of superconducting fault current limiters (SFCLs) –Adaptive relays for precise fault detection and response	[92]–[94]
Inertia	System Inertia Reduction	–Use of synthetic inertia from wind turbine control –ESS-based inertia emulation –Virtual synchronous machines to mimic conventional inertia	[95]–[97]
Ancillary Services Provision	Provision of Frequency Regulation	–Battery Energy Storage Systems (BESS) –Synthetic inertia for fast frequency response –Advanced control algorithms	[98]–[100]
	Provision of Voltage Control and Reactive Power Support	–Use of FACTS devices (STATCOM, SVC) –Wind turbine converters with reactive power support	[101]–[104]
	Provision of Reserve Power	–Novel large-scale ESS –Coordinated operation with other RES	[59, 105]–[108]
	Black Start Capability	–Implement black start capability in ESS –Specific wind turbines designed for black start operations –Coordinated black-start strategy	[109]–[112]
Sizing of Converters and Efficiency	Converter Weight and Volume	–Use of modular multilevel converters (MMC) –Advanced materials to reduce size and weight –Novel collection systems	[33, 113]–[116]
	Converter Losses	–Use of high-efficiency semiconductor technologies (e.g., SiC or GaN) –Advanced converter topologies for lower losses	[117, 118]
Grid Code Compliance	Compliance with Grid Codes	–Adaptive control schemes to meet diverse grid code requirements –Ensuring LVRT/HVRT capabilities	[119, 120]

TABLE 9: Comparison Of DC Collection Grid Architectures

Aspects	Parallel DC Collection Grid	Series DC Collection Grid	Series-Parallel DC Collection Grid
Redundancy & Reliabilitv	- High redundancy within branches. - Faults in one branch don't affect others.	- Vulnerable to single-point failure. - Complex fault detection and protect mechanisms.	- Moderate redundancy; faults don't disrupt entire system. - Fault isolation and protection better managed than series.
Voltage Level & Transmission	- Common voltage level, limited distance without boosting. - Better suited for shorter transmissio distances.	- Aggregated voltage, ideal for long distance transmission. - Best for large offshore distances.	- Moderate voltage aggregation; suitable for mid-range distances. - Balanced voltage control for mid-range transmission.
Complexity & Cost	- Simple design, lower cost, easier installation. - Independent converters reduce infrastructure expenses.	- Complex design and high maintenar costs. - Expensive insulation and power management requirements.	- Moderate complexity; costs balance between series and parallel. - More sophisticated control than parallel but simpler than series.
Scalability	- Easily scaled for smaller installation incremental growth. - Ideal for near-shore or small installations.	- Challenging to scale due to voltage management. - Best suited for large offshore projects.	- Balanced scalability; well-suited for medium-sized installations. - Ideal for mid-sized OWFs with moderate scalability.
Suitability	- Near-shore installations, redundancy and simplicity.	- Long-distance offshore, high power installations.	- Medium-range OWFs with balanced performance and cost.

DC OWPPs have comparable capital costs to AC systems and lower energy losses, making them a potential option for future installations. DC collection grids can be broadly classified into three main topologies: parallel, series, and hybrid (series-parallel) configurations [71, 132] (Figure 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 [76, 133]. More complex designs involve multiple feeder strings attached to a passive offshore point, offering fault tolerance redundancy and increasing the system's reliability [134] [32]. This approach suits large farm systems but may incorporate offshore hubs for greater distances, albeit with increased complexity and cost [116]. Figure 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 [135], a DC wind

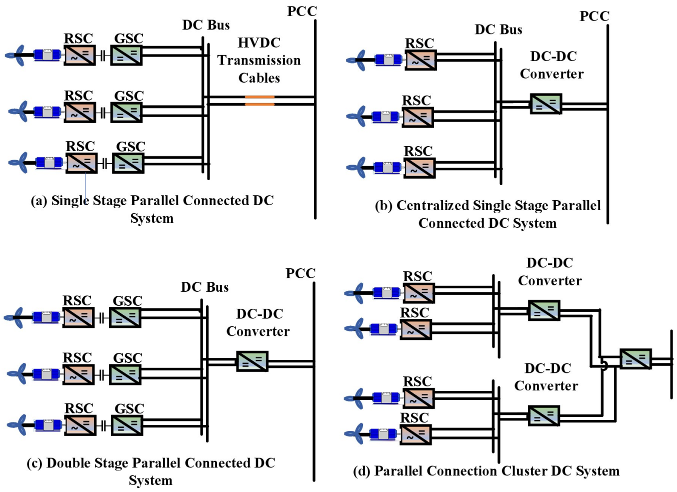


FIGURE 13: DC Parallel collection architecture.

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 among series-connected WTs present significant technical challenges, particularly for the final power converter in the string [32]. 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 [136, 137]. Another key drawback of series-connected turbines is their low resilience; a fault in one of them will shut down entire connected turbines [71]. Figure 14 represents different architectures based on DC Series collection for HVDC transmission.

3) Series-parallel Collection Grids

In [138], 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 [139]. Hence, reducing footprint and cost compared with the AC collection system and traditional DC alternatives, The study by [140] 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. [141] explores the series-parallel wind farm (SPWF) 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.

While 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. Installing 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 disruption, especially when multiple wind farms share substations and transmission lines [142]. Managing harmonics and resonance is crucial for HVDC-connected wind farms, as discussed in [81]. Although 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 [16].

E. EMERGING TRENDS IN ARCHITECTURES

To address an offshore converter's size and weight challenges, a High-Voltage Diode Rectifier (DR) is suggested [16, 32]. 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 [143]. Another promising architecture that is being proposed is mesh-connected architecture, in which there is always more than one path between any two points (Figure 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 [144]. 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 advancements, New York mandates mesh-ready designs to support its renewable energy transition and enhance grid reliability [145].

The Multi-Terminal Direct Current (MTDC) connection is another promising solution for seamlessly integrating offshore multi-use platforms into continental grids, as shown in Figure 16. 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 [146], an MTDC connection is proposed to integrate offshore multi-use platforms into continental grids. [147] presents a comprehensive method for minimizing transmission power loss in mesh and radial MTDC networks.

TABLE 10: HVDC Offshore Connection Topologies Comparison

HVDC Offshore Connection Topologies	Advantages	Limitations	Feasibility	Reliability	Cost	Complexity
Parallel AC Collection System with HVDC Transmission [148]	Higher voltage/power transmission, Longer distances from shore	Reactive power compensation, Lower reliability	*****	***	***	**
Mesh-Connected AC Collection System with HVDC Transmission [149]	Enhanced system reliability, Improved redundancy	Infrastructure cost, Complex mesh structure	****	****	****	****
Multi-terminal DC Collection Grid with Mesh HVDC Transmission [150]	Higher reliability, Continued power transfer under cable failures	Infrastructure cost, Complex	****	*****	*****	****
Parallel DC Collection with Medium-Frequency Transformer Embedded HVDC Transmission [151]	Reduced offshore converter station footprint and weight	Initial cost and transformer technology	** Under research	***	****	***
Series DC Collection System with HVDC Transmission [28, 152]	Reduced infrastructure requirements Eliminates the need for offshore stations	Voltage maintenance, Reliability	** Under research	**	***	***

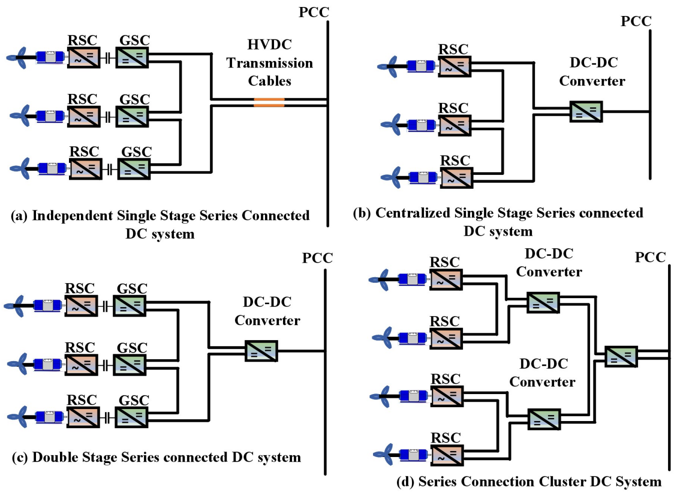


FIGURE 14: DC Series collection architecture.

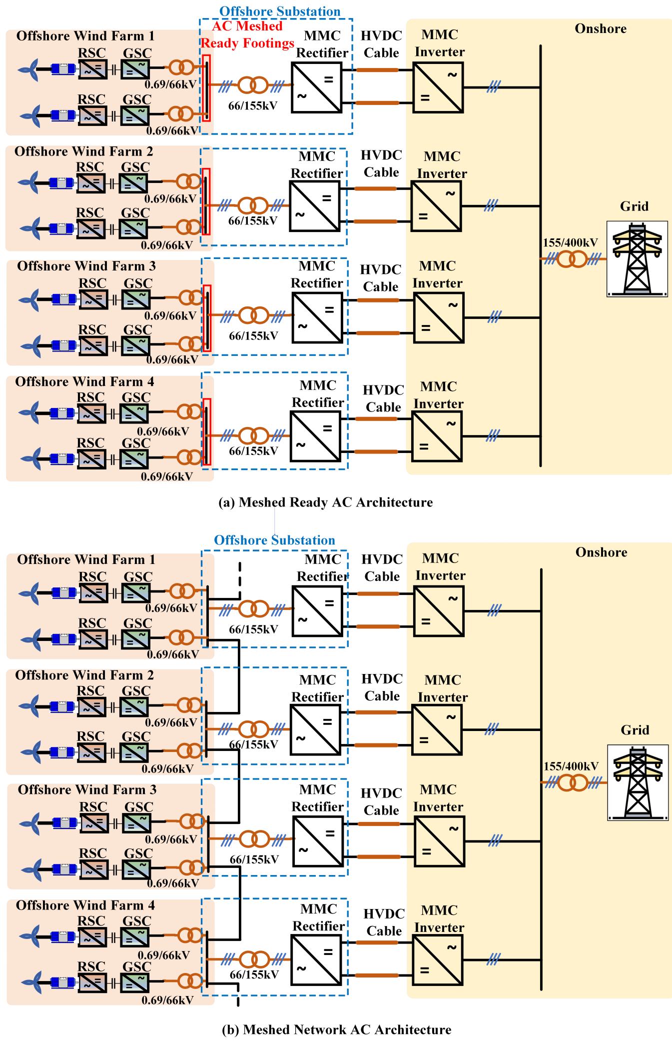


FIGURE 15: Meshed AC Architecture for Offshore Wind Farm [145].

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 OSWFs, 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 Figure 17. Such analyses are essential to identify configurations that minimize energy losses and infrastructure costs, thus improving the overall economic viability of OSWFs [26, 36].

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 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

TABLE 11: Cost of Cable for Collection and Transmission Architecture

Cable Name	Current	Voltage (KV)	Diameter (mm^2)	Amperage (A)	$\mu\Omega$/km	Transmission loss per km (Watt/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	220	1600	1640	10.5	28.24
3	DC	500	1200	1375	14	26.46
4	DC	500	2500	2145	6.72	30.92
5	DC	500	800	1095	21	25.18
6	DC	500	2500	2145	6.72	30.92

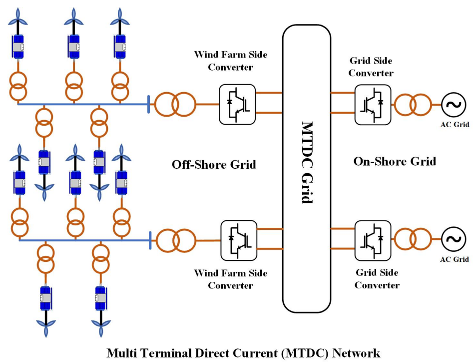


FIGURE 16: Multi Terminal Direct Current (MTDC) Network

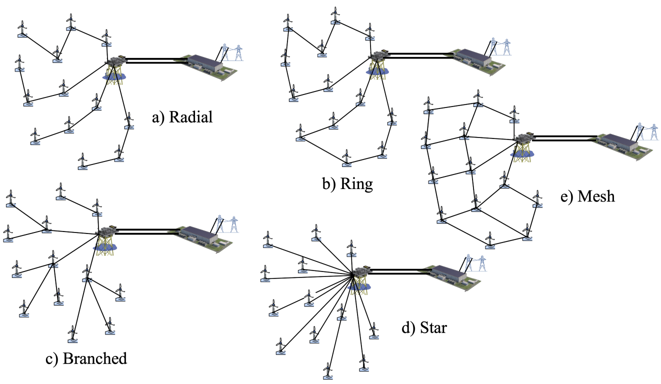


FIGURE 17: Collection architecture Techno-economic analysis.

architectures, as presented in Table 11. These cable types are utilized across both collection and transmission architectures [29]. Copper serves as the conductor material in subsea cable cores, and consequently, the cable's resistance per kilometer is determined based on the resistivity of copper [153].

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 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

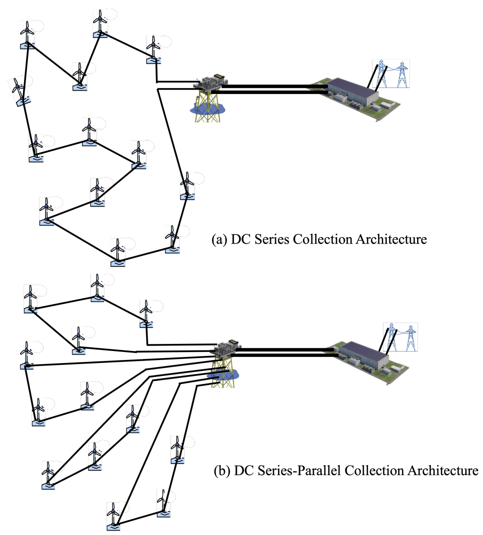


FIGURE 18: DC Series Collection architecture Techno-economic analysis.

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 (Figure 18), and DC

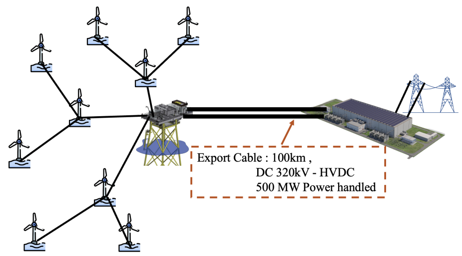


FIGURE 19: Single Point Transmission Architecture

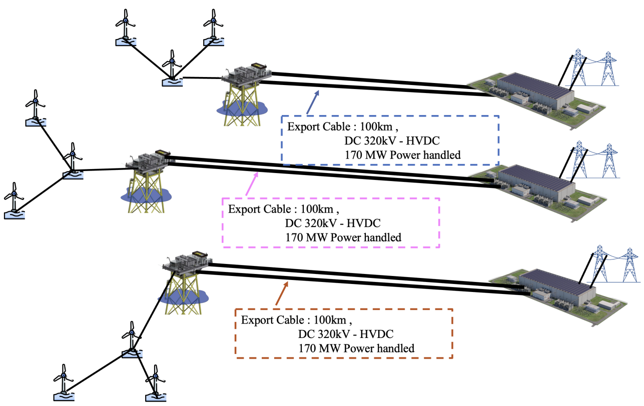


FIGURE 20: Multi-terminal grid design Point to Point Transmission Architecture

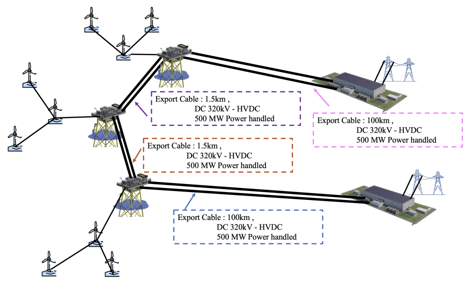


FIGURE 21: Multi-terminal grid design Radial Transmission Architecture

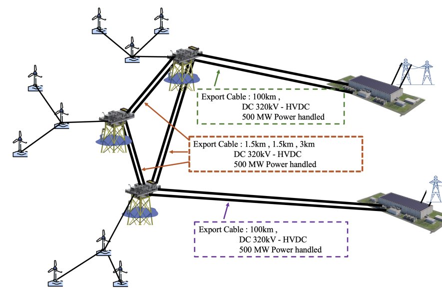


FIGURE 22: Multi-terminal grid design Meshed Transmission Architecture

parallel architectures (comparable to the radial configuration shown in Figure 17(a)) is conducted and summarized in Table 13. 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 Figures 19, 20, 21, and 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, response time to grid disturbances, and system performance, thus making the selection of the converter technology a significant step in designing the HVDC transmission system [12]. Each converter technology provides unique characteristics and suitability for specific applications [16, 154]. Criteria for selection depend on various factors such as the distance of transmission, 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 [90, 155, 156]. Figure 23 shows the power electronic converter classification used for HVDC applications in OWFs.

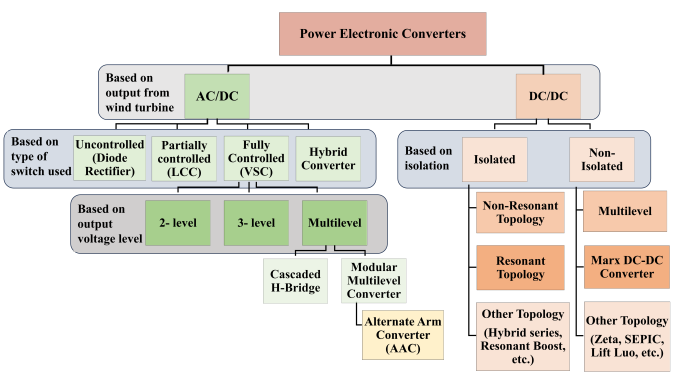


FIGURE 23: Classification of Power Electronic Converters in HVDC in OWF.

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 (kW)	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	****

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 (kW)	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	**

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, but they are generally not the preferred choice for HVDC transmission systems associated with OWFs [157]. Due to the variable nature of wind power, the uncontrolled operation of DRs makes them unsuitable for such applications. Additionally, 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 [32].

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 [158]–[160]. 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 [161]. Compared to the flexible, reactive power control of VSCs, LCC's adaptability is limited [32, 158, 162, 163].

Furthermore, LCC-HVDC systems are unsuitable for weak grids with SCR < 2 due to stability concerns and reliance on strong AC systems for commutation [164]. 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, which make it impractical for offshore wind farms (OWFs), where space optimization is critical [156, 165]. 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 like VSCs, which utilize fully controllable transistors such as IGBTs [159]. VSCs offer bidirectional power flow control, enhance voltage stability through reactive power management, and provide black start capability, making them reliable for HVDC applications [166, 167]. However, the adoption of VSCs has been relatively slow, partly due to the need for additional filters to manage high rates of current change (di/dt), which increases costs and complexity [159, 168]. To improve market penetration, VSC systems must address challenges like switching losses and harmonic distortion [32, 162]. Nonetheless, their adaptability positions them well for future integration into OWFs [158, 169].

The VSCs are classified as (i) Two-level, (ii) Three-level, and (iii) Multilevel, based on output voltage levels. Two-level VSCs switch between positive and negative DC voltage, making them simple and cost-effective but limited in HVDC applications. Three-level VSCs add a zero voltage level, offering lower harmonic distortion and better efficiency for high-power systems [179]. 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 systems for their higher efficiency, better control, superior harmonic performance, scalability, and better fault tolerance and reliability in high-voltage settings

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	****

TABLE 15: Comparative Analysis of Converter for OSW HVDC

Converter Type	Line Commuted Converter	Voltage Source Converter	Modular Multilevel Converter - MMC	Alternate Arm Modular Converter
Losses	Low switching losses [158]	High switching losses [158, 170]	<1% semiconductor losses [171]	Lower than MMC and VSC. [172]
Commutation	External Commutation [158]	Self Commuted	Self Commuted	Self Commuted
Reactive Power Compensation	Limited [161, 162]	Flexible [158]	Flexible modes [173]	Offers compensation [172]
DC - Fault tolerance	Short circuit withstand [159]	Vulnerable to line faults [159, 174]	Half-bridge SMs lacks dc-side fault handling [171, 172]	Strong fault tolerance [175, 176]
Power Flow direction	DC polarity inversion [158]	Bidirectional control [170]	Bidirectional [173, 176]	Bidirectional [176]
Suitability for OWF	Less suitable [158]	Optimal for renewables [158, 159]	Suitable for OSW [177]	Suitable for OSW [172]
EMI Challenges	Fewer challenges [159]	Requires additional filters [159]	Continuous arm reduces EMI [178]	Lower di/dt, superior EMI [176]
Foot Print and Weight	High Volume and weight [158]	Smaller footprints [27]	Reduced footprint [178]	Smaller footprint and weight [172]

[180]–[182].

MMC is a promising technology for HVDC transmission, particularly in integrating OWFs [12]. Its modular design enables high voltage levels and low switching frequencies, reducing harmonics and electromagnetic interference (EMI) [171]. MMC independently controls active and reactive power, enhancing grid stability [183, 184]. Modular redundancy bolsters fault tolerance, ensuring reliability in demanding HVDC conditions [185]. Additionally, MMC supports bidirectional power flow, making it ideal for dynamic energy systems [177]. While still under development, ongoing research on MMCs continues to focus on enhancing their reliability [171, 177, 186, 187].

Conventional MMC structures are modified for various HVDC applications, including transmission, multi-terminal systems, and tapping applications, among other HVDC uses [188]. The Alternate Arm Modular Converter (AAC), a variation of MMC topology, stands out for its excellent fault-tolerant features [175]. With high reactive power compensation and lower di/dt, AAC ensures superior EMI performance

[176]. Additionally, the compact design and reduced footprint further increase its suitability for space-limited projects [172]. Although less widely deployed than LCC and VSC, AAC's reliability in DC fault scenarios positions it as a valuable option in specific HVDC applications [172, 175].

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 [32, 189]. 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. While 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 assures 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 [190, 191]. 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 HVDC-connected OWPPs, emphasizing 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. Highly efficient and lightweight high-voltage, high-power DC/DC converters are thus core components for integrating wind farms into HVDC systems. DC/DC converter topologies can be classified into two types: Isolated and Non-Isolated [192], as shown in Figure 23.

Figure 24 gives a glimpse of some of the basic and advanced DC-DC converter topologies which are found in literature [24, 193]–[200]. Each of the mentioned topologies further has several variants to enhance the performance of the converter further.

In [24], 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 it may lose its soft-switching capability under light load conditions, necessitating careful control system design. The Series Load Resonant (SLR) converter also performs

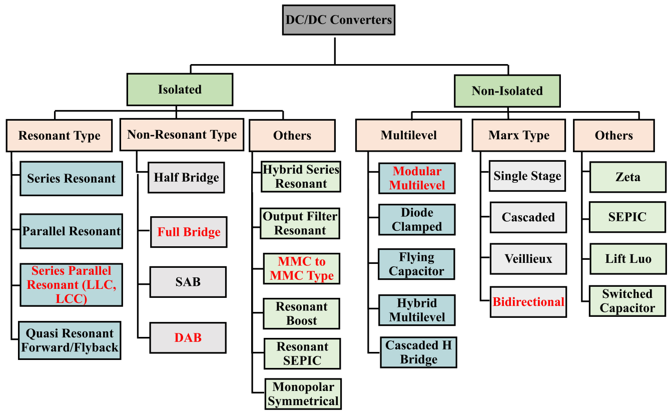


FIGURE 24: DC/DC Converter Topologies

well, but its variable operating frequency can limit 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 [193], an improved DAB sub-module 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 [194], 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 [194], 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, [194] 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. [194] also presents the Modular Hybrid DC/DC (MHDC) converter, reducing the number of IGBTs in FB-SMs. 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.

[195] 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 absent in HB and FB configurations. Using a high-frequency transformer reduces transformer weight, and soft switching minimizes switching losses, resulting in efficiencies on the order of 95%. However, challenges in multilevel power conversion include 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.

Based on the above analysis, some potential candidate topologies for the OWF application are highlighted in red in Figure 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. 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 [201, 202].

[8] 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, [28, 203] perform complete reliability assessments of DC collection systems and find that a radial topology with a single platform DC-DC converter is more economical and reliable than alternatives. [33] reviews various architectures, including fully DC-DC systems, and provides insight into the main challenges in moving towards fully integrated DC collection. Chief among the challenges is the state of the art of 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 decrease LCOE and deal with significant challenges to HVDC systems.

Future research should continue to pursue the economic component of DC-DC grids for OWF, emphasizing the evaluation of how costs can be brought down while bringing reliability up. Of particular interest is how DC-DC grids could be used in combined offshore wind and marine energy farms to reduce the effects of fixed costs further [74, 204]. Additionally, improved loss and fault monitoring technologies may improve performance [205].

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 [206]. 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, necessitating innovative approaches for more accurate and reliable analyses (Figure 25) [207, 208].

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 [209], the OWF disruption in England on August 9, 2019, [210], the cascaded trips power outages in South Australia in 2016 and 2018 [211], and the BowWin1 OWF commissioning issue [212] 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 [213]. Failure to detect such phenomena during the modeling phase, as seen in the BowWin1 incident, can lead to significant operational setbacks and disruptions.

Therefore, continual advancements in modeling methodologies are imperative for enhancing 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.

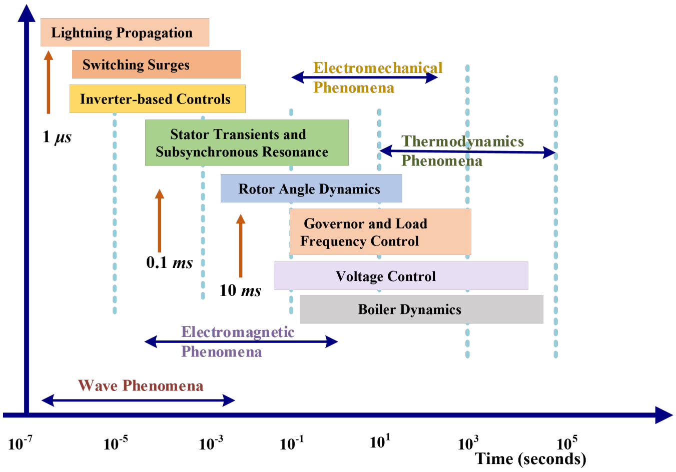


FIGURE 25: Time Scales of Power System Dynamic Phenomena [214].

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 [215]–[217]. 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 [206, 218]. Furthermore, the distance from shore introduces logistical challenges for data collection and monitoring, necessitating sophisticated remote sensing techniques for model validation [219].

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, posing challenges for grid connection and power transmission. Modeling the interaction between OWFs and onshore grid systems requires accurately representing power electronics, grid dynamics, and control strategies to prevent instability and grid disturbances [121, 220].

Additionally, the variability and intermittency of wind resources present challenges for predicting power output and optimizing energy generation [221]. 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 [222]–[224].

Moreover, offshore wind projects' increasing scale and complexity introduce challenges for modeling and simulation [225]. 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 [226]. High-fidelity simulation tools, coupled with parallel computing techniques, are essential for capturing the spatial and temporal dynamics of OWFs accurately [227, 228]. Addressing these challenges requires interdisciplinary research efforts and the development of advanced modeling techniques tailored to the unique characteristics of offshore wind energy 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 in maintaining system stability and reliability [77]. However, capturing these intricate dynamics introduces computational challenges, requiring advanced modeling techniques to accurately reflect fast-changing behaviors without overwhelming computational resources [229].

These systems evolve rapidly, demanding simulations that can keep up with real-time changes while still providing meaningful results [230]. 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 [231]. The optimal level of abstraction depends on factors such as the specific phenomena under study, simulation time constraints, and the system's overall complexity. While 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 [14].

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

[34] 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 methods are essential for understanding complex system dynamics and are particularly crucial in complex interactions threatening stability. Frequency domain impedance modeling offers advantages such as wideband oscillation study, grey/black 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 alongside examples of models used in the economic domain. [229] compares modeling accuracy and computational performance across

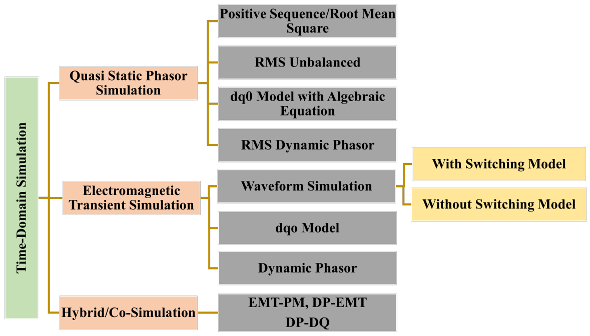


FIGURE 26: Classification of Time Domain Simulation Methods.

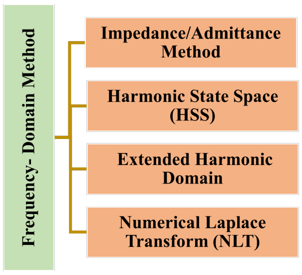


FIGURE 27: Classification of Time Domain Simulation Methods.

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. [232] introduces a comprehensive RMS modeling framework for dynamic studies of DFIG-based wind farms in multi-terminal VSC-HVDC grids, offering high fidelity and faster simulations than EMT solutions.

[233] develops an offshore AC side impedance model for MMC-HVDC wind power integration, considering the effects of offshore/onshore 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. [234] develops the impedance model and stability analysis for All-DC offshore PMSG wind farms, with simulations validating the model's effectiveness by reproducing time-domain oscillations. [235] investigates the stability of DR-HVDC connected OWFs by developing and validating an impedance model in the dq frame and analyzes the impacts of DR-HVDC DC smoothing reactor and AC filter sizes on system stability using PSCAD/EMTDC simulations. Figures 26 and 27 provide a systematic categorization of modeling techniques in both the time and frequency domains applied in system simulation studies.

Model accuracy heavily depends on the level of detail incorporated into the representation. To ensure precision, nonlinearities 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, effectively addressing nonlinearities such as PWM and limiters remains a challenge. There's 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. While significant progress has been made in developing 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 [237], data-driven modeling [238], and multi-scale modeling [239], enable real-time monitoring and predictive analysis [240]. 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 offshore wind energy 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 like reduced-order models can help simplify the representation of high-frequency switching without sacrificing accuracy [241]. 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 for integrating different models to capture various aspects of OWF operations [242]. By combining phasor-based grid models with detailed models of converter-interfaced devices (such as wind turbine power electronics), researchers can study interactions between the grid and converters under complex scenarios [243]. This holistic approach is crucial for identifying potential risks and designing robust control schemes for hybrid AC/DC systems.

TABLE 16: Examples of HVDC Offshore Wind Farm Models

Topology	Modelling Techniques	Key Points and Outcome	Reference
VSC-HVDC	MMC and OWF Modelling (Time Domain) DM, DECM, ESFM, AVM models	– Accuracy vs. computational efficiency for MMC and OWF models. – AVM (OWF) + DECM (MMC) boosts speed with minimal accuracy loss.	[229]
	Time domain modeling	– A comprehensive techno-economic comparison of MT-HVDC OWFs. – A semidefinite programming model for optimal economic operation in MT-HVDC systems.	[78, 236]
	RMS Modelling	– Introduction of RMS model for MTAC/DC grids for VSC-DFIG WFs. – Flexible and numerically efficient.	[232]
	AC Side Impedance Modelling	– AC side impedance model for MMC-HVDC wind integration. – Analysis with different DC system configurations. – Influence of dual closed-loop control indicated.	[233]
All - DC	Impedance Modelling	– Harmonic linearization for impedance modeling of All-DC WF with PMSG and LCC-inverter. – Verification through simulation and oscillation analysis.	[234]
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.	[235]

Full Phasor Model (PM) for CIG Integration: Implementing full PM for studies involving converter-interfaced generation (CIG) enables a more comprehensive analysis of system stability, protection, and control [244]. 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 [245]–[247]. HVDC architectures potentially provide more parameters to OWF operators, including control over line losses, faster interaction with the grid, and potential for black [248]. 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 ESS [249, 250]. Recent developments in reinforcement learning algorithms may have potential in this domain [251].

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 play a crucial role in selecting grid configurations. Effective *load management techniques* are required to address the challenges of integrating offshore systems with existing onshore grids.
- **Converter Technologies:**
  - While 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.
- **Modeling and Computational Advances**
  - **Modeling Techniques:** Future research should focus on enhancing *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. A *system-wide approach* to reliability is essential rather than focusing on isolated components.

-- **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 both viable and resilient.

VII. CONCLUSIONS

This review paper explores the **techno-economic aspects of HVDC OWFs**, focusing on transmission costs, system reliability, and architecture. It analyzes both **levelized cost of energy (LCOE) and levelized avoided cost of energy (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 connection architectures, with particular attention to emerging designs such as *MTDC grids* and *All-DC collection systems*, which offer improved scalability, efficiency, and reliability with reduced footbprint for large OWFs.

Additionally, the paper examines power converter topologies, emphasizing the role of **AC-DC and DC-DC converters**. A comparison between *LCC* and *VSC* is presented, alongside an exploration of innovative technologies like *MMC* and *AAMC*. VSCs are identified as the optimal choice for renewable energy transmission, with MMCs offering substantial advantages for offshore wind integration. **Modeling** offshore wind systems presents 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 grid stability as offshore wind penetration increases.

The review concludes with key **future research directions**, highlighting the need to enhance **scalability, reduce complexity**, and develop **new converter technologies**. It also emphasizes the importance of **interdisciplinary collaboration** to align technical solutions with economic feasibility. Ultimately, the paper offers a comprehensive overview of the current state of offshore wind research and outlines a path toward a **sustainable, resilient, and economically viable future**.

REFERENCES

[1] W. Musial, P. Spitsen, P. Duffy, P. Beiter, M. Shields, D. Mulas Hernando, R. Hammond, M. Marquis, J. King, and S. Sathish, "Offshore wind market report: 2023 edition," tech. rep., National Renewable Energy Laboratory (NREL), Golden, CO (United States), 2023.

[2] "Global Wind Power Tracker - Global Energy Monitor — globalenergymonitor.org." https://globalenergymonitor.org/projects/global-wind-power-tracker/. [Accessed 09-01-2024].

[3] P. Beiter, W. Musial, L. Kilcher, M. Maness, and A. Smith, "An assessment of the economic potential of offshore wind in the united states from 2015 to 2030," tech. rep., National Renewable Energy Lab.(NREL), Golden, CO (United States), 2017.

[4] P. Beiter, W. Musial, A. Smith, L. Kilcher, R. Damiani, M. Maness, S. Sirnivas, T. Stehly, V. Gevorgian, M. Mooney, *et al.*, "A spatial-economic cost-reduction pathway analysis for us offshore wind energy development from 2015–2030," tech. rep., National Renewable Energy Lab.(NREL), Golden, CO (United States), 2016.

[5] Q. Jiang, B. Li, and T. Liu, "Tech-economic assessment of power transmission options for large-scale offshore wind farms in china," *Processes*, vol. 10, no. 5, p. 979, 2022.

[6] A. Stan, S. Costinaș, and G. Ion, "Overview and assessment of hvdc current applications and future trends," *Energies*, vol. 15, no. 3, p. 1193, 2022.

[7] S. Rahman, I. Khan, H. I. Alkhammash, and M. F. Nadeem, "A comparison review on transmission mode for onshore integration of offshore wind farms: Hvdc or hvac," *Electronics*, vol. 10, no. 12, p. 1489, 2021.

[8] V. Timmers, A. Egea-Àlvarez, A. Gkountaras, R. Li, and L. Xu, "All-dc offshore wind farms: When are they more cost-effective than ac designs?," *IET Renewable Power Generation*, vol. 17, no. 10, pp. 2458–2470, 2023.

[9] A. Elahidoost, "Stability improvement of mmc-based multiterminal hvdc grids," 2024.

[10] S. Paul and Z. H. Rather, "A novel approach for optimal cabling and determination of suitable topology of mtdc connected offshore wind farm cluster," *Electric Power Systems Research*, vol. 208, p. 107877, 2022.

[11] A. Korompili, Q. Wu, and H. Zhao, "Review of vsc hvdc connection for offshore wind power integration," *Renewable and Sustainable Energy Reviews*, vol. 59, pp. 1405–1414, 2016.

[12] A. Inamdar and A. Bhole, "Converters for hvdc transmission for offshore wind farms: A review," in *2018 International Conference on Current Trends towards Converging Technologies (ICCTCT)*, pp. 1–7, IEEE, 2018.

[13] T. Abedin, M. S. H. Lipu, M. A. Hannan, P. J. Ker, S. A. Rahman, C. T. Yaw, S. K. Tiong, and K. M. Muttaqi, "Dynamic modeling of hvdc for power system stability assessment: A review, issues, and recommendations," *Energies*, vol. 14, no. 16, p. 4829, 2021.

[14] J. Xia and G. Zou, "Operation and maintenance optimization of offshore wind farms based on digital twin: A review," *Ocean Engineering*, vol. 268, p. 113322, 2023.

[15] W. Wang, G. Li, and J. Guo, "Large-scale renewable energy transmission by hvdc: Challenges and proposals," *Engineering*, vol. 19, pp. 252–267, 2022.

[16] Z. Li, Q. Song, F. An, B. Zhao, Z. Yu, and R. Zeng, "Review on dc transmission systems for integrating large-scale offshore wind farms," *Energy Conversion and Economics*, vol. 2, no. 1, pp. 1–14, 2021.

[17] L. Yu, Z. Fu, R. Li, and J. Zhu, "Dru-hvdc for offshore wind power transmission: A review," *IET Renewable Power Generation*, 2024.

[18] N. P. HK, L. S. Kumar, S. Anand, *et al.*, "Review paper on multilevel converters topology for vsc-based hvdc transmission system connected offshore wind power plant," *World Journal of Advanced Research and Reviews*, vol. 22, no. 1, pp. 924–937, 2024.

[19] Z. Xu, Y. Jin, Z. Zhang, and Y. Huang, "Eight typical schemes of offshore wind power transmission and their key technical problems," *Energies*, vol. 16, no. 2, p. 658, 2023.

[20] J. Li, J. Yin, Y. Guan, Z. Wang, T. Niu, H. Zhen, Z. Han, and X. Guo, "A review on topology, operating and control methods of hvdc transmission system for offshore wind farms," in *E3S Web of Conferences*, vol. 165, p. 06012, EDP Sciences, 2020.

[21] S. Hardy, K. Van Brusselen, S. Hendrix, D. Van Hertem, and H. Ergun, "Techno-economic analysis of hvac, hvdc and ofac offshore wind power connections," in *2019 IEEE Milan PowerTech*, pp. 1–6, IEEE, 2019.

[22] S. Kucuksari, N. Erdogan, and U. Cali, "Impact of electrical topology, capacity factor and line length on economic performance of offshore wind investments," *Energies*, vol. 12, no. 16, p. 3191, 2019.

[23] A. Fernández-Guillamón, K. Das, N. A. Cutululis, and Á. Molina-García, "Offshore wind power integration into future power systems: Overview and trends," *Journal of Marine Science and Engineering*, vol. 7, no. 11, p. 399, 2019.

[24] X. Xiang, S. Fan, Y. Gu, W. Ming, J. Wu, W. Li, X. He, and T. C. Green, "Comparison of cost-effective distances for lfac with hvac and hvdc in their connections for offshore and remote onshore wind energy," *CSEE Journal of Power and Energy Systems*, vol. 7, no. 5, pp. 954–975, 2021.

[25] T. Houghton, K. Bell, and M. Doquet, "Offshore transmission for wind: Comparing the economic benefits of different offshore network configurations," *Renewable Energy*, vol. 94, pp. 268–279, 2016.

[26] G. Stamatiou, "Techno-economical analysis of dc collection grid for offshore wind parks," *Master's thesis,, University of Nottingham, Nottingham, UK*, 2010.

[27] P. Bresesti, W. L. Kling, R. L. Hendriks, and R. Vailati, "Hvdc connection of offshore wind farms to the transmission system," *IEEE Transactions on energy conversion*, vol. 22, no. 1, pp. 37–43, 2007.

[28] R. Sun, G. Abeynayake, J. Liang, and K. Wang, "Reliability and economic evaluation of offshore wind power dc collection systems," *Energies*, vol. 14, no. 10, p. 2922, 2021.

[29] Y. Meng, S. Yan, K. Wu, L. Ning, X. Li, X. Wang, and X. Wang, "Comparative economic analysis of low frequency ac transmission system for the integration of large offshore wind farms," *Renewable Energy*, vol. 179, pp. 1955–1968, 2021.

[30] N. Saraswati, P. Nguyen, Y. Sun, and P. Domellan, "Offshore wind grid integration-a techno-economic comparison of mvdc and hvac," in *2022 IEEE PES Innovative Smart Grid Technologies-Asia (ISGT Asia)*, pp. 160–164, IEEE, 2022.

[31] A. Alassi, S. Bañales, O. Ellabban, G. Adam, and C. MacIver, "Hvdc transmission: Technology review, market trends and future outlook," *Renewable and Sustainable Energy Reviews*, vol. 112, pp. 530–554, 2019.

[32] B. Yang, B. Liu, H. Zhou, J. Wang, W. Yao, S. Wu, H. Shu, and Y. Ren, "A critical survey of technologies of large offshore wind farm integration: Summary, advances, and perspectives," *Protection and Control of Modern Power Systems*, vol. 7, no. 1, p. 17, 2022.

[33] P. Lakshmanan, R. Sun, and J. Liang, "Electrical collection systems for offshore wind farms: A review," *CSEE Journal of Power and Energy Systems*, vol. 7, no. 5, pp. 1078–1092, 2021.

[34] J. Deng, F. Cheng, L. Yao, J. Xu, B. Mao, X. Li, and R. Chen, "A review of system topologies, key operation and control technologies for offshore wind power transmission based on hvdc," *IET Generation, Transmission & Distribution*, 2023.

[35] H. Assessing, "Transmission for impacts of non-dispatchable generation," *US Energy Information Administration*, 2018.

[36] B. Van Eeckhout, D. Van Hertem, M. Reza, K. Srivastava, and R. Belmans, "Economic comparison of vsc hvdc and hvac as transmission system for a 300 mw offshore wind farm," *European Transactions on Electrical Power*, vol. 20, no. 5, pp. 661–671, 2010.

[37] J. S. Gifford and R. C. Grace, "Crest cost of renewable energy spreadsheet tool: A model for developing cost-based incentives in the united states; user manual version 4, august 2009-march 2011 (updated july 2013)," tech. rep., National Renewable Energy Lab.(NREL), Golden, CO (United States), 2013.

[38] M. J. B. Kabeyi and O. A. Olanrewaju, "The levelized cost of energy and modifications for use in electricity generation planning," *Energy Reports*, vol. 9, pp. 495–534, 2023.

[39] M. Day, "The state and local planning for energy (slope) platform and additional doe/nrel resources for clean energy planning," tech. rep., National Renewable Energy Lab.(NREL), Golden, CO (United States), 2022.

[40] J. Liu, D. Song, Q. Li, J. Yang, Y. Hu, F. Fang, and Y. H. Joo, "Life cycle cost modelling and economic analysis of wind power: A state of art review," *Energy Conversion and Management*, vol. 277, p. 116628, 2023.

[41] M. T. García-Álvarez, L. Cabeza-García, and I. Soares, "Analysis of the promotion of onshore wind energy in the eu: Feed-in tariff or renewable portfolio standard?," *Renewable energy*, vol. 111, pp. 256–264, 2017.

[42] J. S. Heeter, B. K. Speer, and M. B. Glick, "International best practices for implementing and designing renewable portfolio standard (rps) policies," tech. rep., National Renewable Energy Lab.(NREL), Golden, CO (United States), 2019.

[43] M. Welisch and R. Poudineh, "Auctions for allocation of offshore wind contracts for difference in the uk," *Renewable Energy*, vol. 147, pp. 1266–1274, 2020.

[44] P. Beiter, J. Guillet, M. Jansen, E. Wilson, and L. Kitzing, "The enduring role of contracts for difference in risk management and market creation for renewables," *Nature Energy*, vol. 9, no. 1, pp. 20–26, 2024.

[45] M. Jansen, P. Beiter, I. Riepin, F. Müsgens, V. J. Guajardo-Fajardo, I. Staffell, B. Bulder, and L. Kitzing, "Policy choices and outcomes for offshore wind auctions globally," *Energy Policy*, vol. 167, p. 113000, 2022.

[46] A. Papalexopoulos, C. Hansen, D. Perrino, and R. Frowd, "Modeling and analysis of wholesale electricity market design: Understanding the missing money problem," *Tech. Rep. NREL/SR-5D00-64255*, 2015.

[47] S. A. Mozdawar, A. Akbari Foroud, and M. Amirahmadi, "Multiple electricity markets design undergoing asymmetric policies on renewables expansion: Capacity adequacy and revenue sufficiency," *Arabian Journal for Science and Engineering*, vol. 47, no. 3, pp. 2781–2796, 2022.

[48] D. A. Schiro, T. Zheng, F. Zhao, and E. Litvinov, "Convex hull pricing in electricity markets: Formulation, analysis, and implementation challenges," *IEEE Transactions on Power Systems*, vol. 31, no. 5, pp. 4068–4075, 2015.

[49] A. J. Lamadrid and T. Mount, "Ancillary services in systems with high penetrations of renewable energy sources, the case of ramping," *Energy Economics*, vol. 34, no. 6, pp. 1959–1971, 2012.

[50] X. Zou, R. Qiu, M. Yuan, Q. Liao, Y. Yan, Y. Liang, and H. Zhang, "Sustainable offshore oil and gas fields development: Techno-economic feasibility analysis of wind–hydrogen–natural gas nexus," *Energy Reports*, vol. 7, pp. 4470–4482, 2021.

[51] A. Kumar, N. K. Meena, A. R. Singh, Y. Deng, X. He, R. Bansal, and P. Kumar, "Strategic integration of battery energy storage systems with the provision of distributed ancillary services in active distribution systems," *Applied Energy*, vol. 253, p. 113503, 2019.

[52] X. Wang, L. Li, A. Palazoglu, N. H. El-Farra, and N. Shah, "Optimization and control of offshore wind farms with energy storage systems," *IFAC-PapersOnLine*, vol. 51, no. 18, pp. 862–867, 2018.

[53] A. Botterud, C. R. Knittel, J. Parsons, J. R. Senga, and D. Story, "Bridging the gaps: The impact of interregional transmission on emissions and reliability," tech. rep., National Bureau of Economic Research, 2024.

[54] L. E. Gonzales, K. Ito, and M. Reguant, "The dynamic impact of market integration: Evidence from renewable energy expansion in chile," tech. rep., National Bureau of Economic Research, 2022.

[55] J. Chen, J. Wang, and A. Ni, "Recycling and reuse of composite materials for wind turbine blades: An overview," *Journal of Reinforced Plastics and Composites*, vol. 38, no. 12, pp. 567–577, 2019.

[56] J. P. Jensen and K. Skelton, "Wind turbine blade recycling: Experiences, challenges and possibilities in a circular economy," *Renewable and Sustainable Energy Reviews*, vol. 97, pp. 165–176, 2018.

[57] C. Li, J. M. Mogollón, A. Tukker, J. Dong, D. von Terzi, C. Zhang, and B. Steubing, "Future material requirements for global sustainable offshore wind energy development," *Renewable and Sustainable Energy Reviews*, vol. 164, p. 112603, 2022.

[58] R. Nguyen, M. Severson, B. Zhang, B. Vaagensmith, M. M. Rahman, A.-L. Toba, P. Price, R. Davis, and S. Williams, "Electric grid supply chain review: large power transformers and high voltage direct current systems," tech. rep., USDOE Office of Policy (OP), Washington, DC (United States), 2022.

[59] Q. Gao, A. Bechlenberg, B. Jayawardhana, N. Ertugrul, A. I. Vakis, and B. Ding, "Techno-economic assessment of offshore wind and hybrid wind–wave farms with energy storage systems," *Renewable and Sustainable Energy Reviews*, vol. 192, p. 114263, 2024.

[60] B. L. Tarufelli, B. C. Eldridge, and A. Somani, "Capacity markets for transactive energy systems," tech. rep., Pacific Northwest National Laboratory (PNNL), Richland, WA (United States), 2022.

[61] Executive Order, "Executive Order No. 13423, Strengthening Federal Environmental, Energy, and Transportation Management." 3 C.F.R. 919 (2007), 2007. Issued by the President of the United States.

[62] P. D. Schwabe, D. J. Feldman, D. E. Settle, and J. Fields, "Wind energy finance in the united states: Current practice and opportunities," tech. rep., National Renewable Energy Lab.(NREL), Golden, CO (United States), 2017.

[63] V. de Rugy, "Assessing the department of energy loan guarantee program," *Mercatus Center, June*, vol. 19, 2012.

[64] J. Stefek, C. Constant, C. Clark, H. Tinnesand, C. Christol, and R. Baranowski, "Us offshore wind workforce assessment," tech. rep., National Renewable Energy Lab.(NREL), Golden, CO (United States), 2022.

[65] D. J. Keyser and S. Tegen, "The wind energy workforce in the united states: Training, hiring, and future needs," tech. rep., National Renewable Energy Lab.(NREL), Golden, CO (United States), 2019.

[66] G. Gowrisankaran, A. Langer, and W. Zhang, "Policy uncertainty in the market for coal electricity: The case of air toxics standards," tech. rep., National Bureau of Economic Research, 2022.

[67] J. Hu, R. Harmsen, W. Crijns-Graus, and E. Worrell, "Barriers to investment in utility-scale variable renewable electricity (vre) generation projects," *Renewable Energy*, vol. 121, pp. 730–744, 2018.

[68] M. Liu, J. Qin, D.-G. Lu, W.-H. Zhang, J.-S. Zhu, and M. H. Faber, "Towards resilience of offshore wind farms: A framework and application to asset integrity management," *Applied Energy*, vol. 322, p. 119429, 2022.

[69] C. MacIver, K. R. Bell, and D. P. Nedić, "A reliability evaluation of offshore hvdc grid configuration options," *IEEE transactions on power delivery*, vol. 31, no. 2, pp. 810–819, 2015.

[70] A. Madariaga, I. M. de Alegría, J. Martín, P. Eguía, and S. Ceballos, "Current facts about offshore wind farms," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 5, pp. 3105–3116, 2012.

[71] S. Lundberg, "Evaluation of wind farm layouts," *EPE journal*, vol. 16, no. 1, pp. 14–21, 2006.

[72] A. Madariaga, J. Martín, I. Zamora, I. M. De Alegría, and S. Ceballos, "Technological trends in electric topologies for offshore wind power plants," *Renewable and Sustainable Energy Reviews*, vol. 24, pp. 32–44, 2013.

[73] P. Lakshmanan, J. Liang, and N. Jenkins, "Assessment of collection systems for hvdc connected offshore wind farms," *Electric Power Systems Research*, vol. 129, pp. 75–82, 2015.

[74] C. Fjellstedt, M. I. Ullah, J. Forslund, E. Jonasson, I. Temiz, and K. Thomas, "A review of ac and dc collection grids for offshore renewable energy with a qualitative evaluation for marine energy resources," *Energies*, vol. 15, no. 16, p. 5816, 2022.

[75] P. Le Métayer, P. Dworakowski, and J. Maneiro, "Unidirectional thyristor-based dc-dc converter for hvdc connection of offshore wind farms," in *2020 22nd European Conference on Power Electronics and Applications (EPE'20 ECCE Europe)*, pp. P–1, IEEE, 2020.

[76] J. B. Glasdam, L. Zeni, M. Gryning, J. Hjerrild, Ł. Kocewiak, B. Hesselbaek, K. Andersen, T. Sørensen, M. Blanke, P. E. Sørensen, *et al.*, "Hvdc connected offshore wind power plants: review and outlook of current research," in *12th Wind Integration Workshop*, Energynautics GmbH, 2013.

[77] Y. Zhang, J. Ravishankar, J. Fletcher, R. Li, and M. Han, "Review of modular multilevel converter based multi-terminal hvdc systems for offshore wind power transmission," *Renewable and Sustainable Energy Reviews*, vol. 61, pp. 572–586, 2016.

[78] A. Raza, M. Younis, Y. Liu, A. Altalbe, K. Rouzbehi, and G. Abbas, "A multi-terminal hvdc grid topology proposal for offshore wind farms," *Applied Sciences*, vol. 10, no. 5, p. 1833, 2020.

[79] A. Nami, J. L. Rodriguez Amenedo, S. Arnaltes Gomez, and M. A. Cardiel Alvarez, "Active power filtering embedded in the frequency control of an offshore wind farm connected to a diode-rectifier-based hvdc link," *Energies*, vol. 11, no. 10, p. 2718, 2018.

[80] Y. Zhang, C. Klabunde, and M. Wolter, "Study of resonance issues between dfig-based offshore wind farm and hvdc transmission," *Electric Power Systems Research*, vol. 190, p. 106767, 2021.

[81] C. Karlsson, "Managing harmonics and resonances in hvdc connected 66 kv offshore windfarms," 2023.

[82] K. Schönleber, E. Prieto-Araujo, S. Rates-Palau, and O. Gomis-Bellmunt, "Handling of unbalanced faults in hvdc-connected wind power plants," *Electric Power Systems Research*, vol. 152, pp. 148–159, 2017.

[83] R. Ferdinand, P. Melzer, and A. Monti, "Power quality issues at the grid connection point of hvdc connected offshore wind farms and their influence on the production," in *2018 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, pp. 1–6, IEEE, 2018.

[84] S. A. Almohaimeed and M. Abdel-Akher, "Power quality issues and mitigation for electric grids with wind power penetration," *Applied Sciences*, vol. 10, no. 24, p. 8852, 2020.

[85] G.-S. Lee, D.-H. Kwon, and S.-I. Moon, "Dc current and voltage droop control method of hybrid hvdc systems for an offshore wind farm connection to enhance ac voltage stability," *IEEE Transactions on Energy Conversion*, vol. 36, no. 1, pp. 468–479, 2020.

[86] J. Jallad, S. Mekhilef, and H. Mokhlis, "Frequency regulation strategies in grid integrated offshore wind turbines via vsc-hvdc technology: A review," *Energies*, vol. 10, no. 9, p. 1244, 2017.

[87] K. Jia, X. Dong, Z. Wen, W. Wu, and T. Bi, "Harmonic injection based fault ride-through control of mmc-hvdc connected offshore wind farms," *IEEE Transactions on Sustainable Energy*, vol. 14, no. 3, pp. 1796–1806, 2023.

[88] C. Chao, X. Zheng, Y. Weng, H. Ye, Z. Liu, H. Liu, Y. Liu, and N. Tai, "High-sensitivity differential protection for offshore wind farms collection line with mmc-hvdc transmission," *IEEE Transactions on Power Delivery*, 2024.

[89] J. Li, Q. Yang, H. Mu, S. Le Blond, and H. He, "A new fault detection and fault location method for multi-terminal high voltage direct current of offshore wind farm," *Applied energy*, vol. 220, pp. 13–20, 2018.

[90] B. Mitra, B. Chowdhury, and M. Manjrekar, "Hvdc transmission for access to off-shore renewable energy: a review of technology and fault detection techniques," *IET Renewable Power Generation*, vol. 12, no. 13, pp. 1563–1571, 2018.

[91] S. H. Ashrafi Niaki, J. Sahebkar Farkhani, Z. Chen, B. Bak-Jensen, and S. Hu, "An intelligent method for fault location estimation in hvdc cable systems connected to offshore wind farms," *Wind*, vol. 3, no. 3, pp. 361–374, 2023.

[92] G. M. G. Guerreiro, R. Sharma, F. Martin, P. Ghimire, and G. Yang, "Concerning short-circuit current contribution challenges of large-scale full-converter based wind power plants," *IEEE Access*, vol. 11, pp. 64141–64159, 2023.

[93] J. Song, M. Cheah-Mane, E. Prieto-Araujo, and O. Gomis-Bellmunt, "A novel methodology for effective short-circuit calculation in offshore wind power plants considering converter limitations," *Electric Power Systems Research*, vol. 211, p. 108352, 2022.

[94] B. Qin, W. Liu, R. Zhang, J. Liu, and H. Li, "Review on short-circuit current analysis and suppression techniques for mmc-hvdc transmission systems," *Applied Sciences*, vol. 10, no. 19, p. 6769, 2020.

[95] W. Zeng, R. Li, L. Huang, C. Liu, and X. Cai, "Approach to inertial compensation of hvdc offshore wind farms by mmc with ultracapacitor energy storage integration," *IEEE Transactions on Industrial Electronics*, vol. 69, no. 12, pp. 12988–12998, 2021.

[96] L. Tu, Y. Yang, J. Yang, and T. Sun, "The synthetic inertia controller for mmc-hvdc based offshore wind farm integration," in *2021 IEEE 1st International Power Electronics and Application Symposium (PEAS)*, pp. 1–4, IEEE, 2021.

[97] J. Zhu, M. Shi, L. Yu, J. Zhao, S. Bu, C. Y. Chung, and C. D. Booth, "Supercapacitor-based coordinated synthetic inertia scheme for voltage source converter-based hvdc integrated offshore wind farm," *IET Energy Systems Integration*, vol. 6, no. 1, pp. 5–17, 2024.

[98] A. Bidadfar, O. Saborío-Romano, J. N. Sakamuri, N. A. Cutululis, V. Akhmatov, and P. E. Sørensen, "On feasibility of autonomous frequency-support provision from offshore hvdc grids," *IEEE Transactions on Power Delivery*, vol. 35, no. 6, pp. 2711–2721, 2020.

[99] C.-H. Lin and Y.-K. Wu, "Overview of frequency control technologies for wind power systems," in *2020 International Symposium on Computer, Consumer and Control (IS3C)*, pp. 272–275, IEEE, 2020.

[100] M. Kabsha and Z. H. Rather, "A new control scheme for fast frequency support from hvdc connected offshore wind farm in low-inertia system," *IEEE Transactions on Sustainable Energy*, vol. 11, no. 3, pp. 1829–1837, 2019.

[101] Y.-K. Wu, D.-Y. Gau, and T.-D. Tung, "Overview of various voltage control technologies for wind turbines and ac/dc connection systems," *Energies*, vol. 16, no. 10, p. 4128, 2023.

[102] T. Tanaka, K. Ma, H. Wang, and F. Blaabjerg, "Asymmetrical reactive power capability of modular multilevel cascade converter based statcoms for offshore wind farm," *IEEE Transactions on Power Electronics*, vol. 34, no. 6, pp. 5147–5164, 2018.

[103] P. Meng, W. Xiang, and J. Wen, "Communication-less reactive power control of grid-forming wind turbines connected to cascaded lcc-dr hvdc system," *IEEE Transactions on Power Systems*, 2024.

[104] S. Gupta and A. Shukla, "Improved dynamic modelling of dfig driven wind turbine with algorithm for optimal sharing of reactive power between converters," *Sustainable Energy Technologies and Assessments*, vol. 51, p. 101961, 2022.

[105] P. Jiang, H. Bai, Q. Xu, and A. Arsalanloo, "Thermodynamic, exergoeconomic, and economic analyses with multi-objective optimization of a novel liquid air energy storage coupled with an off-shore wind farm," *Sustainable Cities and Society*, vol. 90, p. 104353, 2023.

[106] M. N. Hellesnes, "Use of battery energy storage for power balancing in a large-scale hvdc connected wind power plant," Master's thesis, NTNU, 2017.

[107] A. Rabanal, A. M. Smith, C. C. Ahaotu, and E. Tedeschi, "Energy storage systems for services provision in offshore wind farms," *Renewable and Sustainable Energy Reviews*, vol. 200, p. 114573, 2024.

[108] J. M. Kluger, M. N. Haji, and A. H. Slocum, "The power balancing benefits of wave energy converters in offshore wind-wave farms with energy storage," *Applied Energy*, vol. 331, p. 120389, 2023.

[109] D. Pagnani, Ł. Kocewiak, J. Hjerrild, F. Blaabjerg, and C. L. Bak, "Integrating black start capabilities into offshore wind farms by grid-forming

batteries," *IET Renewable Power Generation*, vol. 17, no. 14, pp. 3523–3535, 2023.

[110] Y. Liu, Z. Duan, P. Hu, C. Hu, J. Zheng, and Z. Li, "Mmc submodule topology with cvsb and dcfrt capability for offshore wind farms black-start," *IEEE Transactions on Industry Applications*, 2023.

[111] D. Pagnani, F. Blaabjerg, C. L. Bak, F. M. Faria da Silva, Ł. H. Kocewiak, and J. Hjerrild, "Offshore wind farm black start service integration: Review and outlook of ongoing research," *Energies*, vol. 13, no. 23, p. 6286, 2020.

[112] H. Tang, X. Guo, X. Shen, R. Yang, and G. Shi, "Coordinated black-start strategy for offshore wind farms and vsc-hvdc system," in *2024 7th International Conference on Energy, Electrical and Power Engineering (CEEPE)*, pp. 1322–1327, IEEE, 2024.

[113] M. Diaz, R. Cárdenas Dobson, E. Ibaceta, A. Mora, M. Urrutia, M. Espinoza, F. Rojas, and P. Wheeler, "An overview of applications of the modular multilevel matrix converter," *Energies*, vol. 13, no. 21, p. 5546, 2020.

[114] M. Ghassemi, "High power density technologies for large generators and motors for marine applications with focus on electrical insulation challenges," *High Voltage*, vol. 5, no. 1, pp. 7–14, 2020.

[115] B. Zhou, Z. Zhang, G. Li, D. Yang, and M. Santos, "Review of key technologies for offshore floating wind power generation," *Energies*, vol. 16, no. 2, p. 710, 2023.

[116] A. Follo, O. Saborío-Romano, E. Tedeschi, and N. Cutululis, "Challenges in all-dc offshore wind power plants. energies 2021, 14, 6057," 2021.

[117] S. Tian, "Novel hybrid hvdc system for resilient and efficient operation of offshore wind farms," 2024.

[118] A. Garcés and M. Molinas, "Impact of operation principle on the losses of a reduced matrix converter for offshore wind parks," in *2010 IEEE International Symposium on Industrial Electronics*, pp. 2412–2419, IEEE, 2010.

[119] A. Mishra, M. K. Pandey, and S. Singh, "Grid-connected wind technology: Integration challenges and grid compliance," in *Renewable Energy Integration in Utility Grids*, pp. 19–49, Elsevier, 2025.

[120] M. M. Kabsha and Z. H. Rather, "Adaptive control strategy for frequency support from mtdc connected offshore wind power plants," *IEEE Transactions on Power Electronics*, vol. 38, no. 3, pp. 3981–3991, 2022.

[121] S. W. Ali, M. Sadiq, Y. Terriche, S. A. R. Naqvi, M. U. Mutarraf, M. A. Hassan, G. Yang, C.-L. Su, J. M. Guerrero, *et al.*, "Offshore wind farm-grid integration: A review on infrastructure, challenges, and grid solutions," *IEEE Access*, vol. 9, pp. 102811–102827, 2021.

[122] D. CAMPOS GAONA, O. Anaya-Lara, and J. O. Tande, "Offshore wind farm technology and electrical design," *Offshore Wind Energy Technology*, p. 239, 2018.

[123] N. Kushwaha and S. Kaur, "A review of the statcom device for improving wind farm stability," *J. Elect. Eng*, vol. 16, no. 3, pp. 41–48, 2023.

[124] A. Rehman, M. A. Koondhar, Z. Ali, M. Jamali, and R. A. El-Sehiemy, "Critical issues of optimal reactive power compensation based on an hvac transmission system for an offshore wind farm," *Sustainability*, vol. 15, no. 19, p. 14175, 2023.

[125] C. Ruiz, G. Abad, M. Zubiaga, D. Madariaga, and J. Arza, "Wind turbine oriented solutions to improve power quality and harmonic compliance of ac offshore wind power plants," *IEEE Access*, vol. 9, pp. 167096–167116, 2021.

[126] C. J. Pillay, *Comparative analysis of high voltage alternating current & high voltage direct current offshore collection grid systems*. PhD thesis, 2021.

[127] K. Musasa, N. I. Nwulu, M. N. Gitau, and R. C. Bansal, "Review on dc collection grids for offshore wind farms with high-voltage dc transmission system," *IET Power Electronics*, vol. 10, no. 15, pp. 2104–2115, 2017.

[128] G. Abeynayake, G. Li, J. Liang, and N. A. Cutululis, "A review on mvdc collection systems for high-power offshore wind farms," in *2019 14th Conference on Industrial and Information Systems (ICIIS)*, pp. 407–412, IEEE, 2019.

[129] Y. Song, Z. Zhang, and Z. Xu, "Modular combined dc-dc autotransformer for offshore wind power integration with dc collection," *Applied Sciences*, vol. 12, no. 4, p. 1810, 2022.

[130] V. Timmers, A. E. Alvarez, and A. Gkountaras, "A systematic review of dc wind farm collector cost-effectiveness," 2021.

[131] M. D. P. Gil, J. L. Domínguez-García, F. Díaz-González, M. Aragüés-Peñalba, and O. Gomis-Bellmunt, "Feasibility analysis of offshore wind power plants with dc collection grid," *Renewable Energy*, vol. 78, pp. 467–477, 2015.

[132] J. Pan, L. Qi, J. Li, M. Reza, and K. Srivastava, "Dc connection for large-scale wind farms," in *Proceedings of the 9th Wind Integration Workshop, Quebec City, QC, Canada*, pp. 18–19, 2010.

[133] Y. Zhang, S. Liu, J. Lyu, Z. Yang, Z. Li, and X. Cai, "A low-cost power-taking scheme for self-starting of unidirectional diode-rectified dc wind turbines with medium-voltage direct current transmission," 2019.

[134] Y. Song, X. Chang, and H. Wang, "Comprehensive evaluation model and methodology for offshore wind farm collection and transmission systems," *Journal of Marine Science and Engineering*, vol. 11, no. 11, p. 2169, 2023.

[135] M. Pape and M. Kazerani, "An offshore wind farm with dc collection system featuring differential power processing," *IEEE Transactions on Energy Conversion*, vol. 35, no. 1, pp. 222–236, 2019.

[136] M. A. Bahmani, T. Thiringer, A. Rabiei, and T. Abdulahovic, "Comparative study of a multi-mw high-power density dc transformer with an optimized high-frequency magnetics in all-dc offshore wind farm," *IEEE Transactions on power delivery*, vol. 31, no. 2, pp. 857–866, 2015.

[137] P. Li, D. Jovcic, E. Hodge, and J. Fitzgerald, "Analysis of bidirectional 15 mw current source dc/dc converter for series-connected superconducting-based 1 gw/100 kv offshore wind farm," *Electric Power Systems Research*, vol. 202, p. 107618, 2022.

[138] H. J. Bahirat and B. A. Mork, "Operation of dc series–parallel connected offshore wind farm," *IEEE Transactions on Sustainable Energy*, vol. 10, no. 2, pp. 596–603, 2018.

[139] J. Guo, X. Wang, Z. Zhang, H. Li, P. Lakshmanan, and J. Liang, "Energy curtailment analysis of offshore wind farms with dc series-parallel collection systems," in *2015 5th International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT)*, pp. 2014–2019, IEEE, 2015.

[140] P. Lakshmanan, "Power curtailment analysis of dc series–parallel offshore wind farms," *Wind*, vol. 2, no. 3, pp. 466–478, 2022.

[141] H. Zhang, F. Gruson, D. M. F. Rodriguez, and C. Saudemont, "Overvoltage limitation method of an offshore wind farm with dc series-parallel collection grid," *IEEE Transactions on Sustainable Energy*, vol. 10, no. 1, pp. 204–213, 2018.

[142] M. S. Mastoi, S. Zhuang, M. Haris, M. Hassan, and A. Ali, "Large-scale wind power grid integration challenges and their solution: a detailed review," *Environmental Science and Pollution Research*, vol. 30, no. 47, pp. 103424–103462, 2023.

[143] A. Darwish and G. A. Aggidis, "A review on power electronic topologies and control for wave energy converters," *Energies*, vol. 15, no. 23, p. 9174, 2022.

[144] D. Jovcic, H. Zhang, D. Findlay, A. Annuar, and B. Li, "Subsea dc collection grid with high power security for offshore renewables," *International Transactions on Electrical Energy Systems*, vol. 27, no. 2, p. e2249, 2017.

[145] New York State Energy Research and Development Authority (NYSERDA), "Nyserda mesh-ready guidelines for offshore wind integration," 2023. Accessed: November 22, 2024.

[146] V. Mier, P. Casielles, J. Coto, and L. Zeni, "Voltage margin control for offshore multi-use platform integration," in *Proceedings of the 2012 International Conference on Renewable Energies and Quality (ICREPQ12)*, pp. 28–30, 2012.

[147] S. Sayed and A. Massoud, "Minimum transmission power loss in multi-terminal hvdc systems: A general methodology for radial and mesh networks," *Alexandria Engineering Journal*, vol. 58, no. 1, pp. 115–125, 2019.

[148] J. L. Rodríguez-Amenedo, S. Arnaltes-Gómez, M. Aragüés-Peñalba, and O. Gomis-Bellmunt, "Control of the parallel operation of vsc-hvdc links connected to an offshore wind farm," *IEEE Transactions on Power Delivery*, vol. 34, no. 1, pp. 32–41, 2018.

[149] E. Pierri, O. Binder, N. G. Hemdan, and M. Kurrat, "Challenges and opportunities for a european hvdc grid," *Renewable and Sustainable Energy Reviews*, vol. 70, pp. 427–456, 2017.

[150] P. Rodriguez and K. Rouzbehi, "Multi-terminal dc grids: challenges and prospects," *Journal of Modern Power Systems and Clean Energy*, vol. 5, no. 4, pp. 515–523, 2017.

[151] Q. Wei, B. Wu, D. Xu, and N. R. Zargari, "Medium frequency transformer based configuration for voltage source converter based offshore wind farm," in *2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia)*, pp. 3521–3525, IEEE, 2016.

[152] H. J. Bahirat, G. H. Kjølle, B. A. Mork, and H. K. Høidalen, "Reliability assessment of dc wind farms," in *2012 IEEE Power and Energy Society General Meeting*, pp. 1–7, IEEE, 2012.

[153] M. Cullinane, F. Judge, M. O'Shea, K. Thandayutham, and J. Murphy, "Subsea superconductors: The future of offshore renewable energy transmission?," *Renewable and Sustainable Energy Reviews*, vol. 156, p. 111943, 2022.

[154] W. C. S. Amorim, D. do Carmo Mendonça, R. O. de Sousa, A. F. Cupertino, and H. A. Pereira, "Analysis of double-star modular multilevel topologies applied in hvdc system for grid connection of offshore wind power plants," *Journal of Control, Automation and Electrical Systems*, vol. 31, pp. 436–446, 2020.

[155] A. K. Biswas, S. I. Ahmed, S. K. Akula, and H. Salehfar, "High voltage ac (hvac) and high voltage dc (hvdc) transmission topologies of offshore wind power and reliability analysis," in *2021 IEEE Green Technologies Conference (GreenTech)*, pp. 271–278, IEEE, 2021.

[156] R. Ryndzionek and Ł. Sienkiewicz, "Evolution of the hvdc link connecting offshore wind farms to onshore power systems," *Energies*, vol. 13, no. 8, p. 1914, 2020.

[157] L. Cai, "Offshore wind farm grid connection with diode rectifier unit hvdc and phase shifting transformer," in *Wind Turbines-Advances and Challenges in Design, Manufacture and Operation*, IntechOpen, 2022.

[158] O. E. Oni, I. E. Davidson, and K. N. Mbangula, "A review of lcc-hvdc and vsc-hvdc technologies and applications," in *2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC)*, pp. 1–7, IEEE, 2016.

[159] N. Flourentzou, V. G. Agelidis, and G. D. Demetriades, "Vsc-based hvdc power transmission systems: An overview," *IEEE Transactions on power electronics*, vol. 24, no. 3, pp. 592–602, 2009.

[160] P. Singh, T. Bhattacharya, and D. Chatterjee, "Voltage and frequency control of the ac grid at offshore wind farms during disturbances in the hvdc link to onshore grid," in *2022 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)*, pp. 1–6, IEEE, 2022.

[161] Y. Xue and X.-P. Zhang, "Reactive power and ac voltage control of lcc hvdc system with controllable capacitors," *IEEE transactions on power systems*, vol. 32, no. 1, pp. 753–764, 2016.

[162] G. Buigues, V. Valverde, A. Etxegarai, P. Eguía, and E. Torres, "Present and future multiterminal hvdc systems: current status and forthcoming developments," in *Proc. Int. Conf. Renewable Energies Power Quality*, vol. 1, pp. 83–88, 2017.

[163] F. Fein and B. Orlik, "Dual hvdc system with line-and self-commutated converters for grid connection of offshore wind farms," in *2013 International Conference on Renewable Energy Research and Applications (ICRERA)*, pp. 280–285, IEEE, 2013.

[164] S. Lu, Z. Xu, L. Xiao, W. Jiang, and X. Bie, "Evaluation and enhancement of control strategies for vsc stations under weak grid strengths," *IEEE Transactions on Power Systems*, vol. 33, no. 2, pp. 1836–1847, 2017.

[165] R. Blasco-Gimenez, N. Aparicio, S. Añó-Villalba, and S. Bernal-Perez, "Lcc-hvdc connection of offshore wind farms with reduced filter banks," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 6, pp. 2372–2380, 2012.

[166] M. A. Koondhar, G. S. Kaloi, A. S. Saand, S. Chandio, W. Ko, S. Park, H.-J. Choi, and R. A. El-Sehiemy, "Critical technical issues with a voltage-source-converter-based high voltage direct current transmission system for the onshore integration of offshore wind farms," *Sustainability*, vol. 15, no. 18, p. 13526, 2023.

[167] Z. Zhang and X. Zhao, "Coordinated power oscillation damping from a vsc-hvdc grid integrated with offshore wind farms: Using capacitors energy," *IEEE Transactions on Sustainable Energy*, vol. 14, no. 2, pp. 751–762, 2022.

[168] M. Jiang, Q. Guo, and H. Sun, "Day-ahead voltage scheduling method based on a two-stage robust optimisation for vsc-hvdc connected wind farms," *IET Renewable Power Generation*, vol. 12, no. 13, pp. 1470–1477, 2018.

[169] B. Xu, H. Gao, and F. Peng, "Amplitude comparison protection for the collection system of vsc-hvdc connected offshore wind farms," in *2023 International Conference on Power System Technology (PowerCon)*, pp. 1–5, IEEE, 2023.

[170] E. Spahic and G. Balzer, "Offshore wind farms-vsc-based hvdc connection," in *2005 IEEE Russia Power Tech*, pp. 1–6, IEEE, 2005.

[171] S. Debnath, J. Qin, B. Bahrani, M. Saeedifard, and P. Barbosa, "Operation, control, and applications of the modular multilevel converter: A review," *IEEE transactions on power electronics*, vol. 30, no. 1, pp. 37–53, 2014.

[172] M. M. Merlin, T. C. Green, P. D. Mitcheson, D. R. Trainer, R. Critchley, W. Crookes, and F. Hassan, "The alternate arm converter: A new hybrid multilevel converter with dc-fault blocking capability," *IEEE transactions on power delivery*, vol. 29, no. 1, pp. 310–317, 2013.

[173] X. Yu, G. Bu, S. Wang, and B. Zhao, "Bpa based selection method for mmc reactive power control mode," in *2021 3rd Asia Energy and Electrical Engineering Symposium (AEEES)*, pp. 259–263, IEEE, 2021.

[174] J. B. Soomro, F. Akhtar, R. Hussain, J. Ahmed Ansari, H. M. Munir, *et al.*, "A detailed review of mmc circuit topologies and modelling issues," *International Transactions on Electrical Energy Systems*, vol. 2022, 2022.

[175] H. R. Wickramasinghe, G. Konstantinou, Z. Li, and J. Pou, "Alternate arm converters-based hvdc model compatible with the cigre b4 dc grid test system," *IEEE Transactions on Power Delivery*, vol. 34, no. 1, pp. 149–159, 2018.

[176] P. Sun, H. R. Wickramasinghe, and G. Konstantinou, "Hybrid lcc-aac hvdc transmission system," *Electric Power Systems Research*, vol. 192, p. 106910, 2021.

[177] R. Li, L. Yu, L. Xu, and G. P. Adam, "Coordinated control of parallel dr-hvdc and mmc-hvdc systems for offshore wind energy transmission," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 8, no. 3, pp. 2572–2582, 2019.

[178] F. Martinez-Rodrigo, D. Ramirez, A. B. Rey-Boue, S. De Pablo, and L. C. Herrero-de Lucas, "Modular multilevel converters: Control and applications," *Energies*, vol. 10, no. 11, p. 1709, 2017.

[179] J. Beerten, O. Gomis-Bellmunt, X. Guillaud, J. Rimez, A. Van Der Meer, and D. Van Hertem, "Modeling and control of hvdc grids: A key challenge for the future power system," in *2014 Power Systems Computation Conference*, pp. 1–21, IEEE, 2014.

[180] J. Zhong, W. Liu, H. Zhang, X. Zhao, X. Guan, and X. Li, "Topology and performance analysis of hybrid dc circuit breaker based on cascaded insulated gate bipolar translator full bridge submodules," in *2020 4th International Conference on HVDC (HVDC)*, pp. 124–128, IEEE, 2020.

[181] S. K. Chattopadhyay and C. Chakraborty, "Full-bridge converter with naturally balanced modular cascaded h-bridge waveshapers for offshore hvdc transmission," *IEEE Transactions on Sustainable Energy*, vol. 11, no. 1, pp. 271–281, 2019.

[182] A. Nami, J. L. R. Amenedo, S. Arnaltes, M. Á. C. Álvarez, and R. A. Baraciarte, "Frequency control of offshore wind farms with series-connected diode rectifier units-based hvdc connection," in *IECON 2019-45th Annual Conference of the IEEE Industrial Electronics Society*, vol. 1, pp. 7057–7062, IEEE, 2019.

[183] H. Zhou, W. Yao, M. Zhou, X. Ai, J. Wen, and S. Cheng, "Active energy control for enhancing ac fault ride-through capability of mmc-hvdc connected with offshore wind farms," *IEEE Transactions on Power Systems*, vol. 38, no. 3, pp. 2705–2718, 2022.

[184] H. Lin, T. Xue, J. Lyu, and X. Cai, "Impact of different ac voltage control modes of wind farm side mmc on the stability of mmc-hvdc with offshore wind farms," *Journal of Modern Power Systems and Clean Energy*, 2023.

[185] P. Tu, S. Yang, and P. Wang, "Reliability- and cost-based redundancy design for modular multilevel converter," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 3, pp. 2333–2342, 2019.

[186] H. Zhang, W. Xiang, Y. He, and J. Wen, "Optimal energy utilization of mmc-hvdc system integrating offshore wind farms for onshore weak grid inertia support," *IEEE Transactions on Power Systems*, 2023.

[187] H. Zhou, W. Yao, K. Sun, X. Ai, J. Wen, and S. Cheng, "Characteristic investigation and overvoltage suppression of mmc-hvdc integrated offshore wind farms under onshore valve-side spg fault," *IEEE Transactions on Power Systems*, 2023.

[188] P. Sun, Y. Tian, J. Pou, and G. Konstantinou, "Beyond the mmc: Extended modular multilevel converter topologies and applications," *IEEE Open Journal of Power Electronics*, vol. 3, pp. 317–333, 2022.

[189] M. S.-N. Thi and L. Wang, "Stability analysis of different offshore wind farms feeding into a large power grid through a hybrid hvdc link," in *2013 IEEE International Symposium on Industrial Electronics*, pp. 1–6, IEEE, 2013.

[190] R. E. Torres-Olguin, M. Molinas, and T. Undeland, "Hybrid hvdc connection of large offshore wind farms to the ac grid," in *2012 IEEE international symposium on industrial electronics*, pp. 1591–1597, IEEE, 2012.

[191] C. Li, P. Zhan, J. Wen, M. Yao, N. Li, and W.-J. Lee, "Offshore wind farm integration and frequency support control utilizing hybrid multiterminal hvdc transmission," *IEEE Transactions on Industry Applications*, vol. 50, no. 4, pp. 2788–2797, 2013.

[192] M. ElMenshawy and A. Massoud, "Medium-voltage dc-dc converter topologies for electric bus fast charging stations: State-of-the-art review," *Energies*, vol. 15, no. 15, p. 5487, 2022.

[193] H. Ding, G. Zou, N. Ding, and C. Wang, "Study of the ipos dc/dc converter for dc offshore wind farm," in *Journal of Physics: Conference Series*, vol. 2320, p. 012016, IOP Publishing, 2022.

[194] L. Li, H. Tian, B. Li, M. Yang, T. Wei, W. Li, and D. Xu, "High ratio dc/dc converter for offshore wind farms with mvdc collection system," in *PCIM Asia 2022; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*, pp. 1–8, VDE, 2022.

[195] S. Alagab, *DC-DC Converter for Power Collection in Wind Farms*. PhD thesis, Staffordshire University, 2019.

[196] V. Timmers, A. Egea-Àlvarez, A. Gkountaras, and L. Xu, "Design and comparison of dc/dc converters for dc-connected offshore wind turbines," *Dc Converters for Dc-Connected Offshore Wind Turbines*.

[197] Y. Lian, "Dc/dc converter for offshore dc collection network," 2016.

[198] P. Hu, R. Yin, B. Wei, Y. Luo, and F. Blaabjerg, "Modular isolated llc dc/dc conversion system for offshore wind farm collection and integration," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 9, no. 6, pp. 6713–6725, 2021.

[199] C. Dincan, P. Kjaer, Y.-h. Chen, S.-M. Nielsen, and C. L. Bak, "Selection of dc/dc converter for offshore wind farms with mvdc power collection," in *2017 19th European Conference on Power Electronics and Applications (EPE'17 ECCE Europe)*, pp. P–1, IEEE, 2017.

[200] A. Erat and A. M. Vural, "Dc/dc modular multilevel converters for hvdc interconnection: A comprehensive review.," *International Transactions on Electrical Energy Systems*, 2022.

[201] C. Zhan, C. Smith, A. Crane, A. Bullock, and D. Grieve, "Dc transmission and distribution system for a large offshore wind farm," 2010.

[202] H. J. Bahirat, B. A. Mork, and H. K. Hoidalen, "Comparison of wind farm topologies for offshore applications," in *2012 IEEE Power and Energy Society General Meeting*, pp. 1–8, IEEE, 2012.

[203] X. Bai, Y. Fan, and J. Hou, "Reliability assessment method of wind power dc collection system based on mlfta-smc," *Scientific Reports*, vol. 14, no. 1, p. 25341, 2024.

[204] C. P'erez-Collazo, D. Greaves, and G. Iglesias, "A review of combined wave and offshore wind energy," *Renewable and sustainable energy reviews*, vol. 42, pp. 141–153, 2015.

[205] H. Givi, E. Farjah, and T. Ghanbari, "A comprehensive monitoring system for online fault diagnosis and aging detection of non-isolated dc–dc converters' components," *IEEE Transactions on Power Electronics*, vol. 34, no. 7, pp. 6858–6875, 2018.

[206] A. Otter, J. Murphy, V. Pakrashi, A. Robertson, and C. Desmond, "A review of modelling techniques for floating offshore wind turbines," *Wind Energy*, vol. 25, no. 5, pp. 831–857, 2022.

[207] A. A. van der Meer, M. Ndreko, M. Gibescu, and M. A. van der Meijden, "The effect of frt behavior of vsc-hvdc-connected offshore wind power plants on ac/dc system dynamics," *IEEE Transactions on Power Delivery*, vol. 31, no. 2, pp. 878–887, 2015.

[208] W. Tahaguas, "Modeling and simulation of power system dynamics for studying the impacts of increasing wind power in a weak grid system," in *Res Electricae Magdeburgenses. Magdeburger Forum zur Elektrotechnik*, vol. 94, 2023.

[209] L. Fan and Z. Miao, "Wind in weak grids: 4 hz or 30 hz oscillations?," *IEEE Transactions on Power Systems*, vol. 33, no. 5, pp. 5803–5804, 2018.

[210] J. Bialek, "What does the gb power outage on 9 august 2019 tell us about the current state of decarbonised power systems?," *Energy Policy*, vol. 146, p. 111821, 2020.

[211] A. E. M. Operator, "Final report-queensland and south australia system separation on 25 august 2018," *AEMO Information & Support Hub, Tech. Rep., Australia*, 2019.

[212] C. Buchhagen, C. Rauscher, A. Menze, and J. Jung, "Borwin1-first experiences with harmonic interactions in converter dominated grids," in *International ETG Congress 2015; Die Energiewende-Blueprints for the new energy age*, pp. 1–7, VDE, 2015.

[213] M. Cheah-Mane, A. Egea-Alvarez, E. Prieto-Araujo, H. Mehrjerdi, O. Gomis-Bellmunt, and L. Xu, "Modeling and analysis approaches for small-signal stability assessment of power-electronic-dominated systems," *Wiley Interdisciplinary Reviews: Energy and Environment*, vol. 12, no. 1, p. e453, 2023.

[214] J. Vega-Herrera, C. Rahmann, F. Valencia, and K. Strunz, "Analysis and application of quasi-static and dynamic phasor calculus for stability assessment of integrated power electric and electronic systems," *IEEE Transactions on Power Systems*, vol. 36, no. 3, pp. 1750–1760, 2020.

[215] A. Sajadi, S. Zhao, K. Clark, and K. A. Loparo, "Small-signal stability analysis of large-scale power systems in response to variability of offshore wind power plants," *IEEE Systems Journal*, vol. 13, no. 3, pp. 3070–3079, 2018.

[216] J. Jia, C. Yang, H. Cui, M. Wu, J. Shao, B. Zhao, and K. He, "Systems and challenges in operation and maintenance of offshore wind power: A review," in *2023 8th Asia Conference on Power and Electrical Engineering (ACPEE)*, pp. 1407–1412, IEEE, 2023.

[217] P. Veers, C. L. Bottasso, L. Manuel, J. Naughton, L. Pao, J. Paquette, A. Robertson, M. Robinson, S. Ananthan, T. Barlas, *et al.*, "Grand challenges in the design, manufacture, and operation of future wind turbine systems," *Wind Energy Science*, vol. 8, no. 7, pp. 1071–1131, 2023.

[218] R. J. Barthelmie, K. Hansen, S. T. Frandsen, O. Rathmann, J. Schepers, W. Schlez, J. Phillips, K. Rados, A. Zervos, E. Politis, *et al.*, "Modelling and measuring flow and wind turbine wakes in large wind farms offshore," *Wind Energy: An International Journal for Progress and Applications in Wind Power Conversion Technology*, vol. 12, no. 5, pp. 431–444, 2009.

[219] G. Rinaldi, P. R. Thies, and L. Johanning, "Current status and future trends in the operation and maintenance of offshore wind turbines: A review," *Energies*, vol. 14, no. 9, p. 2484, 2021.

[220] M. Quester, V. Yellisetti, F. Loku, and R. Puffer, "Assessing the impact of offshore wind farm grid configuration on harmonic stability," in *2019 IEEE Milan PowerTech*, pp. 1–6, IEEE, 2019.

[221] S. Sulaeman, M. Benidris, J. Mitra, and C. Singh, "A wind farm reliability model considering both wind variability and turbine forced outages," *IEEE Transactions on Sustainable Energy*, vol. 8, no. 2, pp. 629–637, 2016.

[222] J. P. Arenas-López and M. Badaoui, "Stochastic modelling of wind speeds based on turbulence intensity," *Renewable Energy*, vol. 155, pp. 10–22, 2020.

[223] Z. Gong, A. Wan, Y. Ji, A.-B. Khalil, and Z. Yao, "Improving short-term offshore wind speed forecast accuracy using a vmd-pe-fcgru hybrid model," *Energy*, vol. 295, p. 131016, 2024.

[224] K. T. Hoang, C. A. Thilker, B. R. Knudsen, and L. Imsland, "Probabilistic forecasting-based stochastic nonlinear model predictive control for power systems with intermittent renewables and energy storage," *IEEE Transactions on Power Systems*, 2023.

[225] K. O. Yoro, M. O. Daramola, P. T. Sekoai, U. N. Wilson, and O. Eterigho-Ikelegbe, "Update on current approaches, challenges, and prospects of modeling and simulation in renewable and sustainable energy systems," *Renewable and Sustainable Energy Reviews*, vol. 150, p. 111506, 2021.

[226] Y.-K. Wu, W.-C. Wu, and J.-J. Zeng, "Key issues on the design of an offshore wind farm layout and its equivalent model," *Applied Sciences*, vol. 9, no. 9, p. 1911, 2019.

[227] M. Zou, C. Zhao, and J. Xu, "Modeling for large-scale offshore wind farm using multi-thread parallel computing," *International Journal of Electrical Power & Energy Systems*, vol. 148, p. 108928, 2023.

[228] S. Nomandela, M. E. Mnguni, and A. K. Raji, "Modeling and simulation of a large-scale wind power plant considering grid code requirements," *Energies*, vol. 16, no. 6, p. 2897, 2023.

[229] U. Karaagac, J. Mahseredjian, L. Cai, and H. Saad, "Offshore wind farm modeling accuracy and efficiency in mmc-based multiterminal hvdc connection," *IEEE Transactions on Power Delivery*, vol. 32, no. 2, pp. 617–627, 2016.

[230] S. Ganesh, A. Perilla, J. Rueda Torres, P. Palensky, A. Lekić, and M. van der Meijden, "Generic emt model for real-time simulation of large disturbances in 2 gw offshore hvac-hvdc renewable energy hubs," *Energies*, vol. 14, no. 3, p. 757, 2021.

[231] M. Zou, Y. Wang, C. Zhao, J. Xu, X. Guo, and X. Sun, "Integrated equivalent model of permanent magnet synchronous generator based wind turbine for large-scale offshore wind farm simulation," *Journal of Modern Power Systems and Clean Energy*, vol. 11, no. 5, pp. 1415–1426, 2023.

[232] L. M. Castro and E. Acha, "On the dynamic modeling of marine vsc-hvdc power grids including offshore wind farms," *IEEE Transactions on Sustainable Energy*, vol. 11, no. 4, pp. 2889–2900, 2020.

[233] K. Ji, G. Tang, H. Pang, and J. Yang, "Impedance modeling and analysis of mmc-hvdc for offshore wind farm integration," *IEEE Transactions on Power Delivery*, vol. 35, no. 3, pp. 1488–1501, 2019.

[234] M. Wang, Z. Cao, B. Liu, J. Li, T. Fernando, and X. Liu, "Impedance modeling and stability analysis of all-dc delivered offshore wind farm," *IEEE Journal on Emerging and Selected Topics in Circuits and Systems*, vol. 12, no. 1, pp. 20–28, 2022.

[235] L. Yu, L. Xu, J. Zhu, and R. Li, "Impedance modelling and stability analysis of diode-rectifier based hvdc connected offshore wind farms," *IEEE Transactions on Power Delivery*, vol. 37, no. 1, pp. 591–602, 2021.
[236] Y. Zhou, L. Zhao, W.-J. Lee, Z. Zhang, and P. Wang, "Optimal power flow in hybrid ac and multi-terminal hvdc networks with offshore wind farm integration based on semidefinite programming," in *2019 IEEE Innovative Smart Grid Technologies-Asia (ISGT Asia)*, pp. 207–212, IEEE, 2019.
[237] A. Haghshenas, A. Hasan, O. Osen, and E. T. Mikalsen, "Predictive digital twin for offshore wind farms," *Energy Informatics*, vol. 6, no. 1, p. 1, 2023.
[238] X. Wang, Y. Qi, X. Xu, R. Huang, Y. Ruan, and X. Bian, "A mixed model- and data-driven approach for subsynchronous oscillation analysis of vsc-hvdc grid-connected offshore wind farm," in *2021 IEEE 5th Conference on Energy Internet and Energy System Integration (EI2)*, pp. 848–853, IEEE, 2021.
[239] B. Marinescu, O. Gomis-Bellmunt, F. Dorfler, H. Schulte, and L. Sigrist, "Dynamic virtual power plant: A new concept for grid integration of renewable energy sources," *IEEE Access*, vol. 10, pp. 104980–104995, 2022.
[240] T.-T. Nguyen, T. Vu, T. Ortmeyer, G. Stefopoulos, G. Pedrick, and J. MacDowell, "Real-time transient simulation and studies of offshore wind turbines," *IEEE Transactions on Sustainable Energy*, vol. 14, no. 3, pp. 1474–1487, 2023.
[241] S. Subedi, M. Rauniyar, S. Ishaq, T. M. Hansen, R. Tonkoski, M. Shirazi, R. Wies, and P. Cicilio, "Review of methods to accelerate electromagnetic transient simulation of power systems," *IEEE Access*, vol. 9, pp. 89714–89731, 2021.
[242] L. T. F. da Silva, M. A. Tomim, P. G. Barbosa, P. M. de Almeida, and R. F. da Silva Dias, "Modeling and simulating wind energy generation systems by means of co-simulation techniques," *Energies*, vol. 16, no. 19, p. 7013, 2023.
[243] A. Raab, D. Frauenknecht, M. Luther, A. Kuri, and A. Wellhoefer, "Hybrid emt and phasor based mmc-hvdc model for advanced power system simulation," in *2022 IEEE Power & Energy Society General Meeting (PESGM)*, pp. 1–5, IEEE, 2022.
[244] V. A. Lacerda, E. P. Araujo, M. Cheah-Mañe, and O. Gomis-Bellmunt, "Phasor modeling approaches and simulation guidelines of voltage-source converters in grid-integration studies," *IEEE access*, vol. 10, pp. 51826–51838, 2022.
[245] G. Rinaldi, A. Garcia-Teruel, H. Jeffrey, P. R. Thies, and L. Johanning, "Incorporating stochastic operation and maintenance models into the techno-economic analysis of floating offshore wind farms," *Applied Energy*, vol. 301, p. 117420, 2021.
[246] K. Sun, K.-J. Li, W.-J. Lee, W. Bao, Z. Liu, M. Wang, *et al.*, "Vsc-mtdc system integrating offshore wind farms based optimal distribution method for financial improvement on wind producers," *IEEE Transactions on Industry Applications*, vol. 55, no. 3, pp. 2232–2240, 2019.
[247] A. Rabiee, A. Soroudi, and A. Keane, "Information gap decision theory based opf with hvdc connected wind farms," *IEEE Transactions on Power Systems*, vol. 30, no. 6, pp. 3396–3406, 2014.
[248] J. N. Sakamuri, Ö. Göksu, A. Bidadfar, O. Saborío-Romano, A. Jain, and N. A. Cutululis, "Black start by hvdc-connected offshore wind power plants," in *IECON 2019-45th Annual Conference of the IEEE Industrial Electronics Society*, vol. 1, pp. 7045–7050, IEEE, 2019.
[249] A. Shahmohammadi, R. Sioshansi, A. J. Conejo, and S. Afsharnia, "Market equilibria and interactions between strategic generation, wind, and storage," *Applied energy*, vol. 220, pp. 876–892, 2018.
[250] A. Çiçek and O. Erdinç, "Optimal bidding strategy considering bilevel approach and multistage process for a renewable energy portfolio manager managing ress with ess," *IEEE Systems Journal*, vol. 16, no. 4, pp. 6062–6073, 2021.
[251] J. Wu, J. Wang, and X. Kong, "Strategic bidding in a competitive electricity market: An intelligent method using multi-agent transfer learning based on reinforcement learning," *Energy*, vol. 256, p. 124657, 2022.

DEEPI SINGH received the bachelor's degree in electrical engineering from Muzaffarpur Institute of Technology, Muzaffarpur, Bihar, India, and the master's degree in power and controls from the Indian Institute of Information Technology, Jabalpur, Madhya Pradesh, India, in 2017. She is currently working toward the Ph.D. degree in electrical engineering with Stony Brook University, Stony Brook, New York, USA. She has three years of teaching and research experience as an Assistant Professor with Government Engineering College, Bilaspur, Chhattisgarh, India, under the Technical Education Quality Improvement Project III of the World Bank. She has been involved in research projects with the Atlantic Marine Energy Centre, Durham, NH, USA, and Office of Naval Research, Arlington, VA, USA. She has recently completed her research internship as Power and Control Engineer at Mitsubishi Electrical research Lab (MERL). Her research interests include the domain of distributed energy resources and their impeccable grid integration, advanced control methodologies, the augmentation of microgrid resiliency, and the intricate realm of real- time power system monitoring.

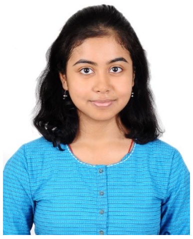
DANA GOLDEN received B.S. and M.S. degrees in economics from the Georgia Institute of Technology in Atlanta, in 2018. She also received an M.S. degree in analytics in 2022.

From 2019 to 2021, she worked as an Agricultural Economist for the USDA Economic Research Service. She interned as an Industry Analyst the Federal Energy Regulatory Commission in the Summer of 2022. She also worked as a Data Scientist for the Treasury and an economist for the USDA Economic Research Service in 2023. Since 2021, She has been a PhD Student in economics at Stony Brook University. Her research interests research interests focus mainly on energy markets, machine learning, and empirical industrial organization.

Ms. Golden was a recipient of the Stony Brook Economics Diversity Fellowship in 2021 and the Bias NRT Fellowship in 2023.

GAURAV BHANSALI earned his degree in Electrical Engineering from Jai Narain Vyas University (JNVU), in 2012 and did his Masters in Power Systems from Malaviya National Institute of Technology (MNIT), Jaipur, India in 2014. Currently, he is pursuing Ph.D. in Electrical Engineering from the Stony Brook University, New York, USA. His research interest includes development of DC-DC and AC-DC power electronic converters utilizing wide band gap (WBG) devices for renewable energy and hydrogen generation applications. His work emphasizes control and optimization strategies for Hybrid Energy Grid networks. Prior to joining PhD, he worked extensively in the power sector focusing on design and execution of power distribution grid networks for smart cities, as well as in power trading for the distribution business.

ALI ANWAR received the B.S. degree in Electrical Engineering from GIK Institute, Pakistan, in 2010, and the M.E. degree in Electrical Engineering from RMIT University, Melbourne, Australia, in 2016. He is currently pursuing the Ph.D. degree in Electrical Engineering with the Spellman High Voltage Power Electronics Laboratory, Department of Electrical and Computer Engineering, Stony Brook University, New York, USA. His research interests include power electronic converter design, the analysis and mitigation of electromagnetic interference (EMI) in wide-bandgap (WBG) device-based power converters, partial discharge phenomena, and reflected wave modeling in motor drives.



SHREEPOOJA SINGH received the B.Tech. degree in Electrical and Electronics Engineering from SRM Institute of Science and Technology, India, and the M.Tech. degree in Power Electronics and Systems from Delhi Technological University, India. She is currently pursuing the Ph.D. degree in Power Electronics with the Spellman High Voltage Power Electronics Laboratory, Department of Electrical and Computer Engineering, Stony Brook University, New York, USA. Her research interests include the integration of power electronic converters and advanced battery management systems for renewable energy applications, as well as enhancing the reliability and resiliency of microgrids to improve the efficiency and sustainability of future energy networks.

FANG LUO received the bachelor's and Ph.D. degrees in power electronics from the Huazhong University of Science and Technology, Wuhan, China, and jointly from Virginia Tech, Blacksburg, VA, USA, in 2003 and 2010, respectively. He was an Assistant Professor with the Electrical Engineering Department, University of Arkansas, Fayetteville, AR, USA, from 2017 to 2020, and a Research Assistant Professor with The Ohio State University, Columbus, OH, USA, from 2014 to 2017. He was a Visiting Ph.D. student, from 2007 to 2010, and then a Postdoctoral Researcher, from 2010 to 2014, with Virginia Tech, Blacksburg, VA, USA. He is currently an Empire Innovation Associate Professor and the Director of the Spellman High Voltage Laboratory, Stony Brook University (SUNY Stony Brook), Stony Brook, NY, USA, with his background in power electronics. His research interests include high power density converter design, high-density electromagnetic interference filter design and integration, and power module packaging/integration for wide bandgap devices. Dr. Luo is also a Member of American Institute of Aeronautics and Astronautics and American Society of Mechanical Engineers. He was the recipient of the NSF CAREER Award.

YIYI ZHOU received a BA in Finance from University of International Business and Economics in Beijing, China. She then received an MA in economics from Peking University in Peking, China followed by a PhD in economics from from the University of Virginia in Charlottesville, Virginia.

Since 2012, she has served as a Professor in the Departments of Economics and Business at Stony Brook University. Her publications include "The Market for Electric Vehicles: Indirect Network Effects and Policy Impacts" and "An Equilibrium Search Model of Inventory Management." Her research interests focus on Industrial Organization, Environmental Economics, and Health Economics.

Dr. Zhou recieved the Snavely Dissertation Prize from the University of Virginia in 2012 and the Summer Grant of the NET Institute in 2015.