

Review on Emerging Collection and Transmission Technologies for Large-scale Offshore Wind Power

Huangqing Xiao, Huichen Gan, Ying Huang, Lidong Zhang, and Ping Yang

Abstract—The rapid development of large-scale offshore wind power (OWP) calls for more cost-effective and reliable collection and transmission technologies. This paper explores three emerging collection technologies: medium-frequency alternating current (AC) collection, direct current (DC) collection, and AC collection without substation; and three transmission technologies: voltage source converter-based high-voltage direct current based on compact modular multilevel converters (MMCs), diode rectifier unit (DRU) based high-voltage direct current (DRU-HVDC), and high-voltage direct current (HVDC) based on hybrid converters. It systematically reviews recent research advancements in these technologies, analyzes critical technical challenges, and identifies key future development trends, providing practical insights to guide the design and optimization of OWP projects. At the collection level, a higher frequency reduces the size of critical equipment in offshore platforms but also leads to increased cable costs. DC offshore wind farms offer advantages such as lower cable costs. However, the design of high-power DC transformers presents challenges. At the transmission level, the size and weight of MMCs can be minimized through topology improvement and control optimization. The practical deployment of DRUs and HVDC systems depends on the technology maturity of grid-forming wind turbines. Moreover, critical aspects of hybrid converters such as capacity design, coordinated control, and stability analysis require further in-depth investigation.

Index Terms—Offshore wind power (OWP), medium-frequency alternating current (AC) collection, direct current (DC) collection, modular multilevel converter (MMC), high-voltage direct current (HVDC), diode rectifier unit (DRU), hybrid converter.

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I. INTRODUCTION

TO combat global climate change and accelerate carbon reduction, offshore wind power (OWP) is advancing globally towards larger scale, greater clusters, longer distance, and deeper water. By the end of 2023, the global cumulative installed capacity of OWP reached 75.2 GW, representing a year-on-year growth of approximately 17.2% [1]. Additionally, several countries have set offshore wind capacity targets for 2030, including 60 GW for China, 50 GW for the UK, 30 GW for Germany, and 30 GW for the United States [2]. Although OWP has grown significantly, integrating such large-scale wind power into the onshore grid remains a major challenge [3].

To fill the gap, the voltage source converter (VSC)-based high-voltage direct current (HVDC), i. e., VSC-HVDC, has been widely adopted for long-distance OWP integration [4]. In 2010, Germany commissioned the world's first offshore wind VSC-HVDC project, known as BorWin1 project, with a capacity of 400 MW and a bipolar voltage of ± 150 kV. The entire converter station weighs approximately 5000 tons [5]. The BorWin3 project, commissioned in 2019 with the capacity of 900 MW and the voltage of ± 320 kV, has a top-side converter station weighing 18500 t [6]. It is evident that as transmission capacity continues to increase, the size and weight of key equipment in offshore converter stations will also grow [7]. This increase poses major challenges in installation, transportation, and maintenance, creating significant economic and technical barriers to OWP grid integration. These limitations critically constrain the large-scale development of far-offshore wind farms [8].

To improve the cost-effectiveness and reliability of far-OWP integration systems, scholars have proposed various solutions at both the collection and transmission levels.

At the collection level, three primary technologies have been proposed. The first is the medium-frequency alternating current (MFAC) collection. MFAC collection adopts higher operation frequencies to dramatically reduce transformer and filter sizes through electromagnetic induction principles, thereby decreasing both capital costs and design complexity of offshore platforms. The second is the direct current (DC) collection, which provides an effective solution to the escalating reactive power and overvoltage challenges associated with longer alternating current (AC) collector cables in ex-

panding offshore wind farms. And the size and weight of offshore platform can be further reduced by eliminating large-capacity AC/DC converters. The third is the AC collection without substation. The innovative 66 kV direct-connection links the AC collection system directly to the converter station, which improves the economic viability of far-offshore integration.

At the transmission level, three primary technologies have been developed. The first is the VSC-HVDC based on compact modular multilevel converter (MMC). MMC represents the bulkiest component in offshore converter stations, owing to its large number of power devices and series-connected submodules (SMs) compared with equivalent-capacity line-commutated converters (LCCs). SM capacitor accounts for 60% of the SM volume and contributes approximately 40% of the total cost [9]. Thus, compact MMC designs can be realized by reducing the SM capacitance. The second is the diode rectifier unit (DRU)-based HVDC (DRU-HVDC). The DRU-HVDC has several advantages, including a smaller size, lower cost, higher power density, and simpler control. Compared with VSC-HVDC, it achieves 80% platform volume reduction, 65% weight reduction, and 30% capital expenditure savings [10]. These compelling economic benefits position DRU-HVDC as a transformative technology for next-generation OWP transmission systems. The third is the HVDC based on hybrid converters. A hybrid converter configuration integrates the voltage control capabilities of MMCs with the economic advantages of DRUs. In this configuration, the small-capacity MMC regulates offshore AC voltage/frequency and provides reactive power support and harmonic mitigation, whereas the DRU transmits the majority of wind farm output power to optimize the overall system economics.

Cost-effective, high-efficiency, and reliable integration technologies are crucial for enabling the clustered development and large-scale deployment of offshore wind farms. This paper provides a comprehensive review of the emerging collection and transmission technologies for large-scale OWP. Sections II and III analyze emerging collection and transmission system technologies for large-scale OWP, respectively. Section IV presents development trends and prospect of efficient technologies for large-scale OWP. The conclusions are summarized in Section V.

II. EMERGING COLLECTION TECHNOLOGIES FOR LARGE-SCALE OWP

A. MFAC Collection

The MFAC collection is proposed in [11]-[13], where the rated operation frequency of the offshore AC system is increased from the power frequency to the medium frequency (100-200 Hz). The configuration of the MFAC collection is shown in Fig. 1.

Increasing the operation frequency of offshore AC systems is advantageous to the reduction of the size and weight of the transformer, particularly in wind farms, offshore substations, and offshore converter stations [14]. This is because the operation frequency exhibits an inverse proportionality

with both the product of winding geometric parameters (e.g., length, turns, core area) and leakage inductance under constant voltage and power conditions, as established by classical transformer theory.

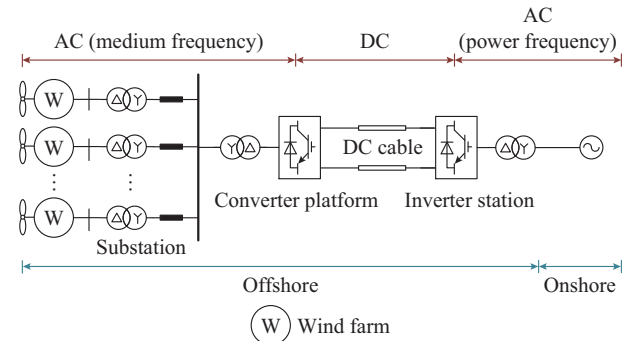


Fig. 1. Configuration of MFAC collection.

Increasing the frequency can also reduce the size of the filters in wind farms and offshore converter stations. According to fundamental design rule for tuned filters, at a given AC voltage level, the required inductance and capacitance are inversely proportional to the system operation frequency. Thus, increasing the operation frequency can proportionally reduce the required capacitance and inductance of the AC filters.

Increasing the operation frequency of offshore AC system also benefits the size and weight of MMC. This is because the system operation frequency is inversely proportional to the fluctuation of the SM capacitance of MMC.

However, higher system operation frequencies increase the charging currents of submarine cable, potentially requiring the cables with larger conductor cross-sectional areas. But this impact remains manageable for offshore AC collection systems due to their limited spatial coverage, preserving the cost-effectiveness of the MFAC collection. Furthermore, while higher system operation frequencies may exacerbate AC line losses, transformer losses, and converter operation losses, these effects can be effectively mitigated through optimized converter control strategies and appropriate technical measures. Moreover, the offshore wind farm should operate at a medium frequency. For phase-locked loop (PLL)-based wind turbines (WTs), only the grid-side converter requires adaptation, while other components remain largely unchanged. The grid-forming WTs require both the main circuit and controller to support medium-frequency operation. Although MFAC collection has not yet been adopted in commercial projects, the underlying technologies, particularly medium-frequency-compatible WTs, are technically mature and hold strong potential for future deployment.

In conclusion, the MFAC collection has advantages in reducing the size of key equipment such as transformers and filters within offshore platforms, facilitating a more cost-effective design for offshore converter stations. Future research will primarily focus on the economic analysis of different configuration of OWP transmission systems with MFAC collection [15], including determining the optimal operation frequency range for offshore AC systems, selecting

main circuit parameters, and exploring engineering applications based on the results of these economic studies [16].

B. DC Collection

Currently, OWP mostly employs medium-voltage AC (MVAC) collection and HVDC transmission. However, as wind farms move farther from shore, two challenges arise, including the excessive reactive power in long AC cables and the weight limitations of offshore platform [17]. To address these challenges, fully DC OWP systems with DC collection and transmission are emerging.

Depending on whether there is a substation or not, a fully DC OWP system can be divided into two types: the system without and with offshore substation. In the system without an offshore substation [18], [19], the wind farm voltage is directly increased to the transmission level by connecting DC-side WTs (DCWTs) in series. This design reduces both size and investment costs since it eliminates the need for an offshore converter station. However, due to the series connection of the DCWTs, the turbine positioned at the highest voltage level must endure the full DC voltage, significantly complicating the insulation design.

In systems with an offshore substation [20]-[23], the networking scheme can be categorized into two structures based on energy collecting forms: parallel-connected networking [24] and series-connected networking [18]. Figure 2 illustrates the DC collection structure for OWP.

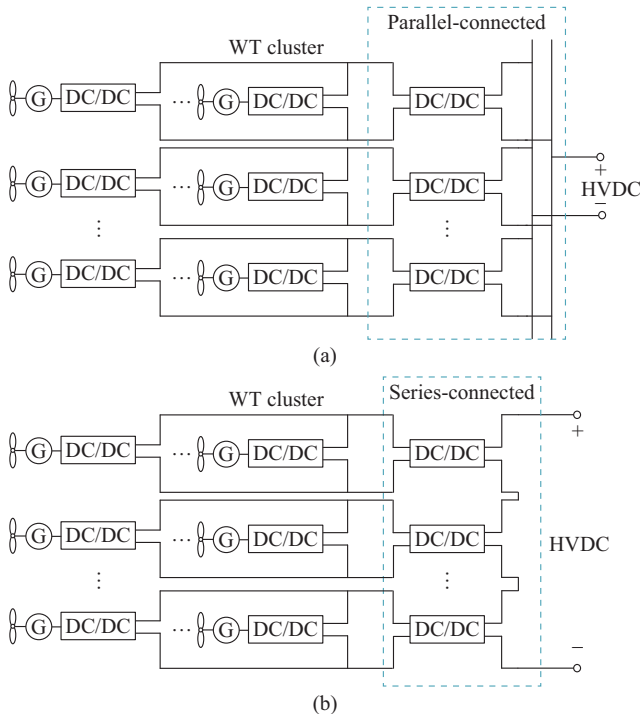


Fig. 2. DC collection structure for OWP. (a) Parallel-connected networking. (b) Series-connected networking.

In the parallel-connected networking, the DC/DC converter is connected to each WT cluster, stepping up medium DC voltage to transmission level for HVDC bus integration. This architecture provides enhanced system reliability and operation flexibility through decentralized power conversion. How-

ever, present power electronic limitations necessitate multiple small-capacity isolated DC/DC converters connected in series and parallel configurations to achieve medium-voltage operation, resulting in the increase in volume and mass of the DC collection [25], [26]. To address the limitations, a modular high-power DC-DC converter is proposed in [27] that parallels SMs at the low-voltage side to share current stress and connects them in series at the high-voltage side to share voltage stress. This configuration offers high efficiency and reduced cost and volume.

In the series-connected networking, WT clusters with low-voltage DC (LVDC) outputs are connected to the LVDC terminals of “DC/AC + AC/DC” converters, achieving HVDC transmission through sequential voltage boosting [18]. This configuration reduces the number of SMs in the DC/DC converters, significantly decreasing the volume and cost of the DC collection. However, each WT unit operates as a coupled controlled voltage source, requiring precise and complex system coordination, which increases the difficulty in system control and fault protection. Additionally, wind speed variations cause voltage mismatches that hinder the maximum power point tracking (MPPT), reducing captured energy and efficiency. Moreover, achieving fault isolation and fault ride-through is critical in offshore environments due to the high maintenance costs. Although solutions such as solid-state circuit breakers, redundant cabling, and chopper circuits are available, they considerably increase the overall system complexity and cost. To address tight coupling, complex coordination, and limited MPPT capability, [28] proposes a multifunctional DC collector that decouples series-connected WTs, enabling independent MPPT under varying wind conditions. This collector also supports fault isolation, dynamic cut-in/out, and controlled energy dissipation.

Future technological advancements will focus on the development of key equipment [28]-[30]. For instance, increasing the frequency of isolated DC/DC converters to further reduce the size and weight of isolation transformers, decreasing arm inductances and SM capacitances, and refining the topology and control strategies of DC/DC converters.

C. AC Collection Without Substation

In the conventional collection schemes, the wind energy is first collected and then stepped up via collector transformers before the transmission through the offshore converter station. Notably, the roles of the collector transformer and the converter transformer overlap. Integrating these transformers on a single platform can significantly reduce the investment of the offshore platforms and shorten the installation and construction timelines.

In 2016, the concept of a modular HVDC platform was proposed for OWP. As shown in Fig. 3, this design of AC collection structure for OWP enables offshore wind farms to transmit power directly to the offshore converter station via 66 kV AC cables, eliminating the need for a collector transformer [31]. The modular components can be assembled onshore. Compared with the DolWin2 project, the modular platform reduces the top-side weight by approximately 50% to 60%. The modular HVDC platform was implemented in the

DolWin5 project [32]. Reference [27] evaluates the technical maturity and economic benefits of two OWP integration schemes: one without offshore AC substation and the other with an AC substation that increases voltage from 35 kV to 220 kV. The result shows that the former scheme is better in both technical and economic terms. Optimizing the layout of a 66 kV offshore wind farm can further improve the cost-effectiveness of the OWP integration system [33]. Overall, the AC collection without substation is well-suited for large-scale OWP integration system.

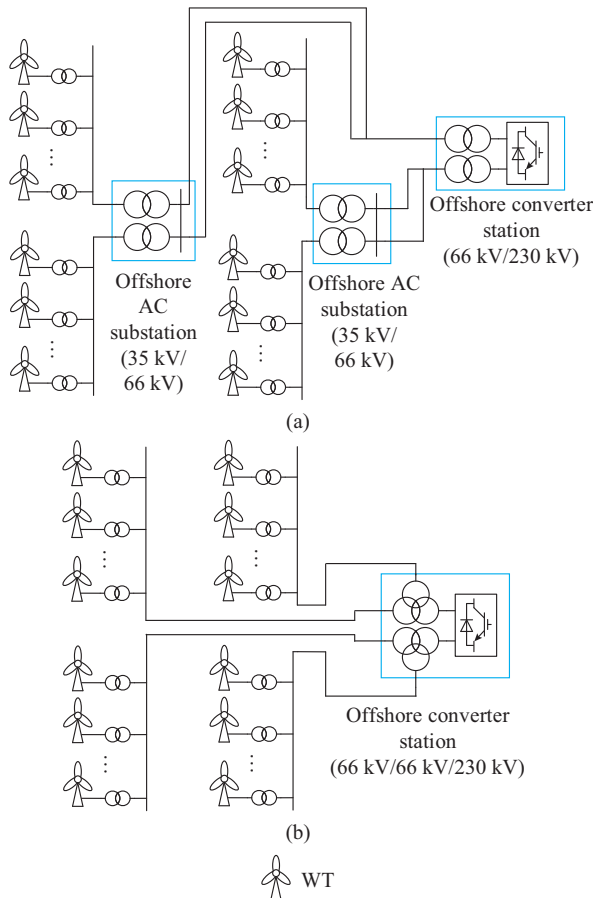


Fig. 3. AC collection structure for OWP. (a) Conventional AC collection. (b) AC collection without substation.

In summary, MFAC collection reduces transformer and filter size but may increase cable costs, requiring careful frequency optimization. DC collection, whether parallel- or series-connected, offers significant reductions in the size of offshore converter station and cable size but faces challenges to developing high-frequency DC/DC converters. AC collection without substation simplifies system architecture by eliminating collector transformers, with proven application through DolWin5 project. Each of the above schemes presents distinct trade-offs between complexity and cost, and their suitability depends on specific offshore deployment scenarios.

III. EMERGING TRANSMISSION TECHNOLOGIES FOR LARGE-SCALE OWP

To address the limitations of conventional transmission

systems in large-scale and remote OWP applications such as bulky offshore converter stations and inefficient power transmission, we introduce three emerging technologies as follows.

A. VSC-HVDC Based on Compact MMCs

The capacitor voltage fluctuation in MMCs is inversely proportional to the capacitance. Smaller voltage fluctuations allow for smaller capacitors, which can make the MMC more compact. Generally, the methods for reducing voltage fluctuations of SM capacitor can be primarily divided into topology improvement and control optimization methods.

1) Topology Improvement Methods

The methods that modify the MMC topology to reduce its inherent capacitor requirements are referred to as the topology improvement methods. These methods primarily focus on optimizing the operation of conventional MMC topologies or integrating supplementary hardware elements to reduce the reliance on large SM capacitors.

In terms of optimizing the operation of the MMC, [34] introduces a high-ripple operation method, which involves slightly increasing the number of SMs to lower the rated SM capacitor voltage. As a result, the SMs can be made smaller and more cost-effective while maintaining a consistent peak capacitor voltage. Due to its simplicity and practicality, this method is suitable for practical implementation. Reference [35] introduces a variable DC voltage operation mode of hybrid MMC. It implies that a higher power factor will result in a lower AC/DC voltage ratio, which reduces the fundamental and second harmonic fluctuations in the SM capacitor voltage [36]. Additionally, [37] and [38] propose a segmented switching operation scheme based on arm inductance of SMs. By adjusting the arm inductance, the arm current is modified, which helps suppress SM capacitor voltage fluctuations.

In terms of integrating supplementary hardware elements to reduce capacitor fluctuations, existing methods can be categorized into three main types.

The first method focuses on suppressing low-frequency capacitor voltage fluctuations by sharing a central SM. Reference [39] initially proposes a structure where the upper and lower arms of the MMC share a central SM, which achieves equivalent output voltage levels with fewer SMs. Reference [40] proposes connecting the three top SMs of the upper arms and the three bottom SMs of the lower arms using cables, as shown in Supplementary Material A Fig. SA1(a). Since the three-phase power of the MMC is balanced in normal operation, the top and bottom SMs function as a three-phase converter, inherently minimizing the capacitor voltage fluctuations. However, voltage fluctuations are only reduced in the central, top, and bottom SMs, showing reduced efficacy in systems with numerous SMs.

The second method focuses on reducing the capacitor voltage fluctuations by parallelizing active power filters (APFs) or adding power circuits, as shown in Supplementary Material A Fig. SA1(b). Reference [41] proposes adding isolated bi-directional converters between the corresponding SMs of the upper and lower arms in each phase to counteract the funda-

mental and third harmonic power fluctuations of opposite signs. This method eliminates the capacitor voltage fluctuations. However, it necessitates multiple isolation transformers and lacks the capability to absorb low-frequency power fluctuations.

Reference [42] proposes adding APFs to each SM to transfer power ripple from the MMC to the APFs during normal operation. However, this method doubles the number of insulated-gate bipolar transistors (IGBTs) and capacitors compared with conventional MMCs, and necessitates buffer inductors in each SM, elevating power losses. References [43] and [44] propose paralleling APFs between the last SM of the upper arm and the first SM of the lower arm in each phase of the MMC to absorb power fluctuations within the arm. This method can reduce voltage ripple by approximately 50% and decrease switching losses by about 87%. Reference [45] introduces adding flying capacitors in each phase of the MMC to serve as high-frequency power transfer channels, combined with a high-frequency sinusoidal voltage injection method to suppress SM capacitor voltage fluctuations.

The third method focuses on the characteristic of 120° phase difference in the SM capacitor voltages across the three phases. By interconnecting the corresponding SMs from each phase, this method aims to eliminate the capacitor voltage fluctuations. Reference [46] proposes connecting the corresponding SMs of the three phases for MMC through an isolated capacitor-inductor-inductor-capacitor (CLLC) resonant circuit to a common capacitor. This method not only balances the SM capacitor voltages but also eliminates the fundamental and second harmonic voltage ripples. References [47] and [48] introduce high-frequency transformers between the cascaded SMs (C-SMs) of the three phases. These transformers use the coupling effect to eliminate low-order harmonics in the SM capacitor voltage fluctuations, as illustrated in Supplementary Material A Fig. SA1(c). A summary of various topology improvement methods is presented in Table I. It is important to note that topology improvement methods involve higher construction and maintenance costs. In contrast, control optimization method is more flexible and offers a more cost-effective solution for reducing SM capacitor voltage fluctuations.

TABLE I
SUMMARY OF VARIOUS TOPOLOGY IMPROVEMENT METHODS

Method description	Advantage	Disadvantage
Operating in high-ripple mode [34]	Operating with higher technological maturity without changing the original MMC structure and operation strategy	Increasing the number of SMs
Sharing a central SM [39], [40]	Reducing the number of SMs needed to output the same number of levels and increasing the utilization of SMs	Reducing the capacitor voltage fluctuations of the middle, top, and bottom SMs, which is not applicable to the scenario of numerous SMs
Adding power circuits [41], [42]	Introducing additional power loops between the upper and lower arms to offset arm energy fluctuations and reduce capacitance requirements	Requiring extensive detection circuit and operation control resources
Paralleling APF [43], [44]	Transferring the power ripple of MMC to APF during the normal operation and reducing the voltage ripple	Increasing the number of power devices and requiring the buffer inductor
Interconnecting corresponding SMs from three phase [47], [48]	Eliminating capacitive voltage harmonics by high-frequency transformers and CLLC resonant circuit	Requiring a voltage equalization control strategy and additional devices

2) Control Optimization Methods

The control flexibility of MMCs allows for the suppression of SM capacitor voltage fluctuations by regulating fluctuations in arm voltage, arm current, and inter-phase power. Current mainstream control optimization methods include circulating current suppressing control (CCSC), circulating current injection control (CCIC), third harmonic voltage injection (THVI), and dual harmonic injection (DHI), which combine CCIC and THVI.

CCSC reduces the third harmonic fluctuations in SM capacitor voltage by suppressing the circulating current, which does not impact the normal operation of the MMC [49]. However, this method has limited effectiveness in reducing capacitor voltage fluctuation.

CCIC reduces capacitor voltage fluctuations by injecting a second harmonic circulating current into the arms, which helps keep the AC- and DC-side power of the converter matched in real time [50]. For different operation conditions and control objectives, [51]-[56] explore the methods for selecting the amplitude and phase of the second harmonic circulating current injection. References [52] and [54] derive the amplitude and phase of the second harmonic circulating

current that result in the fastest reduction of capacitor voltage fluctuations. References [51] and [53] propose a control strategy to eliminate the second harmonic of capacitor voltage and a method for calculating the circulating current reference value. References [55]-[57] investigate a capacitor voltage fluctuation suppression method based on circulating current injection for unbalanced power grids. However, injecting circulating current increases the current stress on the arms, which introduces additional power losses to the converter [58].

Therefore, [59] proposes a switching strategy between control modes of circulating current injection and suppression for different operation points of the MMC. However, the method of indirect voltage ripple suppression relies on measuring the circulating current value, which, in practical projects, depends on the accuracy of the measuring instruments and inevitably introduces errors. Reference [60] proposes a comprehensive control strategy for capacitor voltage fluctuation in MMC, which enables closed-loop control of the capacitor voltage. This strategy directly eliminates the second harmonic of the capacitor voltage, thereby significantly sup-

pressing voltage ripple and simultaneously reducing the arm current.

Unlike CCIC, THVI directly adds a third harmonic component to the modulation wave of the arm voltage to reduce the root mean square (RMS) value of the AC current and the number of SMs used, thereby reducing the size and cost of converter [61], [62]. CCSC aims to suppress the circulating current to zero, which conflicts with the circulating current injection method used in CCIC. Since THVI does not involve circulating current, it can be combined with either the CCSC or CCIC. The combined harmonic injection control method that integrates both CCSC and CCIC is known as DHI. It can be observed from Fig. 4 that the arm voltage reference changes after the injection of the second and third harmonic voltage components. In Fig. 4, U_0 is the amplitude of the fundamental voltage; and T is the time period of the fundamental voltage waveform.

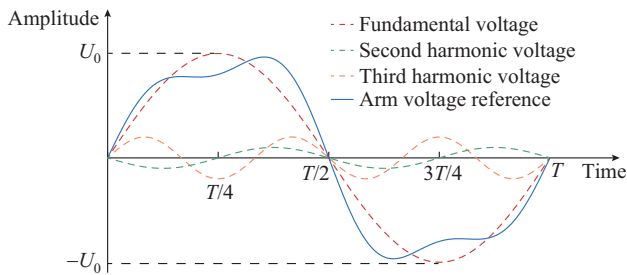


Fig. 4. Arm voltage reference with DHI.

DHI typically has two control objectives: minimizing the SM capacitor voltage fluctuation to reduce the size of the capacitors and minimizing the arm current to reduce power losses. For a single control objective, [62] achieves the minimization of the fundamental component of the capacitor voltage by adjusting the amplitude and phase angle of the inject-

ed harmonics, under the condition that the second harmonic of the SM capacitor voltage is zero. However, this method is constrained by the modulation index. Reference [63] optimizes the amplitude and phase angle of the jointly injected third-order voltage, second harmonic and fourth harmonic circulating currents to minimize capacitor voltage fluctuation. To address multiple control objectives, [64] introduces a harmonic injection ratio k , defined as the amplitude ratio of the second harmonic current to the fundamental component. It shows the relationship of the capacitor voltage fluctuation and the RMS value of the arm current with k value, which allows for achieving different control objectives by adjusting k value. Reference [65] presents an optimal DHI method via multi-objective genetic algorithm that simultaneously reduces capacitor voltage fluctuation and arm current.

Existing research predominantly concentrates on voltage ripple suppression for the MMC under steady-state conditions. In the case of severe grid faults, the fluctuation characteristics of the capacitor voltage will change. Therefore, it is also necessary to investigate the applicability of capacitor voltage fluctuation control strategies under unbalanced grid conditions. Reference [66] evaluates the performance of the capacitor voltage fluctuation controller for the MMC under single line-to-ground (SLG) fault conditions. However, the study only considers the SLG fault scenario and does not account for the impact of the second harmonic voltage of arm inductors on the capacitor voltage. Building on [66], [67] takes into account the effect of arm inductance and various types of faults. It optimizes modulation coefficients and injection parameters (e.g., third harmonic voltage amplitude/angle, second harmonic current) to develop a capacitor fluctuation suppression strategy for unbalanced grid conditions. A summary of control optimization methods is shown in Table II.

TABLE II
SUMMARY OF CONTROL OPTIMIZATION METHODS

Method description	Advantage	Disadvantage
CCSC [49]	Achieving high technology maturity	Providing limited suppression of capacitor voltage ripple
CCIC with indirect ripple suppression [55], [56]	Offering an indirect method for ripple suppression	Increasing arm current and losses, depending on measurement accuracy, and introducing errors
CCIC with direct ripple suppression [60]	Offering a direct method for ripple suppression, reducing arm current and suppressing the need for circulating current calculation	Having lower technology maturity
DHI [62]-[65]	Allowing flexible achievement of different control objectives	Causing interaction between circulating current and third-harmonic voltage, presenting controller stability challenges, and lacking studied grid fault ride-through strategies

B. DRU-HVDC

DRU-HVDC offers notable advantages; however, its inherent limitations, which includes the inability to provide stable AC voltage, lack of black-start capability, and the need for additional filtering and reactive power compensation, continue to constrain its direct application in OWP transmission systems [68]. Therefore, on one hand, the grid-side converters of the WTs must be utilized to form the offshore grid

and enable self-synchronized operation. On the other hand, dedicated black-start solutions for wind farm are necessary.

1) WT Control

WT control can be divided into two types based on whether a communication system is required: centralized and decentralized.

Centralized control requires remote collection of control variables, primarily including bus voltage control based on communication systems [69], [70] and FixReF wind farm

voltage control based on the global positioning system (GPS) [71]-[73]. Reference [69] adopts a grid-forming method similar to that used in MMCs, where the active current output from WTs is used to regulate the bus voltage at point of common coupling (PCC), while the reactive current is used to control the frequency. However, this method is dependent on the communication to transmit signals from remote locations, which reduces reliability and increases costs. Reference [73] proposes using GPS to provide each WT with a constant reference for voltage and frequency to ensure the static stability of the WTs. In this method, active current controls the DC voltage, while reactive current controls the output voltage angle [74]. However, since both the frequency and turbine synchronization rely on GPS communication, this method is costly. Additionally, when the wind farm is disconnected from the DRU or under low wind speed conditions, auxiliary equipment is required to establish the wind farm voltage.

Distributed control focuses on the electrical singles of the converter itself, avoiding the need for a communication system. References [75] and [76] propose a voltage closed-loop control and frequency open-loop control based on the active and reactive current outputs of the converter. However, the frequency is not controlled when the WTs connect to the grid. To address this, researchers have proposed a frequency closed-loop control based on a PLL [77]-[79]. PLL-based control strategies typically use P - V and Q - f control. This is due to the fact that, the sensitivity of WT active power to the output voltage is always positive, while the sensitivity of

reactive power to the offshore AC system frequency is always negative for different operation conditions [80]. PLL-based control strategies facilitate the synchronization of WTs with the offshore grid and provide plug-and-play functionality. For PLL-based grid-forming WTs, stability and fault ride-through issues have been further investigated [81], [82]. Reference [78] proposes a phase angle feedforward control to reduce the interaction between active and reactive power, thereby improving the control dynamics. References [83] and [84] present fault ride-through solutions for DC faults and protection schemes for offshore AC system faults, respectively. However, when the connected offshore AC grid has low strength, PLL can adversely affect the system stability [85]-[88].

To address the stability concerns related to PLL, [89]-[91] propose a reactive power synchronization grid-forming control based on Q - f droop control, where the phase angle of each WT is determined through the Q - f control loop. However, this control lacks a d -axis voltage control loop, precluding its application in island operation modes or under low wind speed conditions. Building on this, [92] proposes a self-synchronizing frequency control (SSFC) strategy for wind farms in the DRU-HVDC system. This strategy employs P - V and Q - f control, allowing for stable operation of the wind farm under passive and low wind speed conditions. The P - V and Q - f grid-forming control diagrams can be found in Supplementary Material B Fig. SB1 [77] and [92]. The comparison of the control strategies for WTs is shown in Table III.

TABLE III
COMPARISON OF CONTROL STRATEGIES FOR WTs

Type	Description	Reference	Is communication required?	Is WT control modified?	Advantage	Disadvantage
Centralized control	Bus voltage control	[69], [70]	Yes	No	Mature technology and simple control	Dependency on communication system, low reliability, and high cost
	FixReF wind farm voltage control	[71]-[73]	Yes	No	Simple control	Dependency on GPS communication, and high cost
Distributed control	Frequency open-loop control	[75], [76]	No	Yes	Simple control loop	Inability to control WT frequency when grid is connected
	Frequency closed-loop control based on PLL	[77]-[79]	No	Yes	Active synchronization of WTs with offshore grid	Stability problems of PLL on weak AC grids
	Reactive power synchronization grid-forming control based on Q - f droop control	[80]-[91]	No	Yes	Avoidance of PLL stability problems	Inapplicability under islanding mode or low wind speed conditions
	Self-synchronizing frequency control	[92]	No	Yes	Stable operation under passive and low wind speed conditions	Complex transient stabilization and active support capacity assessment

2) Startup Method

The energy requirements for starting the offshore grid involve two main aspects. On one hand, auxiliary equipment of the WTs such as blade pitch controllers, yaw motors, cooling systems, and control systems needs a certain amount of active power to operate. On the other hand, system components such as AC submarine cables and WT transformers require a certain amount of reactive power to function properly

[93].

Since the DRU cannot supply power in reverse and therefore cannot provide startup energy for the WTs, auxiliary startup methods are required. The current mainstream startup methods can be categorized into those based on auxiliary cable/line and those based on auxiliary equipment, as shown in Table IV, where ESS is short for energy storage system, and HVAC is short for high-voltage AC.

TABLE IV
COMPARISON OF STARTUP METHODS

Type	Description	Reference	Advantage	Disadvantage
Auxiliary cable/line	Parallel MVAC umbilical cables	[94], [95]	Providing high technological maturity	Requiring power distribution and adding cost for auxiliary converters
	Auxiliary LVDC cables	[96]	Offering easy expandability, fewer hardware devices, good economy, and high reliability	Involving complicated control due to DC voltage matching between converter and WTs during startup
	Parallel HVDC plus or HVAC lines	[97]	Providing high technological maturity and needing no additional equipment	Limiting expansion to existing HVDC/HVAC lines, and lacking universal applicability
Auxiliary equipment	Diesel generators	[98]-[100]	Providing the highest technological maturity	Increasing the size of the platform, and harming environment
	Source-side ESS	[101]-[104]	Enabling installation at PCC and simplifying planning	Increasing the weight of the offshore platform
	Grid-side ESS	[105], [106]	Providing access to the DC side of WT converters, avoiding increased platform volume, and enabling flexible WT startup	Increasing complexity of nacelle control and weight and cost of nacelle, and having poor reliability

1) Startup methods based on auxiliary cable/line

The use of parallel MVAC umbilical cables is a well-established startup method in engineering [94], [95]. This method employs MVAC umbilical cables to match the voltage of offshore collection system rating to energize grid-side equipment of WT during startup, then disconnects them post-commissioning. It is important to note that during both the startup and normal operation phases of the wind farms, specific control strategies are required to coordinate the active power distribution between the MVAC umbilical cables and the DC cables. A common method is to adjust the output frequency of wind farm to regulate the phase difference between the offshore bus voltage and the onshore bus voltage. Reference [74] suggests installing onshore auxiliary converters to adjust the power of the MVAC umbilical cables, which can reduce system losses. However, the use of auxiliary converters introduces additional equipment costs.

To reduce costs, [96] proposes a startup method for DRU-HVDC systems that utilizes auxiliary LVDC cables. This method utilizes short-distance LVDC cables to interconnect the DC bus of WT with the HVDC bus, enabling the onshore inverter-based power supply to offshore WTs.

Using parallel HVDC plus or HVAC transmission lines is also a relatively mature startup method [97]. However, this method is generally employed for expanding OWP transmission systems that already have existing HVDC plus or HVAC transmission lines. Therefore, it lacks universal applicability.

2) Startup methods based on auxiliary equipment

Diesel generators serve as a critical auxiliary power source for the startup of wind farms, particularly in scenarios with substantial wind power deficits [98]-[100]. To enhance wind power system stability during black-start operations, the grid-side converters of WTs are equipped with coordinated active power and frequency control capabilities [99], [100].

ESS is also viable options for black-start power sources in OWP transmission systems [101], [102]. Based on the integration location, the ESS can be categorized into source-side storage and grid-side storage [103]. A typical configuration involves deploying the ESS directly at grid interconnection

points [104]. However, to enable rapid startup of sufficient WTs for subsequent cascaded activation, additional distributed ESS must be deployed, inevitably increasing converter station dimensions [105]. Another configuration deploys dedicated ESS within each WTs. The ESS is connected to the DCWT converter via DC/DC converters [106]. During startup, the WTs equipped with energy storage units are activated first and operate in grid-forming mode. Once the collection system is integrated, the remaining WTs are then started. However, this method increases the complexity of nacelle control, as well as the weight and cost of the nacelle. The schematic diagram of the startup methods of DRU-HVDC is shown in Supplementary Material C Fig. SC1 [106].

C. HVDC Based on Hybrid Converters

Based on the topology, the HVDC based on hybrid converters can be categorized into two types: the series configuration of DRU and MMC and the parallel configuration of DRU and MMC.

1) Series Configuration of DRU and MMC

References [107]-[111] propose an offshore converter topology, consisting of 12-pulse DRU connected in series with MMC, as shown in Supplementary Material C Fig. SC2. The DRU transmits two-thirds of the active power generated by the wind farm, while the MMC transmits the remaining one-third of the active power. Additionally, the MMC provides voltage and frequency supports to the offshore AC system, compensates for the reactive power of the system, and functions as an APF to compensate for the harmonics generated by the DRU [108]. The power control strategy and harmonic compensation control strategy for series configuration of DRU and MMC are given as:

1) Power control strategy for series configuration of DRU and MMC

The AC-side current of MMC I_{ac} can be expressed as:

$$I_{ac} = \frac{U_{MMC} - U_{PCC}}{jX_{L_f}} \quad (1)$$

where U_{MMC} is the voltage of MMC; U_{PCC} is the AC voltage at the PCC; and X_{L_f} is the reactance of the filter inductor.

The d -axis voltage $U_{d,PCC}$ is controlled to be zero and the

q -axis voltage $U_{q,PCC}$ is controlled to be equal to the voltage magnitude at the PCC. By substituting $U_{d,PCC}$ and $U_{q,PCC}$ into the (1), I_{ac} can be written as:

$$I_{ac} = \frac{U_{d,MMC}}{X_{L_r}} - j \frac{U_{q,MMC} - U_{q,PCC}}{jX_{L_r}} \quad (2)$$

where $U_{d,MMC}$ and $U_{q,MMC}$ are the d - and q -axis voltages of MMC, respectively.

The active power P and reactive power Q of MMC are expressed as:

$$\begin{cases} P = \frac{3}{2} U_{q,MMC} \frac{U_{d,MMC}}{X_{L_r}} \\ Q = \frac{3}{2} U_{q,MMC} \frac{U_{q,MMC} - U_{q,PCC}}{jX_{L_r}} \end{cases} \quad (3)$$

It can be observed from (3) that P and Q of the sending-end MMC are proportional to the d -axis and q -axis components of the AC voltage of MMC. Therefore, $U_{d,MMC}$ is employed to control the DC voltage of MMC, while $U_{q,MMC}$ is employed to control the bus voltage at the PCC. This enables the effective distribution of active power among converters and ensures reactive power compensation within the system.

2) Harmonic compensation control strategy for series configuration of DRU and MMC

The main concept of the harmonic compensation control is to extract the harmonic currents at the PCC under normal operation and design the harmonic controller in MMC to actively suppress these harmonics. Harmonic compensation control primarily involves two steps: harmonic extraction and harmonic injection [112]. Reference [109] utilizes a BPF to extract the subharmonic components of the PCC current. A proportional-resonant (PR) controller is then employed to suppress these components to zero.

References [109], [113], and [114] propose several improvements to the existing series configuration of DRU and MMC. ① The implementation of a full-bridge MMC with thyristor valves is paralleled on the DC side of it to enable effective DC fault protection. ② The optimization of DC current sharing between the DRU and MMC ensures that most active power is transmitted through the DRU, reducing the converter losses. However, this configuration requires the installation of filters on the DRU side and complex start strategies. References [110] and [111] propose a refined power distribution ratio and a black-start strategy for the series configuration of DRU and MMC.

2) Parallel Configuration of DRU and MMC

References [115]-[117] propose an offshore converter topology, where the DRU is paralleled with a small-capacity MMC on both the AC and DC sides, as shown in Supplementary Material C Fig. SC3. The small-capacity MMC is responsible for reactive power compensation and harmonic compensation of the system, thereby eliminating the need for filters and reactive power compensation devices.

1) Power control strategy for parallel configuration of DRU and MMC

To reduce transmission costs, the DRU should transmit

most of the active power of wind farms. The active power and reactive power of the DRU can be expressed as:

$$\begin{cases} P_r = \frac{3\sqrt{2}}{2\pi} n_r k_r U_s (\cos \mu + 1) I_{dcr} \\ Q_r = \frac{2\mu - \sin 2\mu}{1 - \cos 2\mu} P_r \end{cases} \quad (4)$$

where P_r and Q_r are the active and reactive power of DRU, respectively; n_r is the number of pulses; k_r is the transformer ratio; U_s is the voltage amplitude of PCC; I_{dcr} is the DC current of DRU; and μ is the commutation overlap angle. It can be observed from (4) that P_r is proportional to U_s . Therefore, the active power distribution between the DRU and MMC can be coordinated by controlling the voltage amplitude of PCC.

2) Harmonic compensation control strategy for parallel configuration of DRU and MMC

In [117], a multi-synchronous rotating coordinate transformation algorithm is used to extract the characteristic harmonics of the DRU. A composite proportional-integral (PI) controller is used to control the harmonic currents. The composite PI controller integrates the superior steady-state accuracy of repetitive control with the enhanced dynamic response of conventional PI control.

Moreover, [117] proposes a capacity design methodology for the parallel configuration of DRU and MMC, considering three operation aspects of the MMC: black-start energy provision, harmonic compensation, and reactive power compensation. Additionally, a small-signal model of this configuration is built to analyze the impact of controller parameters on the system static stability. The fault ride-through characteristics of the system are simulated.

To reduce the redundancy of SMs in the MMC, [118]-[120] propose an AC/DC converter with high transformation ratio. This converter includes a low-voltage MMC, a series of high-voltage SMs (SHV-SMs), and an inductor-capacitor filter. The DC current flows through the SHV-SMs, which are continuously in a charging or discharging state. To maintain energy stability within the SHV-SMs, it is necessary to exchange power via high-frequency circulating currents between the SHV-SMs and the MMC. The control block diagram of the series of high-voltage SMs is shown in Supplementary Material C Fig. SC4 [120]. The reference value of high-frequency circulating current can be obtained from the capacitor voltage error of the SHV-SMs. The difference between reference value and the actual value of high-frequency circulating current is processed through a PI controller, which then generates the modulation voltage for the SHV-SMs.

In conclusion, VSC-HVDC based on compact MMC offers full controllability and grid support but requires further research into its economic viability and stability under increasing system complexity. DRU-HVDC provides significant cost, size, and efficiency advantages but is limited by its lack of controllability and dependence on mature grid-forming WTs.

In the parallel configuration of DRU and MMC, the DC

voltage of the MMC aligns with the DC voltage of the system, requiring high rated voltage for transformers and SMs. This imposes significant insulation and component requirements, indicating considerable potential for further optimization in size and weight of converter station. The improved parallel configuration of DRU and MMC involves complex topologies and advanced control strategies, which may impact system stability and currently remain largely confined in the theoretical research stage.

In contrast, the series configuration of DRU and MMC allows the MMC to operate at a reduced DC voltage, thereby lowering insulation demands, decreasing SM capacitance,

and reducing power device ratings. However, the primary drawback is the startup complexity. Despite this, the series configuration of DRU and MMC offers superior overall performance and is well-suited for point-to-point transmission applications of large-scale OWP, where a step-down startup method can be employed. The parallel configuration of DRU and MMC offers more flexible control and easier startup, making it more suitable for multi-terminal DC grid transmission projects in large-scale OWP transmission systems. A comparison of several HVDC transmission technologies is shown in Table V.

TABLE V
COMPARISON OF SEVERAL HVDC TRANSMISSION TECHNOLOGIES

Technology	Reference	Is WT control strategy changed?	Technology maturity	Number of diodes per arm	Number of IGBTs per arm	Transmission loss of valve (%)	Size of converter station (p.u.)	Weight of converter station (p.u.)
MMC	[121], [122]	No	+++++	$2N$	$2N$	0.800	1.00	1.000
DRU-HVDC	[78], [92]	Yes	++	N		0.110	0.20	0.350
Series configuration of DRU and MMC	[109]-[114]	No	+++	$2N$	$0.33N$	0.733		
Parallel configuration of DRU and MMC	[117]	No	+++	$4N$	$2N$	0.139	0.79	0.776
Improved parallel configuration of DRU and MMC	[118]	No	+++	$2.62N$	$0.31N$	0.370		

Note: the symbol + indicates the level of technology maturity, with more + denoting higher degree of technology maturity; and N represents the number of SMs in each arm of MMC.

IV. DEVELOPMENT TRENDS AND PROSPECT OF EFFICIENT TECHNOLOGIES FOR LARGE-SCALE OWP

Although current cost-effective collection and transmission technologies for large-scale OWP have advanced, several issues still need further research for practical application.

A. Cost Optimization

As offshore wind farm projects move farther from shore and grow in capacity, minimizing the size, weight, and overall cost of the offshore converter stations becomes increasingly critical.

1) Development of Key Equipment for DC Collection Systems

The transition from AC collection with DC transmission to DC collection and multi-voltage-level DC transmission is motivated by the goal of reducing offshore substation and cable costs. For fully DC offshore wind farms, the primary challenge lies in the development of high-frequency high-gain DC/DC converters and DC circuit breakers.

For example, in the parallel-connected networking, current high-frequency isolated DC transformers are constructed by multiple small-capacity isolated DC/DC converters connected in series and parallel, which results in large size and weight. Future research should focus on high-frequency isolated DC transformer technology with improved topologies, lower energy storage requirements, and enhanced control sta-

bility.

2) Compact MMCs for Co-optimization of Volume and Stability

Compact MMCs offer a promising solution for reducing the size and cost of converter station. Current research focuses on topology simplification and advanced control strategies. However, the increased complexity of control and additional semiconductor components may adversely affect economic viability and dynamic stability. Future design of compact MMC should focus on the co-optimization of volume and stability. Additionally, the adaptability of ripple suppression strategies under non-ideal grid conditions warrants rigorous theoretical analysis.

3) Capacity Design and Control for Hybrid Transmission Scheme of DRU and MMC Station

The hybrid transmission scheme of DRU and MMC station leverages the strength of both technologies: DRUs offer efficient bulk power transfer, while MMCs provide reactive power and harmonic compensation. However, additional components such as power electronic devices will increase system cost. Currently, there is a lack of capacity design guidelines that balance cost, reliability, and performance. Moreover, improved coordination control and reliability assessment need to be further investigated.

B. Grid Stability

The integration of large-scale OWP, especially through VSC-HVDC and DRU-HVDC systems, raises significant grid stability concerns, including reduced inertia, increased control complexity, and vulnerability to oscillations.

1) Resonance Issues and Active Grid-supporting Strategies for VSC-HVDC System

The increasing penetration of power electronic devices and declining share of synchronous generators have resulted in a substantial reduction of inertia in VSC-HVDC-based OWP transmission systems. On one hand, low-inertia and weak-damped characteristics of OWP transmission systems markedly increase the frequency stability risks. The major blackout incidents in Australia (28 September, 2016) [123] and the UK (9 August, 2019) [124] revealed the deficiencies in frequency regulation. On the other hand, the increasing control interactions both among power electronic devices and between these devices and the onshore grid have significantly heightened the system vulnerability to wide-frequency oscillations. For instance, the Borwin1 project experienced severe oscillation incidents in 2014, resulting in prolonged system outages [125]. Owing to the inherent control flexibility of the VSC-HVDC systems, the implementation of specific control strategies enables the systems to provide active grid support to onshore grid [121], [122], [126]. Therefore, a critical research focus for future VSC-HVDC-based OWP transmission systems lies in developing solutions that simultaneously ensure converter resonance stability while providing effective frequency, voltage, and inertia support to onshore grids under complex operation conditions.

2) Stability Analysis for DRU-HVDC System

DRU-HVDC systems, while being economical and compact, cannot regulate voltage or frequency on their own. Consequently, WTs play a vital role in establishing voltage under black-start or weak-grid conditions. However, existing control strategies of WTs face limitations: insufficient DC-side capacitance restricts WTs to obtain enough startup energy under prolonged disturbances, while mechanical energy buffering via turbine drivetrains accelerates wear. Thus, auxiliary equipment is necessary to enable self-starting of WTs. Moreover, complex interactions among grid-forming converters, grid-following converters, and DRUs can introduce stability issues such as oscillations. The current research is limited to the stability analysis of systems with a small number of aggregated WTs and lacks a theoretical foundation and analysis methods for the stability of systems containing heterogeneous converters. Future research should focus on several key areas: establishing system models that include multi-type converters; stability analysis of different control modes, key parameters, and grid-forming penetration; and stability assessment based on crucial metric.

3) Planning and Reliability for Distributed ESSs

Distributed ESSs are essential for enhancing grid stability in integrating OWP via DRUs. By locating ESS on the DC side of WT converters, the black-start capability of WTs is improved. However, the integration of ESSs significantly increases the control complexity of the nacelle and the overall system weight. Moreover, ESSs must adapt to the highly

variable operation conditions of offshore wind farms, thereby posing considerable economic and reliability challenges. Existing research is limited in optimizing energy storage configuration, reducing storage volume, and enhancing the stability of OWP transmission systems with ESSs. ESS capacity optimization must balance operation dynamics and cost-effectiveness in wind farm. Distributed ESS deployment necessitates robust siting strategies to withstand extreme environmental and geospatial conditions. Enhancing the coordinated operation reliability between ESSs and WTs is also imperative to ensure the stability of DRU-HVDC-based OWP transmission systems.

C. Fault Protection

Effective fault management is critical for ensuring the safety and operation continuity of OWP transmission systems, particularly in remote and harsh environments.

The probability of DC cable faults is relatively low. Therefore, the DRU-HVDC system has a low demand for DC fault ride-through. The current AC fault ride-through methods mainly involve two aspects: the active response control of the wind farm and the deployment of DC circuit breakers. Therefore, further analysis should focus on the transient stability characteristics and fault protection measures of the DRU-HVDC-based OWP transmission systems. While practical deployment of DRU-HVDC system has yet to be realized, advancements in power electronics and standardization are expected to bridge the gap from concept to application.

D. Engineering Applications

At the collection level, 66 kV AC collection has progressively supplanted conventional 35 kV solutions, as exemplified by projects such as Yangjiang Qingzhou VII [127], Dogger Bank A [128], Dolwin5 [129], and Dolwin6. These projects employ HVAC submarine cables to directly transmit power to offshore converter stations. It is noteworthy that while MFAC collection and DC collection technologies have demonstrated potential in academic research, they have yet to be implemented in practical engineering applications. Given the immaturity of high-capacity high-gain DC/DC converter, AC collection is anticipated to remain the predominant solution for offshore wind integration in the coming decades. Thus, MFAC collection presents considerable application prospects due to its ability to significantly reduce the size and weight of transformers and power conversion equipment.

At the transmission level, three cost-efficient transmission technologies tailored for OWP applications remain at theoretical research stages [130]. However, their fundamental concepts have been partially implemented in other HVDC applications. Regarding SM capacitor optimization, both the Zhangbei VSC-HVDC project commissioned in 2020 and the currently under-construction Yangjiang Qingzhou 5 and 7 Offshore Wind Farm Projects have adopted the VSC-HVDC based on compact MMC [131]. Although DRU-HVDC lacks practical implementations, the European Horizon 2020 initiative “Progress on Meshed Offshore HVDC Transmission Networks” originally planned a demonstrator at Klim wind farm in Denmark in 2016 [68], indicating both significant in-

dustry attention and thorough technical validation in Europe. Currently, China has built the world's first ± 10 kV/10 MW DRU-based wind power transmission demonstration project in Dabancheng, Xinjiang. HVDC based on hybrid converters has achieved successful deployment in several major Chinese projects including the Kunlilong project (commissioned in 2020) incorporating LCC at the sending end and MMC at the receiving end [132], and the Baihetan Jiangsu project (commissioned in 2022) utilizing hybrid cascaded LCC and VSC [133]. Based on current technological developments and industry roadmaps, these three emerging lightweight technologies are projected to achieve engineering implementation within the next few years [134], [135].

For grid-forming capability of VSC-HVDC-based OWP transmission system, the ongoing BorWin6 project in Germany represents a significant advancement in VSC-HVDC technology [136]. In compliance with the VDE 4131 grid code, this project has implemented an innovative dual-terminal grid-forming control strategy based on DC voltage virtual synchronization. This strategy provides comprehensive active support capabilities for both offshore wind farms and the onshore grid.

In the design optimization of offshore converter station, split-foundation jacket structures are gaining increasing adoption due to their demonstrated advantages in significantly reducing steel consumption for foundations while meeting the requirements for float-over installation methods. The Dolwin3 project represents a notable implementation of this advanced structural solution [137].

V. CONCLUSION

This paper analyzes emerging collection and transmission technologies for large-scale OWP. The major conclusions are drawn as follows.

1) Regarding AC collection, increasing the system operation frequency can reduce transformer and filter sizes on offshore platforms, but raise cable costs. Determining the optimal frequency range for offshore AC systems across different OWP transmission systems is crucial. Besides, modular HVDC platform (ABB, 2016) enables direct 66 kV AC transmission to converter stations without substations, which has been successfully deployed in operation projects. Parallel and series configurations offer the advantages of reduced offshore platform and cable costs but face challenges in the design of critical equipment such as high-frequency isolation-based DC/DC converters.

2) For VSC-HVDC based on compact MMC, the economic and stability impacts of adding power electronic devices and control strategies require further research. Moreover, with increasing penetration of power electronic devices, VSC-HVDC must provide active support to the onshore grids.

3) While DRU-HVDC offers superior cost, size, and efficiency advantages over VSC-HVDC, the commercial adoption of DRU-HVDC faces significant challenges, e.g., immature grid-forming control strategies in WTs and inherent limitations in fault ride-through capability, active power support, and black-start functionality. Future research is poised to

concentrate on the integration of ESSs to mitigate these constraints.

4) HVDC based on hybrid converters eliminates the control modifications of WTs, enables black-start capability, and removes filters and reactive power compensation devices. However, the capacity design, control coordination, and stability analysis of HVDC based on hybrid converters demand deeper investigation.

The future development of far-OWP integration will focus on the overall optimization of both collection and transmission technologies with high efficiency, high reliability, and low cost.

REFERENCES

- [1] GWEC. (2024, Apr.). Global wind report 2024. [Online]. Available: <https://gwec.net/global-wind-report-2024-record-year-for-wind-energy-shows-momentum-but-highlights-need-for-policy-driven-action/>
- [2] U. S. Department of Energy. (2021, Mar.). Energy secretary Granholm announces ambitious new 30 GW offshore wind deployment target by 2030. [Online]. Available: <https://www.energy.gov/articles/energy-secretary-granholm-announces-ambitious-new-30gw-offshore-wind-deployments>
- [3] D. Wu, G. Seo, L. Xu *et al.*, "Grid integration of offshore wind power: standards, control, power quality and transmission," *IEEE Open Journal of Power Electronics*, vol. 5, pp. 583-604, May 2024.
- [4] H. Xiao, K. Sun, J. Pan *et al.*, "Review of hybrid HVDC systems combining line communicated converter and voltage source converter," *International Journal of Electrical Power & Energy Systems*, vol. 129, p. 106713, Jul. 2021.
- [5] TenneT. (2024, Aug.). BorWin1. [Online]. Available: <https://www.tenneT.eu/projects/borwin1>
- [6] TenneT. (2024, Aug.). BorWin3. [Online]. Available: <https://www.tenneT.eu/projects/borwin3>
- [7] S. Debnath, J. Qin, B. Bahrani *et al.*, "Operation, control, and applications of the modular multilevel converter: a review," *IEEE Transactions on Power Electronics*, vol. 30, no. 1, pp. 37-53, Jan. 2015.
- [8] Z. Li, Q. Song, F. An *et al.*, "Review on DC transmission systems for integrating large-scale offshore wind farms," *Energy Conversion and Economics*, vol. 2, no. 1, pp. 1-14, Mar. 2021.
- [9] Y. Tang, M. Chen, and L. Ran, "A compact MMC submodule structure with reduced capacitor size using the stacked switched capacitor architecture," *IEEE Transactions on Power Electronics*, vol. 31, no. 10, pp. 6920-6936, Oct. 2016.
- [10] SIEMENS. (2015, Oct.). 2nd generation DC grid access for large scale offshore wind farms. [Online]. Available: https://rave-offshore.de/files/downloads/konferenz/konferenz-2015/Session72015/7.2_Menke.pdf
- [11] S. Gierschner, H. G. Eckel, and M. M. Bakran, "A competitive medium frequency AC distribution grid for offshore wind farms using HVDC," in *Proceedings of 2013 15th European Conference on Power Electronics and Applications*, Lille, France, Oct. 2013, pp. 1-10.
- [12] J. Chen, X. Pei, H. Wu *et al.*, "Steady state characteristics of diode rectifier unit based grid-forming offshore wind power AC system," in *Proceedings of 2022 5th International Conference on Power and Energy Applications*, Guangzhou, China, Nov. 2022, pp. 651-656.
- [13] X. Pei, Y. Zhou, H. Wu *et al.*, "Economic analysis of offshore wind power DC transmission schemes based on different frequencies," in *Proceedings of 2024 9th Asia Conference on Power and Electrical Engineering*, Shanghai, China, Apr. 2024, pp. 1130-1136.
- [14] R. Barrera-Cardenas and M. Molinas, "Comparative study of wind turbine power converters based on medium-frequency AC-link for offshore DC-grids," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 3, no. 2, pp. 525-541, Jun. 2015.
- [15] X. Pei, H. Wu, J. Chen *et al.*, "Economic transmission distance analysis based on three different offshore wind farm integration schemes," in *Proceedings of 2023 IEEE 7th Conference on Energy Internet and Energy System Integration*, Hangzhou, China, Dec. 2023, pp. 1127-1133.
- [16] X. Pei, H. Wu, Y. Xu *et al.*, "Overvoltage research and insulation coordination for HVDC transmission system based on medium-frequency DRU-MMC," in *Proceedings of 2023 IEEE 7th Conference on Energy Internet and Energy System Integration*, Hangzhou, China, Dec. 2023, pp. 1097-1103.

- [17] J. Robinson, D. Jovicic, and G. Joos, "Analysis and design of an offshore wind farm using a MV DC grid," *IEEE Transactions on Power Delivery*, vol. 25, no. 4, pp. 2164-2173, Oct. 2010.
- [18] A. Garcés and M. Molinas, "Coordinated control of series-connected offshore wind park based on matrix converters," *Wind Energy*, vol. 15, no. 6, pp. 827-845, Sept. 2012.
- [19] N. Holtsmark, H. J. Bahirat, M. Molinas *et al.*, "An all-DC offshore wind farm with series-connected turbines: an alternative to the classical parallel AC model?" *IEEE Transactions on Industrial Electronics*, vol. 60, no. 6, pp. 2420-2428, Jun. 2013.
- [20] F. Sasongko, M. Hagiwara, and H. Akagi, "A front-to-front (FTF) system consisting of multiple modular multilevel cascade converters for offshore wind farms," in *Proceedings of 2014 International Power Electronics Conference*, Hiroshima, Japan, May 2014, pp. 1761-1768.
- [21] C. Zhan, C. Smith, A. Crane *et al.*, "DC transmission and distribution system for a large offshore wind farm," in *Proceedings of 9th IET International Conference on AC and DC Power Transmission*, London, UK, Oct. 2010, pp. 1-5.
- [22] J. D. Páez, D. Frey, J. Maneiro *et al.*, "Overview of DC-DC converters dedicated to HVDC grids," *IEEE Transactions on Power Delivery*, vol. 34, no. 1, pp. 119-128, Feb. 2019.
- [23] V. Timmers, A. Egea-Álvarez, A. Gkountaras *et al.*, "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, Jul. 2023.
- [24] H. A. Hussain and K. A. N. Al-Deen, "Design and control of series-DC wind farms based on three-phase dual active bridge converters," in *Proceedings of 2022 IEEE Energy Conversion Congress and Exposition*, Detroit, USA, Oct. 2022, pp. 1-8.
- [25] S. Kenzelmann, A. Rufer, D. Dujic *et al.*, "A versatile DC/DC converter based on modular multilevel converter for energy collection and distribution," in *Proceedings of IET Conference on Renewable Power Generation*, Edinburgh, UK, Sept. 2011, pp. 1-6.
- [26] X. Wang, G. Tang, X. Wei *et al.*, "A quasi zero-current-switching DC/DC modular-multilevel converter with LCL circuit for DC grids," in *Proceedings of 2015 IEEE Energy Conversion Congress and Exposition*, Montreal, Canada, Sept. 2015, pp. 1450-1454.
- [27] B. Li, J. Liu, Z. Wang *et al.*, "Modular high-power DC-DC converter for MVDC renewable energy collection systems," *IEEE Transactions on Industrial Electronics*, vol. 68, no. 7, pp. 5875-5886, Jul. 2021.
- [28] F. An, B. Zhao, B. Cui *et al.*, "Multi-functional DC collector for future all-DC offshore wind power system: concept, scheme, and implementation," *IEEE Transactions on Industrial Electronics*, vol. 69, no. 8, pp. 8134-8145, Aug. 2022.
- [29] Y. Huang, J. Zhang, G. Wang *et al.*, "Transient stability analysis and improvement of isolated renewable energy bases with VSC-DC transmission," *CSEE Journal of Power and Energy Systems*, doi: 10.17775/CSEEJPES.2024.02140
- [30] H. Xiao, H. Gan, P. Yang *et al.*, "Robust submodule fault management in modular multilevel converters with nearest level modulation for uninterrupted power transmission," *IEEE Transactions on Power Delivery*, vol. 39, no. 2, pp. 931-946, Apr. 2024.
- [31] P. Lundberg. (2016, Nov.). ABB power systems offshore wind connection. [Online]. Available: https://new.abb.com/docs/librariesprovider46/pw2016/seminars/r206-en-abb_offshore_wind_connection_by_hvdc_reformatted.pdf?sfvrsn=2
- [32] TenneT. (2022, Aug.). DolWin5. [Online]. Available: <https://www.tenneT.eu/projects/dolwin5>
- [33] Y. Li, L. Yu, and F. Zhang, "Technical and economic research on far coast wind power transmission based on AC transmission system," in *Proceedings of 2024 7th International Conference on Energy, Electrical and Power Engineering*, Yangzhou, China, Apr. 2024, pp. 1302-1306.
- [34] Q. Song, W. Yang, B. Zhao *et al.*, "Low-capacitance modular multilevel converter operating with high capacitor voltage ripples," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 10, pp. 7456-7467, Oct. 2019.
- [35] Z. Li, L. Gou, Q. Song *et al.*, "Reduction in submodule capacitance in FB- and HYB-MMCs with variable DC voltages," *IEEE Transactions on Industrial Electronics*, vol. 70, no. 6, pp. 5808-5818, Jun. 2023.
- [36] C. Zhao, Y. Li, Z. Li *et al.*, "Capacitance optimization design of hybrid modular multilevel converter," *Proceedings of the Chinese Society of Electrical Engineering*, vol. 37, no. 19, pp. 5717-5729, Oct. 2017.
- [37] Y. Li, S. Li, C. Zhao *et al.*, "Capacitance reduction methods for modular multilevel converter by dynamically switching reactor submodule," *Automation of Electric Power Systems*, vol. 42, no. 19, pp. 90-97, Oct. 2018.
- [38] C. Zhao, Q. Fan, S. Li *et al.*, "Operation method of MMC capacitance reduction under arm inductor switching control," *IEEE Transactions on Power Delivery*, vol. 36, no. 1, pp. 418-428, Feb. 2021.
- [39] K. Wang, Y. Li, Z. Zheng *et al.*, "Voltage balancing and fluctuation-suppression methods of floating capacitors in a new modular multilevel converter," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 5, pp. 1943-1954, May 2013.
- [40] B. Li, Y. Zhang, G. Wang *et al.*, "A modified modular multilevel converter with reduced capacitor voltage fluctuation," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 10, pp. 6108-6119, Oct. 2015.
- [41] L. He, K. Zhang, J. Xiong *et al.*, "New modular multilevel converter with power channels between upper- and lower-arms suitable for MV drives," in *Proceedings of 2015 IEEE Applied Power Electronics Conference and Exposition*, Charlotte, USA, Mar. 2015, pp. 799-805.
- [42] Z. Kong, X. Huang, Z. Wang *et al.*, "Active power decoupling for sub-modules of a modular multilevel converter," *IEEE Transactions on Power Electronics*, vol. 33, no. 1, pp. 125-136, Jan. 2018.
- [43] G. Jia, M. Chen, S. Tang *et al.*, "A modular multilevel converter with active power filter for submodule capacitor voltage ripples and power losses reduction," *IEEE Transactions on Power Electronics*, vol. 35, no. 11, pp. 11401-11417, Nov. 2020.
- [44] G. Jia, M. Chen, S. Tang *et al.*, "Active power decoupling for a modified modular multilevel converter to decrease submodule capacitor voltage ripples and power losses," *IEEE Transactions on Power Electronics*, vol. 36, no. 3, pp. 2835-2851, Mar. 2021.
- [45] S. Du, B. Wu, N. R. Zargari *et al.*, "A flying-capacitor modular multilevel converter for medium-voltage motor drive," *IEEE Transactions on Power Electronics*, vol. 32, no. 3, pp. 2081-2089, Mar. 2017.
- [46] R. Breda, S. Breda, S. Calligaro *et al.*, "Pre-charge/start-up strategy for flying-capacitor modular multilevel converter (FC-MMC) with damping of L-C oscillations," in *Proceedings of 2023 IEEE Applied Power Electronics Conference and Exposition*, Orlando, USA, Mar. 2023, pp. 2788-2795.
- [47] Y. Liu, Y. Si, Z. Zhang *et al.*, "A novel modular multilevel converter with ripple current elimination channels based on isolated CLLC resonant circuits," *IEEE Open Journal of Power Electronics*, vol. 3, pp. 433-449, May 2022.
- [48] Q. Tu, Z. Xu, and L. Xu, "Reduced switching-frequency modulation and circulating current suppression for modular multilevel converters," *IEEE Transactions on Power Delivery*, vol. 26, no. 3, pp. 2009-2017, Jul. 2011.
- [49] Q. Song, W. Liu, X. Li *et al.*, "A steady-state analysis method for a modular multilevel converter," *IEEE Transactions on Power Electronics*, vol. 28, no. 8, pp. 3702-3713, Aug. 2013.
- [50] S. P. Engel and R. W. de Doncker, "Control of the modular multilevel converter for minimized cell capacitance," in *Proceedings of the 2011 14th European Conference on Power Electronics and Applications*, Birmingham, UK, Aug. 2011, pp. 1-10.
- [51] Y. Cai, C. Ren, J. Zhou *et al.*, "Control strategy for suppressing capacitor voltage ripple of MMC-HVDC," *Power System Protection and Control*, vol. 45, no. 5, pp. 45-50, Mar. 2017.
- [52] J. Meng, Q. Song, Q. Sun *et al.*, "Optimization control strategy of capacitor voltage for modular multilevel converter based on mathematical analysis of circulating current," *High Voltage Engineering*, vol. 45, no. 3, pp. 882-889, Mar. 2019.
- [53] J. Pou, S. Ceballos, G. Konstantinou *et al.*, "Circulating current injection methods based on instantaneous information for the modular multilevel converter," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 2, pp. 777-788, Feb. 2015.
- [54] L. He, K. Zhang, J. Xiong *et al.*, "A repetitive control scheme for harmonic suppression of circulating current in modular multilevel converters," *IEEE Transactions on Power Electronics*, vol. 30, no. 1, pp. 471-481, Jan. 2015.
- [55] X. Jiang, S. Zhang, B. Chen *et al.*, "Voltage fluctuation suppression strategy of MMC sub-module under unbalanced grid voltage," in *Proceedings of 2022 4th International Conference on Smart Power & Internet Energy Systems*, Beijing, China, Dec. 2022, pp. 49-52.
- [56] Y. Hu, P. Song, Z. Li *et al.*, "Circulating Current suppression for modular multilevel converter based on predictive control," in *Proceedings of 2022 4th International Conference on Power and Energy Technology*, Beijing, China, Jul. 2022, pp. 1261-1266.
- [57] E. Shi, X. Wu, L. Jing *et al.*, "Analysis of the impact on modular multilevel converter with circulating current injection under unbalanced grid voltage," *Transactions of China Electrotechnical Society*, vol. 33, no. 16, pp. 3719-3731, Aug. 2018.
- [58] R. Picas, J. Pou, S. Ceballos *et al.*, "Optimal injection of harmonics in

- circulating currents of modular multilevel converters for capacitor voltage ripple minimization,” in *Proceedings of 2013 IEEE ECCE Asia Downunder*, Melbourne, Australia, Jun. 2013, pp. 318-324.
- [59] H. Lin and Z. Wang, “Power operating region analysis and circulating current switching control strategy for MMC,” *Electric Power Automation Equipment*, vol. 38, no. 8, pp. 31-37, Aug. 2018.
- [60] H. Gan, H. Xiao, Y. Huang *et al.*, “Capacitor voltage ripple control strategy of lightweight modular multilevel converter for offshore wind power transmission,” in *Proceedings of 2023 IEEE Industry Applications Society Annual Meeting*, Nashville, USA, Oct. 2023, pp. 1-7.
- [61] R. Li, J. E. Fletcher, L. Xu *et al.*, “Enhanced flat-topped modulation for MMC control in HVDC transmission systems,” *IEEE Transactions on Power Delivery*, vol. 32, no. 1, pp. 152-161, Feb. 2017.
- [62] G. Guo, Q. Song, W. Yang *et al.*, “Application of third-order harmonic voltage injection in a modular multilevel converter,” *IEEE Transactions on Industrial Electronics*, vol. 65, no. 7, pp. 5260-5271, Jul. 2018.
- [63] L. Yang, L. Jia, Y. Zhao *et al.*, “Closed-loop control strategies for minimizing submodule capacitance in MMC,” in *Proceedings of 2023 2nd Asia Power and Electrical Technology Conference*, Shanghai, China, Apr. 2023, pp. 501-505.
- [64] J. Wang, X. Han, H. Ma *et al.*, “Analysis and injection control of circulating current for modular multilevel converters,” *IEEE Transactions on Industrial Electronics*, vol. 66, no. 3, pp. 2280-2290, Mar. 2019.
- [65] L. Lin, A. Li, C. Xu *et al.*, “Multi-objective genetic algorithm based coordinated second- and third-order harmonic voltage injection in modular multilevel converter,” *IEEE Access*, vol. 8, pp. 94318-94329, Aug. 2020.
- [66] J. Xu, W. Deng, G. Li *et al.*, “Optimal second-harmonic current injection for capacitor voltage fluctuation reduction in hybrid MMCs under grid-side SLG faults,” *IEEE Transactions on Power Delivery*, vol. 37, no. 4, pp. 2857-2866, Aug. 2022.
- [67] J. Xu, J. Wang, Y. Yang *et al.*, “Optimal suppression strategy for capacitor voltage ripples of hybrid MMCs under unbalanced grid voltages,” *IEEE Transactions on Power Delivery*, vol. 38, no. 1, pp. 244-254, Feb. 2023.
- [68] L. Yu, Z. Fu, R. Li *et al.*, “DRU-HVDC for offshore wind power transmission: a review,” *IET Renewable Power Generation*, vol. 18, no. 13, pp. 2080-2101, Oct. 2024.
- [69] R. Blasco-Gimenez, S. Añó-Villalba, J. Rodríguez-D’Derléc *et al.*, “Distributed voltage and frequency control of offshore wind farms connected with a diode-based HVDC link,” *IEEE Transactions on Power Electronics*, vol. 25, no. 12, pp. 3095-3105, Dec. 2010.
- [70] R. Blasco-Gimenez, S. Añó-Villalba, J. Rodríguez-D’Derléc *et al.*, “Diode based HVDC link for the connection of large off-shore wind farms with self start capability,” in *Proceedings of the 2011 14th European Conference on Power Electronics and Applications*, Birmingham, UK, Aug. 2011, pp. 1-9.
- [71] C. Prignitz, H. G. Eckel, and A. Rafoth, “FixReF sinusoidal control in line side converters for offshore wind power generation,” in *Proceedings of 2015 IEEE 6th International Symposium on Power Electronics for Distributed Generation Systems*, Aachen, Germany, Aug. 2015, pp. 1-5.
- [72] C. Prignitz, H. G. Eckel, and H. J. Knaak, “Voltage and current behavior in a FixReF controlled offshore wind farm using an HVDC transmission system based on uncontrolled diode rectifier units,” in *Proceedings of 2016 18th European Conference on Power Electronics and Applications*, Karlsruhe, Germany, Sept. 2016, pp. 1-6.
- [73] C. Prignitz, H. G. Eckel, S. Achenbach *et al.*, “FixReF: a control strategy for offshore wind farms with different wind turbine types and diode rectifier HVDC transmission,” in *Proceedings of 2016 IEEE 7th International Symposium on Power Electronics for Distributed Generation Systems*, Vancouver, Canada, Jun. 2016, pp. 1-7.
- [74] Y. Tang, Z. Zhang, and Z. Xu, “DRU based low frequency AC transmission scheme for offshore wind farm integration,” *IEEE Transactions on Sustainable Energy*, vol. 12, no. 3, pp. 1512-1524, Jul. 2021.
- [75] R. Blasco-Gimenez, S. Añó-Villalba, J. Rodriguez *et al.*, “HVDC connection of off-shore wind farms based on synchronous generators,” in *Proceedings of 2009 IEEE PES/IAS Conference on Sustainable Alternative Energy*, Valencia, Spain, Sept. 2009, pp. 1-5.
- [76] R. Blasco-Gimenez, S. Añó-Villalba, J. Rodriguez *et al.*, “Variable voltage off-shore distribution network for wind farms based on synchronous generators,” in *Proceedings of 20th International Conference and Exhibition on Electricity Distribution*, Prague, Czech Republic, Jun. 2009, pp. 1-4.
- [77] L. Yu, R. Li, and L. Xu, “Distributed PLL-based control of offshore wind turbines connected with diode-rectifier-based HVDC systems,” *IEEE Transactions on Power Delivery*, vol. 33, no. 3, pp. 1328-1336, Jun. 2018.
- [78] L. Yu, R. Li, L. Xu *et al.*, “Analysis and control of offshore wind farms connected with diode rectifier-based HVDC system,” *IEEE Transactions on Power Delivery*, vol. 35, no. 4, pp. 2049-2059, Aug. 2020.
- [79] A. Bidadfar, O. Saborio-Romano, N. A. Cutululis *et al.*, “Control of offshore wind turbines connected to diode-rectifier-based HVDC systems,” *IEEE Transactions on Sustainable Energy*, vol. 12, no. 1, pp. 514-523, Jan. 2021.
- [80] Z. Zhang, Y. Jin, and Z. Xu, “Grid-forming control of wind turbines for diode rectifier unit based offshore wind farm integration,” *IEEE Transactions on Power Delivery*, vol. 38, no. 2, pp. 1341-1352, Apr. 2023.
- [81] A. A. Ivan, P. G. Ruben, R. Blasco-Gimenez *et al.*, “Control strategy of a HVDC-diode rectifier connected type-4 off-shore wind farm,” in *Proceedings of 2015 IEEE 2nd International Future Energy Electronics Conference*, Taipei, China, Nov. 2015, pp. 1-6.
- [82] L. Harnefors, M. Schweizer, J. Kukkola *et al.*, “Generic PLL-based grid-forming control,” *IEEE Transactions on Power Electronics*, vol. 37, no. 2, pp. 1201-1204, Feb. 2022.
- [83] R. Li, L. Yu, L. Xu *et al.*, “DC fault protection of diode rectifier unit based HVDC system connecting offshore wind farms,” in *Proceedings of 2018 IEEE PES General Meeting*, Portland, USA, Aug. 2018, pp. 1-5.
- [84] R. Li, L. Yu, and L. Xu, “Offshore AC fault protection of diode rectifier unit-based HVDC system for wind energy transmission,” *IEEE Transactions on Industrial Electronics*, vol. 66, no. 7, pp. 5289-5299, Jul. 2019.
- [85] J. Zhou and A. M. Gole, “VSC transmission limitations imposed by AC system strength and AC impedance characteristics,” in *Proceedings of 10th IET International Conference on AC and DC Power Transmission*, Birmingham, UK, Dec. 2012, pp. 1-6.
- [86] L. Fan, “Modeling type-4 wind in weak grids,” *IEEE Transactions on Sustainable Energy*, vol. 10, no. 2, pp. 853-864, Apr. 2019.
- [87] Y. Li and Z. Du, “Stabilizing condition of grid-connected VSC as affected by phase locked loop (PLL),” *IEEE Transactions on Power Delivery*, vol. 37, no. 2, pp. 1336-1339, Apr. 2022.
- [88] H. Xiao, H. He, L. Zhang *et al.*, “Adaptive grid-synchronization based grid-forming control for voltage source converters,” *IEEE Transactions on Power Systems*, vol. 39, no. 2, pp. 4763-4766, Mar. 2024.
- [89] M. N. Cardiel-Ivarez, S. Arnaltes, J. L. Rodriguez-Amenedo *et al.*, “Decentralized control of offshore wind farms connected to diode-based HVdc links,” *IEEE Transactions on Energy Conversion*, vol. 33, no. 3, pp. 1233-1241, Sept. 2018.
- [90] M. N. Cardiel-Ivarez, J. L. Rodriguez-Amenedo, S. Arnaltes *et al.*, “Modeling and control of LCC rectifiers for offshore wind farms connected by HVDC links,” *IEEE Transactions on Energy Conversion*, vol. 32, no. 4, pp. 1284-1296, Dec. 2017.
- [91] L. Yu, J. Miao, J. Zhu *et al.*, “Self-synchronization control of offshore wind turbines connected with DRU-HVDC,” *CSEE Journal of Power and Energy Systems*, doi: 10.17775/CSEEJPES.2022.03690
- [92] H. Xiao, X. Huang, Y. Huang *et al.*, “Self-synchronizing control and frequency response of offshore wind farms connected to diode rectifier based HVDC system,” *IEEE Transactions on Sustainable Energy*, vol. 13, no. 3, pp. 1681-1692, Jul. 2022.
- [93] R. Ramachandran, S. Poullain, A. Benchaib *et al.*, “On the black start of offshore wind power plants with diode rectifier based HVDC transmission,” in *Proceedings of 2019 21st European Conference on Power Electronics and Applications*, Genova, Italy, Sept. 2019, pp. 1-10.
- [94] B. Teng, J. Ma, and M. Zhu, “Diode-rectifier-based offshore platform for wind power collection and HVDC transmission system: implementation and hierarchical control,” *IEEE Transactions on Sustainable Energy*, vol. 16, no. 2, pp. 812-825, Apr. 2025.
- [95] O. Saborio-Romano, A. Bidadfar, J. N. Sakamuri *et al.*, “Novel energisation method for offshore wind farms connected to HVDC via diode rectifiers,” in *Proceedings of 45th Annual Conference of the IEEE Industrial Electronics Society*, Lisbon, Portugal, Oct. 2019, pp. 4837-4841.
- [96] A. Bidadfar, O. Saborio-Romano, J. Naidu Sakamuri *et al.*, “Coordinated control of HVDC and HVAC power transmission systems integrating a large offshore wind farm,” *Energies*, vol. 12, no. 18, p. 3435, Sept. 2019.
- [97] T. Yi, J. Dai, Y. Feng *et al.*, “Cooperative frequency control strategy for wind farm black-start based on virtual inertia,” *Automation of Electric Power Systems*, vol. 41, no. 4, pp. 19-24, Feb. 2017.

- [99] X. Li, C. Yang, X. Gu *et al.*, "Study on black-start process and frequency control of wind farms assisted with diesel generator," *Power System Technology*, vol. 42, no. 6, pp. 1853-1859, Jun. 2018.
- [100] X. Chen, Y. Xin, W. Tang *et al.*, "Coordinated control strategy of wind turbine and diesel generator for black-start system of offshore wind farm," *Automation of Electric Power Systems*, vol. 44, no. 13, pp. 98-105, May 2020.
- [101] L. Miao, J. Wen, H. Xie *et al.*, "Coordinated control strategy of wind turbine generator and energy storage equipment for frequency support," *IEEE Transactions on Industry Applications*, vol. 51, no. 4, pp. 2732-2742, Jul. 2015.
- [102] Q. Zhu, H. Xiao, Q. Yang *et al.*, "General and efficient simulation model for energy storage-embedded MMC with adaptability to multiple submodule topologies," *IEEE Transactions on Industry Applications*, doi: 10.1109/TIA.2025.3590678.
- [103] H. Xiao, Q. Yang, Q. Zhu *et al.*, "Grid-supporting HVDC system with low-voltage energy storage for renewables integration," *IEEE Transactions on Power Delivery*, doi: 10.1109/TPWRD.2025.3609293
- [104] Y. Guangya, "Review on engineering practices and future technology prospects of European offshore wind power," *Automation of Electric Power Systems*, vol. 45, no. 21, pp. 23-32, Sept. 2021.
- [105] F. Luo, K. Meng, Z. Dong *et al.*, "Coordinated operational planning for wind farm with battery energy storage system," *IEEE Transactions on Sustainable Energy*, vol. 6, no. 1, pp. 253-262, Jan. 2015.
- [106] L. Xie, L. Yao, F. Cheng *et al.*, "Coordinate control strategy for stability operation of offshore wind farm integrated with diode-rectifier HVDC," *Global Energy Interconnection*, vol. 3, no. 3, pp. 205-216, Jun. 2020.
- [107] T. H. Nguyen, D. C. Lee, and C. K. Kim, "A cost-effective converter system for HVDC links integrated with offshore wind farms," in *Proceedings of 39th Annual Conference of the IEEE Industrial Electronics Society*, Vienna, Austria, Jan. 2013, pp. 7978-7983.
- [108] T. H. Nguyen, Q. A. Le, and D. C. Lee, "A novel HVDC-link based on hybrid voltage-source converters," in *Proceedings of 2015 IEEE Energy Conversion Congress and Exposition*, Montreal, Canada, Sept. 2015, pp. 3338-3343.
- [109] R. Li and L. Xu, "A unidirectional hybrid HVDC transmission system based on diode rectifier and full-bridge MMC," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 9, no. 6, pp. 6974-6984, Dec. 2021.
- [110] Y. Wu, L. Zhang, Y. Zhou *et al.*, "A hybrid HVDC converter based on MMC and diode rectifier for offshore wind farm integration," in *Proceedings of 2021 International Conference on Power System Technology*, Haikou, China, Aug. 2021, pp. 1476-1480.
- [111] C. Wang, A. Ali, and F. Blaabjerg, "Composition and control of a new type of hybrid voltage-source converter based on DRUs and FB-MMC for large-scale offshore wind power integration and transmission," *IEEE Transactions on Power Electronics*, vol. 39, no. 5, pp. 5721-5732, May 2024.
- [112] J. Wu, X. Xu, Y. Liu *et al.*, "Compound control strategy of active power filter based on modular multilevel converter," in *Proceedings of the 11th World Congress on Intelligent Control and Automation*, Shenyang, China, Jul. 2014, pp. 4771-4777.
- [113] Y. Jin, Z. Zhang, Y. Huang *et al.*, "Harmonic filtering and fault ride-through of diode rectifier unit and modular multilevel converter based offshore wind power integration," *IET Renewable Power Generation*, vol. 17, no. 14, pp. 3554-3567, Oct. 2023.
- [114] Y. Zhu, Y. Li, B. Li *et al.*, "Internal energy distribution control based fault ride-through and postfault recovery strategy for offshore wind farms connected to DR-MMC HVDC under onshore AC grid faults," *IEEE Transactions on Sustainable Energy*, vol. 16, no. 2, pp. 1191-1205, Apr. 2025.
- [115] X. Li, S. Liang, Y. Li *et al.*, "Start-up strategy for DR-MMC paralleled hybrid HVDC integrated with offshore wind power," in *Proceedings of 2020 IEEE 4th Conference on Energy Internet and Energy System Integration*, Wuhan, China, Oct. 2020, pp. 665-669.
- [116] X. Li, "Self-adaptive droop control strategy of DR-MMC hybrid DC grid for offshore wind power transmission," *Power System Technology*, vol. 46, no. 8, pp. 2871-2880, Aug. 2022.
- [117] H. Xiao, H. Gan, Y. Dong *et al.*, "Control and capacity design of station-hybrid HVDC system with DRU and MMC in parallel for offshore wind power integration," *IEEE Transactions on Power Delivery*, vol. 39, no. 3, pp. 1783-1793, Jun. 2024.
- [118] Y. Chang and X. Cai, "Hybrid topology of a diode-rectifier-based HVDC system for offshore wind farms," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 7, no. 3, pp. 2116-2128, Sept. 2019.
- [119] J. Li, X. Wang, J. Lyu *et al.*, "Stability analysis of wind farm connected to hybrid HVDC converter," in *Proceedings of 2020 IEEE 9th International Power Electronics and Motion Control Conference*, Nanjing, China, Nov. 2020, pp. 3258-3262.
- [120] C. Liu, F. Deng, Q. Heng *et al.*, "Crossing thyristor branches-based hybrid modular multilevel converters for DC line faults," *IEEE Transactions on Industrial Electronics*, vol. 68, no. 10, pp. 9719-9730, Oct. 2021.
- [121] J. Deng, F. Cheng, L. Yao *et al.*, "A review of system topologies, key operation and control technologies for offshore wind power transmission based on HVDC," *IET Generation, Transmission & Distribution*, vol. 17, no. 15, pp. 3345-3363, Aug. 2023.
- [122] K. Sun, H. Zhou, W. Yao *et al.*, "Comprehensive control of MMC-HVDC integrated offshore wind farm system including optimized energy control for fast frequency support," *Journal of Modern Power Systems and Clean Energy*, vol. 13, no. 6, pp. 1966-1979, Dec. 2025.
- [123] A. E. M. Commission. (2019, Dec.). Review of the system black event in south Australia on 28 September 2016. [Online]. Available: <https://www.aemc.gov.au/markets-reviews-advice/review-of-the-system-black-event-in-south-australi>.
- [124] NESO. (2019, Sept.). Appendices to the technical report on the events of 9 August 2019. [Online]. Available: <https://www.neso.energy/document/152351/download>.
- [125] C. Buchhagen, C. Rauscher, A. Menze *et al.*, "BorWin1 – first Experiences with harmonic interactions in converter dominated grids," in *Proceedings of International ETG Congress 2015*, Bonn, Germany, Nov. 2015, pp. 1-7.
- [126] H. Wu and X. Wang, "Control of grid-forming VSCs: a perspective of adaptive fast/slow internal voltage source," *IEEE Transactions on Power Electronics*, vol. 38, no. 8, pp. 10151-10169, Aug. 2023.
- [127] Queensland's Critical Minerals. (2025, Aug.). Power plant profile: Guangdong Yangjiang Yangxi Qingzhou seven wind farm, China. [Online]. Available: <https://www.power-technology.com/data-insights/power-plant-profile-guangdong-yangjiang-yangxi-qingzhou-seven-wind-farm-china/?cf-view>
- [128] Dogger Bank Wind Farm. (2025, Aug.). Inter-array cable works completed on Dogger Bank A. [Online]. Available: <https://doggerbank.com/construction/inter-array-cable-works-completed-on-dogger-bank-a/>
- [129] TenneT. (2025, Aug.). DolWin5. [Online]. Available: <https://www.tennet.eu/projects/dolwin5>
- [130] W. Diao, A. Liu, J. Mei *et al.*, "Synchronous voltage reconstruction of VSC-HVDC systems under weak grid conditions," *Journal of Modern Power Systems and Clean Energy*, vol. 13, no. 3, pp. 1040-1051, May 2025.
- [131] S. Tan, J. Liu, X. Du *et al.*, "Multi-port network modeling and stability analysis of VSC-MTDC systems," *Journal of Modern Power Systems and Clean Energy*, vol. 12, no. 5, pp. 1666-1677, Sept. 2024.
- [132] J. Li, B. Zhu, Y. Guo *et al.*, "The simulation of Kunlilong flexible DC project with single station operation and out of operation," in *Proceedings of 2021 IEEE/IAS Industrial and Commercial Power System Asia*, Chengdu, China, Jul. 2021, pp. 1028-1034.
- [133] Z. Li, Z. Wei, R. Zhan *et al.*, "System operational dispatching and scheduling strategy for hybrid cascaded multi-terminal HVDC," *International Journal of Electrical Power & Energy Systems*, vol. 122, p. 106195, Nov. 2020.
- [134] J. Zhang, Q. Xie, Z. Zheng *et al.*, "Coordinated feedback power control method for hybrid multi-feed HVDC system," *Journal of Modern Power Systems and Clean Energy*, vol. 12, no. 6, pp. 2045-2057, Nov. 2024.
- [135] H. Zhao, H. Zhou, W. Yao *et al.*, "Dynamic analysis of uniformity and difference for grid-following and grid-forming voltage source converters using phasor and topological homology methods," *Journal of Modern Power Systems and Clean Energy*, vol. 13, no. 1, pp. 3-14, Jan. 2025.
- [136] TenneT. (2025, Aug.). BorWin6. [Online]. Available: <https://www.tennet.eu/de-en/projects/borwin6>
- [137] TenneT. (2025, Aug.). DolWin3. [Online]. Available: <https://www.tennet.eu/de-en/projects/dolwin3>

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