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OFFSHORE WIND POWER TRANSMISSION: INNOVATIONS & CHALLENGES

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Abstract: *The rapid growth of offshore wind power presents an essential solution in meeting global energy demands while addressing environmental concerns. Europe, especially the UK and Germany, leads in offshore wind power capacity, with estimates projecting 99 GW by 2030. The prevalent transmission technology, VSC-HVDC, offers independent control and reduced losses. However, integrating offshore wind power into existing grids poses challenges. Steady-state and dynamic analyses are crucial for system stability. This review explores transmission technologies, focusing on HVAC, HVDC, hybrid systems, point-to-point vs. multi-terminal transmission, and innovative floating substations. Additionally, it delves into emerging issues like small-signal stability, grid integration challenges, and the use of power hydraulic systems in wind turbine applications. The paper also discusses the global shift towards renewables and the urgency to address environmental concerns, making offshore wind power an indispensable component of the energy landscape..*

Keywords: *Offshore wind power, VSC-HVDC, Small-signal stability, Grid integration, Hybrid transmission systems, Floating substations, Power hydraulic systems, Sustainable energy, Renewable energy.*

I. INTRODUCTION

Offshore wind power, as a clean and sustainable technology, has been developed rapidly in recent years. At present, the total installed capacity in Europe is increasing every year, among which the UK and Germany dominate the offshore wind power industry. According to Wind Europe's High Scenario, it is estimated that the offshore wind energy capacity in Europe will reach 99 GW by 2030. Nowadays, the mainstream transmission technology is VSC-HVDC. In contrast to conventional transmission modes, this particular mode boasts several distinct advantages, including the ability for independent control over the active and reactive power output, reduced power losses, and diminished voltage drop, thereby enhancing overall system efficiency and reliability. The realm of small-signal stability analysis is dedicated to the examination of the dynamic response characteristics within power systems subsequent to minor disturbances, encompassing fluctuations in power generation or consumption that may occur at random intervals. The primary objective of this analysis is to assess the system's capability to effectively mitigate oscillations and maintain a stable operating state, thus ensuring the seamless and uninterrupted transmission of power across the network [1]. This critical evaluation serves as a cornerstone for enhancing the resilience and performance of modern power transmission systems. Integration of offshore wind power plants into an existing power grid can cause operational challenges for the grid. This is because of the topological and technological changes that occur as a result of the wind power plant integration. Within the comprehensive framework of wind integration planning, a pivotal aspect involves the meticulous execution of both steady-state and dynamic analyses. These analyses are performed with the primary goal of assessing the power system's capacity to effectively absorb and integrate the wind power plant while preserving the essential attributes of system stability. The ultimate aim is to guarantee that the power system, even after the integration of wind power facilities, remains resilient and capable of sustaining secure and uninterrupted operations [2]. These analyses serve as an indispensable part of the planning process, providing valuable insights and recommendations to fine-tune the infrastructure and strategies for accommodating wind power, thereby enhancing the overall reliability and performance of the integrated power grid. This holistic approach is fundamental to ensuring the successful and sustainable incorporation of wind energy into the existing power system. The issues of environmental pollution and insufficient fossil fuel energy are becoming increasingly severe. To mitigate environmental degradation and optimize energy structure, renewable energy sources (RESs), such as solar energy and wind energy, have received widespread attention all over the world [3]. The voltage source converter based on high-voltage direct current (VSC-HVDC) transmission technology has attracted increasing attention because of its advantages such as flexible control, supply to passive system, and the need for few filter banks; further, it has gained popularity for use in offshore wind farm integration. Efficient control of AC voltage within offshore wind farms holds paramount significance, as it directly impacts the seamless transmission of offshore wind-generated power. Typically, this control is managed through the rectifier converter situated at the transmission end in Variable-Speed Constant-Frequency High-Voltage Direct Current (VSCHVDC) systems. However, there exists an innovative and alternative control strategy for offshore voltage regulation, which offers a novel perspective on this critical aspect.

This innovative approach entails the application of a voltage control strategy initially developed for microgrid systems to the wind turbines within the offshore wind farm. This pioneering strategy empowers the wind turbines to function as grid-forming units, effectively assuming the role of orchestrators within the power network. These turbines, by harnessing this control strategy, are not only capable of generating wind energy but also take on the pivotal role of providing precise voltage and frequency control. This pioneering approach, detailed in [4], introduces a dynamic and flexible method for enhancing the stability and reliability of offshore wind energy integration, potentially revolutionizing the offshore wind power landscape.

The transmission of wind power from offshore plants to the onshore grid is a major challenge for industry and academia as well. Many transmission configurations and design topologies have been proposed for power transfer. HVAC transmission is one of the good solutions for transmission of offshore power at 50 or 60 Hz, if the distance is less than 50 km to shore [4]. The traditional wind farms near to shore are built with HVAC transmission as considering the cost [5]. HVDC is another promising solution for offshore wind power for long distance transmission to near shore grid. HVDC transmission with VSC or Line Commutated Converter (LCC) based transmissions are the two approaches for offshore wind power for greater distances [5].

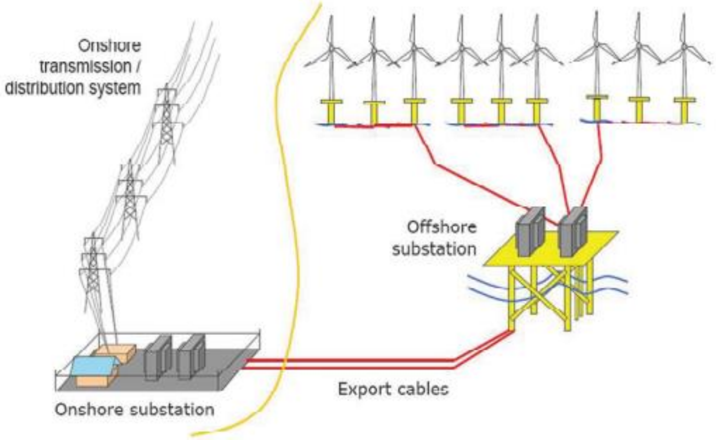

Figure 1. A typical construction of offshore wind farm integration.

Offshore converter is one of the major challenges, because of large power electronic equipment. It may reduce the reliability and increased cost for far offshore. If any failure occurs, the O&M are concerned problem, thereby rising supply interruption and downtime.

Wind energy generation is increasingly becoming one of the key sources of electric energy for industrial as well as domestic use, due to its several advantages over fossil fuel counterparts. This growth in wind energy can be seen from its installed capacity figures, where China is leading with a 237 GW of wind power available followed by US at around. Wind energy growth across Europe shows a remarkable improvement with installed capacity of 1.48 GW in 2008 to 25 GW in 2020.

The UK and Germany having the largest installed capacity with a total of thirteen countries contributed in wind energy to achieve these numbers. When it comes to offshore wind energy, the main advantage over its onshore counterpart is the consistency in generating power at a steady rate due to stronger and more consistent wind gusts. Offshore wind farms are distributed in various countries around the world, mostly in Europe followed by Asia and America [6]. While previous studies have indeed delved into various methods for addressing power quality (PQ) issues and their mitigation in the context of wind energy systems, it is worth noting that a comprehensive and all-encompassing review, particularly one that encompasses the emerging challenges associated with the integration, transmission, PQ, and stability of offshore wind energy, is yet to be presented in a fully inclusive manner. Although several research papers have explored methods to mitigate PQ issues in conventional wind farms, and some authors have undertaken reviews concerning stability, low voltage ride-through (LVRT) standards, and grid codes as they relate to wind energy systems, there is still a notable gap in the literature.

The evolving landscape of offshore wind energy presents unique challenges that necessitate a more thorough examination. These challenges encompass a myriad of aspects, including the intricacies of offshore wind farm integration, transmission across vast expanses of water, and the interplay between PQ and stability. Consequently, there exists an opportunity for a comprehensive review to consolidate and synthesize the existing knowledge while shedding light on novel approaches and methodologies to address these evolving challenges effectively. Such an endeavor would undoubtedly contribute significantly to the field of offshore wind energy and serve as a valuable resource for researchers and practitioners alike.

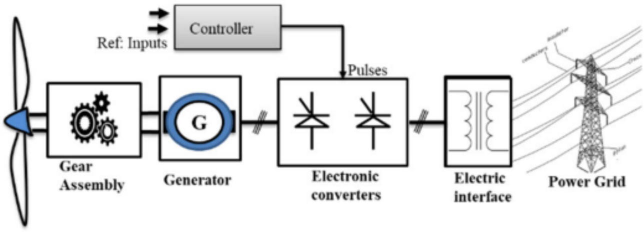

Figure 2. Grid connected wind energy system.

Wind energy has witnessed remarkable and sustained growth over the past two decades, firmly establishing itself as a driving force in the global energy industry. As we entered the 21st century, the world has seen a staggering cumulative installation of wind turbine (WT) power, amounting to an impressive 591 GW, as reported by the Global Wind Energy Council (GWEC). Although the majority of these installations are terrestrial wind turbines, the offshore turbine market has surged in prominence over the past decade, with a substantial 23 GW of capacity now interconnected [7].

Offshore wind turbines (OWTs) continue to be a dependable and viable solution for harnessing wind energy, albeit requiring deployment in water depths that extend below 60 meters. The appeal of offshore installations lies in their ability to tap into several advantages. These include access to a more abundant and consistent wind resource, the potential to utilize extensive and unobstructed expanses of open sea, and the mitigation of visual and noise impacts, which are of concern in onshore installations. Notably, regions like the North Sea, with its relatively shallow depths, have emerged as prime locations for these offshore wind farms, capitalizing on the favorable conditions to expand the capacity of sustainable energy generation.

II. LITERATURE REVIEW

Currently, the application of power hydraulic system i.e. HST in wind turbine is an emerging research field. The transmission system utilized in wind turbines is characterized by two primary configurations: the closed loop system and the open loop system. These systems are tailored for specific applications within the wind energy sector, each featuring distinct characteristics and operational variances. Notably, they differ significantly in terms of their transmitting medium, with the closed loop system relying on oil and the open loop system utilizing seawater. Furthermore, the equipment employed in these systems varies, encompassing components such as fixed and variable displacement pumps, as well as fixed and variable displacement hydraulic motors, each serving a unique purpose in the transmission process. Typically, the closed loop power transmission system finds its prominent application in onshore wind turbines, capitalizing on its specific features and functionalities to ensure optimal performance in land-based settings. On the other hand, the open loop system is predominantly utilized in offshore wind turbine systems, where its distinct design and adaptability cater to the unique demands and challenges posed by the offshore environment [8]. This differentiation underscores the importance of tailoring the transmission system to the specific operational requirements and environmental conditions encountered in onshore and offshore wind energy applications.

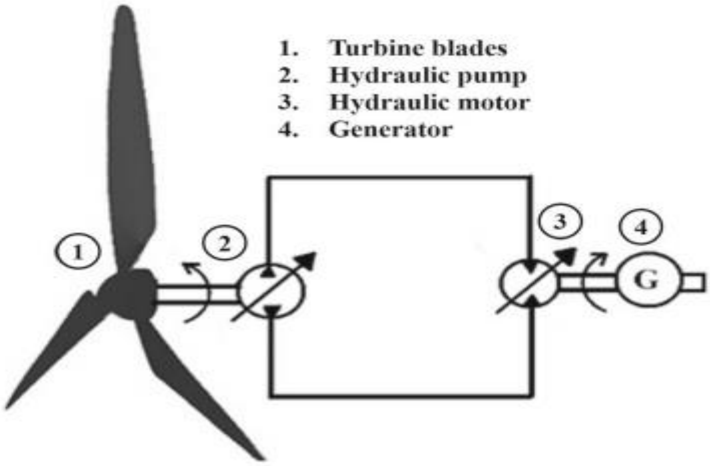

Figure 3. Wind turbine with closed-loop power transmission

With modern electric energy develops, several renewable energies gradually play the important role, among which the wind energy has been developed rapidly due to the environmentally friendly features. From the energy conversion perspective, wind energy in natural wind is captured and transformed by the wind turbine generator systems (WTGSs). WTGSs take the power setpoint as input and electric power as output, and controllers in the WTGS are working coordinately to guarantee the power output following the power demand. Over the past few years, many achievements have been brought in WTGS control to improve the wind turbine load conditions and stabilize the power output. The WTGS is controlled in regions divided by the rated wind speed [9]. Also, the closed loop hydraulic system increases the complexity in control strategy on onshore wind turbine. A similar concept was applied by Laguna for power transmission in wind turbine.

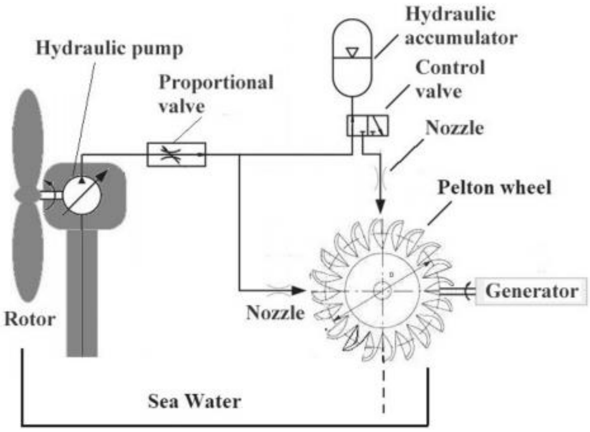

Figure 4. Offshore wind turbine with open-loop power hydraulic system

An open-loop hydraulic system in offshore wind turbine was reported by, where, a variable displacement pump was directly connected with the turbine rotor and pressurized sea water was used as the power transmission medium The application of an open-loop power hydraulic system in offshore wind turbine has shown some limitations attributed to its transmitting medium (sea water), temperature variation and environmental condition (humidity). The sea water is highly corrosive that may affect the performance of the hydraulic equipment and also, it may damage the structural components as well as the Peloton wheel blades.

III. LITERATURE REVIEW

H. Liu and J. Sun, [10] Ensuring the stability of the offshore alternating current (AC) collection bus in the context of offshore wind farms employing high-voltage direct current (HVDC) transmission is a multifaceted challenge. This stability hinges on the precise control of a myriad of converters connected to the bus, including wind turbine inverters, HVDC rectifiers, and Static Compensators (STATCOM). In this paper, we delve into the intricate aspects of maintaining the stability and control of these AC buses, particularly when HVDC rectifiers are implemented through line-commutated converters (LCC). To comprehensively address this issue, a detailed small-signal impedance model is meticulously crafted for each of the involved converters. Subsequently, a comprehensive system-level small-signal model is meticulously formulated. In this model, each wind turbine inverter is represented as a current source, the STATCOM is likened to a voltage source, and the HVDC rectifier is characterized as a load. This holistic modeling approach captures the complex interplay of these components in the context of offshore wind energy systems employing HVDC technology. The paper employs impedance-based stability criteria to systematically evaluate the control requirements for wind inverters and the STATCOM. These requirements are designed to ensure the overall stability of the system while simultaneously optimizing hardware cost. This research underscores the vital role of control strategies in maintaining the stability of offshore AC collection buses in offshore wind farms, especially when HVDC rectifiers with LCC technology are in use.

Fernández-Guillamón, A., et. al. [11] In the present era, wind energy has gained recognition as an exceptional renewable energy source with significant potential for integration into power systems. The majority of wind power plant endeavors have historically centered around onshore installations, given their maturity and established technological solutions within the electricity sector. However, as we chart our course toward the future of power generation, offshore power plants are emerging as a compelling and supplementary energy source, particularly in regions like the North and Baltic seas. Within this evolving energy landscape, this paper explores and delineates the trends and perspectives surrounding offshore wind power plants, aimed at facilitating massive integration into future power systems. These evolving trends encompass various facets, including turbine capacity, wind power plant capacity, water depth, and distance from the shore. The discussions delve into the considerations and implications of these factors in the context of offshore wind energy. Furthermore, the paper delves into the pivotal role of electrical transmission solutions, spanning high voltage alternating current (HVAC) and high voltage direct current (HVDC) technologies. It offers a comprehensive assessment of the advantages and technical constraints inherent in these transmission alternatives, shedding light on their potential applications and limitations in the offshore wind power domain. As we peer into the future, the paper also encapsulates several promising advancements currently under evaluation to bolster offshore wind energy capacity. These ongoing endeavors represent our collective commitment to harnessing the full potential of offshore wind power and its pivotal role in shaping the energy landscape of tomorrow.

I. Erlich, et. al. [12] This paper offers a comprehensive overview of the present state of offshore wind-based power generation technology, focusing primarily on the electrical aspects. It commences with a concise examination of the fundamental control functions, their interplay with operational behavior, and the machine's grid-supporting capabilities, both under normal circumstances and during contingency situations. Subsequently, it delves into the key considerations for wind farm collector design, covering aspects such as network topology, grounding options, and the layout of the offshore substation. The discussion then extends to matters concerning the foundation of offshore wind turbines and provides insights into the typical dimensions of the offshore substation platform, designed to house essential components like the main and grounding transformers, switchgear, and various accessories. The paper also scrutinizes the available options for establishing a transmission link connecting the offshore plant to the onshore grid. This is followed by an exploration of the intricacies of grid integration, including the current grid code requirements that govern these offshore systems. In summation, this paper offers a comprehensive and detailed assessment of the technological aspects and challenges within offshore wind-based power generation, with a particular emphasis on the electrical components.

Deng, J., et. al. [13] Offshore wind farms are seen as an excellent source of carbon-neutral energy for the future power grid. However, as these farms move farther from the shore and into deeper waters, the choice of transmission technology becomes crucial. High-voltage direct current (HVDC) transmission is gaining favor due to its cost-effectiveness and reliability over high-voltage alternating current (HVAC). This paper begins by offering insights into the current state of OWF-HVDC projects. It then introduces innovative converter designs with higher power density and cost-effectiveness, such as the hybrid modular multilevel converter (MMC), alternative arm converter (AAC), and diode rectifier (DR). Various OWF HVDC transmission system setups are explored, including terminal-hybrid, station-hybrid, and all-DC delivery systems, each tailored to the unique demands of offshore wind energy. The paper also summarizes key technologies for OWF HVDC operation and control. This includes grid-forming control strategies for offshore wind turbines, stability analysis methods, measures to enhance system stability, and control strategies for maintaining essential frequency support. Additionally, it addresses fault ride-through and protection strategies for various fault scenarios that may occur in OWF HVDC systems. In conclusion, the paper provides a comprehensive overview of OWF HVDC technology, highlighting its potential and significance in the future of offshore wind energy. It guides us toward a cleaner and more sustainable path for power generation.

Li, J., Wang, et. al. [14] High-voltage direct current (HVDC) transmission has emerged as a highly promising method for efficiently transferring power over extended distances from large-scale offshore wind farms. Currently, the modular multilevel converter (MMC) stands as the predominant choice for HVDC conversion. However, the conventional offshore MMC converter station, with its numerous submodules, presents challenges such as increased volume, weight, and cost.
To address these challenges, a novel hybrid converter scheme has been developed, which combines a diode rectifier with a smaller-scale ancillary converter based on MMC technology. This approach offers a cost-effective solution for offshore HVDC conversion. In the context of this paper, a hybrid HVDC converter is meticulously designed for a practical small-scale wind farm comprising eleven 1.5 MW doubly-fed induction generator (DFIG)-based wind turbines. The interaction and stability of the wind farm connected to the hybrid HVDC converter are analyzed using the impedance-based analysis method. To validate the stability analysis, time-domain simulations are conducted, confirming the robustness and reliability of this innovative hybrid HVDC system.

IV. DIFFERENT TRANSMISSION TOPOLOGIES FOR OFFSHORE POWER

Electricity production from fossil fuels has been widely adopted in the world because of diverse reasons such as higher-energy density in relative large quantity, cheaper cost, and well known technology. Coal-fired-based power plants supply about 41% of global electricity and in some countries such as South Africa it can be as high as 90%. However, it is estimated that if the energy from fossil fuels continue to be consumed at the present rate, it will not last long. Furthermore, electricity generation from coal is no longer a better choice due to several environmental concerns [15]. The global warming experienced due to the use of coal- and oil-fired-based power plants has promoted the use of renewable energy solutions such as photovoltaic, small hydro, and wind. Among various renewable generation technologies, the electric power generated by wind resources has become an increasingly important part of the world's energy production portfolio. Offshore power generation has become increasingly vital in meeting the world's growing energy demands. As technology advances, so do the methods of transmitting the generated power from offshore wind farms to the mainland. The transmission topology plays a pivotal role in ensuring the efficient and reliable delivery of electricity. This article explores various transmission topologies for offshore power, highlighting their advantages and challenges.

A. High Voltage Alternating Current (HVAC) Transmission:

HVAC transmission is a conventional method used for offshore power transmission. It involves converting the generated power to high voltage alternating current, which is then transmitted through undersea cables to onshore substations. HVAC transmission is well-established, reliable, and cost-effective for short to medium distances. However, it suffers from higher transmission losses over long distances and may require larger cables for higher capacities.

B. High Voltage Direct Current (HVDC) Transmission:

HVDC transmission has gained popularity for long-distance offshore power transmission. Unlike HVAC, HVDC transmits electricity in a unidirectional flow, reducing energy losses over extended distances. It also enables the integration of renewable energy sources from different locations into the grid. HVDC technology, with its efficient power conversion capabilities, is suitable for transmitting power over intercontinental distances and deep-sea applications.

C. Hybrid Transmission Systems:

Hybrid transmission systems combine both HVAC and HVDC technologies, leveraging their respective advantages. This approach optimizes the transmission process by using HVAC for moderate distances and HVDC for longer distances. Hybrid systems enhance the overall efficiency of power transmission, providing a balance between reliability, cost-effectiveness, and minimal transmission losses.

D. Point-to-Point Transmission vs. Multi-Terminal Transmission:

Point-to-point transmission connects a single offshore wind farm to an onshore substation. In contrast, multi-terminal transmission interconnects multiple offshore wind farms through a common offshore substation, improving system redundancy and grid stability. Multi-terminal systems allow for efficient utilization of grid infrastructure and enable the integration of diverse renewable energy sources, making them suitable for large-scale offshore power projects.

E. Floating Offshore Substations:

Floating offshore substations are innovative solutions that can act as hubs for multiple offshore wind farms. These substations, located closer to the wind farms, reduce the need for long undersea cables, minimizing transmission losses. Floating substations are particularly advantageous in deep-sea locations where fixed substations are not feasible. They enhance the efficiency and flexibility of offshore power transmission systems.

V. CONCLUSION

Offshore wind power stands as a beacon of hope in the renewable energy landscape, offering a clean and sustainable alternative to fossil fuels. The advancements in transmission technologies, from HVAC to innovative VSC-HVDC systems, signify progress in efficient energy delivery. Addressing challenges like small-signal stability, grid integration, and the development of power hydraulic systems for wind turbines is vital. The global transition towards renewables, driven by environmental concerns and diminishing fossil fuel resources, highlights the urgency of optimizing offshore wind power transmission. Embracing innovative solutions, such as floating substations and hybrid transmission systems, paves the way for a greener, more sustainable future, ensuring that offshore wind power remains a cornerstone in the global pursuit of clean energy solutions.

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