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Research Paper

REVIEW : INTERFACING MULTI-MEGAWATT OFFSHORE WIND TURBINES WITH MODULAR MULTILVEL CONVERTERS.

Kabir Arvind Tekam [1], Atharva Dnyaneshwar Ittadwar[2], Ishaque imran Sheikh[3], Hammad Umair Khan[4],Nikhil Pramodrao Yekhande[5] ,Prof. Archana Shirbhate[6]
[1,2,3,4,5,] Student Electrical Engineering Department ,Anjuman College of Engineering,& Technology Nagpur
[6,] Asso. Professor ,Electrical Engineering Department ,Anjuman College of Engineering,& Technology Nagpur

***Abstract*— : This paper presents a medium voltage wind energy conversion system with integrated storage that implements power electronics converter based on modular multilevel topology. The proposed converter has storage system integrated into its modular cell structure. The paper analyzes the proposed topology and presents detail sizing procedure for both converter and storage system in order to meet new grid connection standards and fault ride through requirements. In order to verify the system operation, high detail model of the converter leg is used to simulate independent power control on AC and DC sides of the converter needed for the successful implementation of the fault ride through control.**

Keywords —Wind Energy Conversion Systems, Modular Multilevel Cascade Converters

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1. Introduction

First, natural resources like oil are finite and non-renewable. As a result, meeting the world's energy demand through oil production will become increasingly difficult in the coming years. Second, burning fossil fuels releases greenhouse gases, such as carbon dioxide, into the atmosphere. While greenhouse gas emissions occur naturally, excessive levels caused by human activity contribute to global warming. This, in turn, drives climate change, which is associated with rising sea levels, reduced food supplies, air pollution, and other environmental issues.

To address these challenges, advancements in Wind Energy Conversion Systems (WECS) are being developed. The new generation of WECS aims to increase power output, with high-MW wind turbines capable of exceeding 10 MW. Most WECS are designed around converters, typically equipped with 1700V Insulated Gate Bipolar Transistors (IGBTs), to connect to low-voltage networks. However, relying on low-voltage switching technology poses several disadvantages, including high copper losses, low efficiency, increased cable costs, and the requirement for high-quality maps before connecting to other grids. These limitations highlight the need for further innovation in wind energy systems to enhance their effectiveness and scalability.

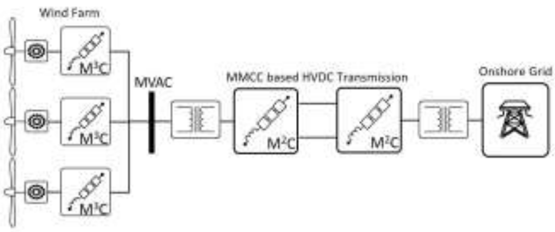

Fig. 1: MMCCs for offshore Wind Energy Generation and Transmission

is predictable in the immediate future. The European Wind Energy Association (EWEA) plan for the coming years is to make the wind industry the most competitive energy source, onshore by 2020 and offshore by 2030 [2]. Due to the presence of higher wind power potential and lower environmental impact, some of the future wind power capacity will be installed offshore. For offshore applications, up-scaling wind turbine dimensions, wind farm capacities, and electrical infrastructure has become the focus of recent research. Large wind turbines can capture more power with less installations compared to a group of small wind turbines, and reduce the structure cost of offshore WECSs [3]. Owing to this fact, wind turbine nominal powers and rotor diameters have increased approximately to 10MW-160m in 2015 [4]. The continuous increase in the power level of Wind Energy Conversion Systems (WECSs) is driving the power electronics technology towards MV operation. Accordingly, MV power converters will be dominant in the next generation Multi-MW WECSs, mainly because they offer cost-effective and compact design [4], [5]. Modular Multilevel Cascade Converters (MMCCs) are an enabling technology which has been proposed recently for wind energy applications [6], [7], due to their several advantages over traditional topologies such as full modularity and easy extendability to reach high voltage levels, redundancy, control flexibility and power quality [8]. For the transmission of power from offshore WECSs, HVDC is gradually replacing High Voltage Alternant Current (HVAC) due to the reactive power generated by the cables using HVAC is considered as a limiting factor in long-distance transmissions lines. In HVDC transmission systems for wind farms, the converter topologies are either current-source converters (CSCs) or voltage-source converters (VSCs). CSCs are used for power ratings over 100 MW, and it is mature technology regarding cost and reliability. For instance, line-commuted CSCs have been applied for offshore wind farms . However, VSCs have been preferred over CSCs because of its capability to control active and reactive power independently, the possibility of connecting to weak grids and feasibility of operating multiterminal DC grids Recently, MMCC topologies has been proposed for HVDC wind farm Among the advantages of MMCCs over other VSC topologies for HVDC applications stand out its modularity and scalability, MMCs can reach higher power ratings using standard semiconductors technology; its high efficiently and low distorted output voltages, as a consequence small filters are required to meet the grid codes. In this context, this paper present an Vector Control Strategy for Wind Energy Generation and Transmission systems based on MMCCs. As shown in Fig. 1, this proposal considers the application of the Modular Multilevel Matrix Converter (M3C) to locally interface a single wind turbine to a medium-voltage ac (MVAC) point of connection. Additionally, the Modular Multilevel Converter (M2C) is proposed to link the wind farm to the grid onshore through an HVDC transmission line. Both converters are controlled using an vector control system. This full based MMCCs configuration results in an high power density. For example, the MMCCs can be operated to synthesise frequencies to reduce the size of transformers and floating capacitors. Experimental results obtained with an 27 power cells M3C connected to a 30 power cell Back-to-Back M2C are presented to validate the effectiveness of the proposed control strategy

2. Literature review

1. Series-connected offshore wind farms with full-bridge modular multilevel converter (G. Guo et al., 2019)

This paper proposes a novel configuration for offshore wind farms using series-connected wind turbines with full-bridge modular multilevel converters (FB-MMCs) as both grid-side and generator-side converters. The series-connected offshore wind farm (SC-OWF) topology offers advantages over traditional parallel-connected systems by reducing the number of submarine cables required and potentially lowering overall system costs. The FB-MMC technology provides enhanced fault-ride-through capabilities and better power quality compared to conventional half-bridge MMCs.

The research addresses key technical challenges in SC-OWF implementation, including voltage balancing among series-connected wind turbines, power flow control, and system stability. The FB-MMC's ability to block DC fault currents and provide black-start capabilities makes it particularly suitable for offshore applications where reliability is crucial. The paper presents control strategies for coordinating multiple FB-MMCs to ensure stable operation under various wind conditions and grid disturbances.

Simulation results demonstrate the effectiveness of the proposed system in maintaining voltage balance, controlling power flow, and providing fault tolerance. The study shows that FB-MMCs can successfully handle asymmetrical conditions and provide improved harmonic performance compared to traditional converter technologies. The research contributes to the advancement of offshore wind farm integration technologies, offering a promising solution for large-scale renewable energy projects. The series-connected topology with FB-MMCs represents a significant step toward more efficient and cost-effective offshore wind energy systems, potentially revolutionizing how future offshore wind farms are designed and operated.

2. Loss evaluation of HVAC and HVDC transmission solutions for large offshore wind farms (N.B. Negra et al., 2006)

This seminal paper presents a comprehensive comparative analysis of High Voltage Alternating Current (HVAC) and High Voltage Direct Current (HVDC) transmission systems for connecting large offshore wind farms to onshore grids. The study evaluates transmission losses, which are critical factors in determining the economic viability of offshore wind projects, particularly for farms located far from shore.

The research methodology involves detailed modeling of various transmission configurations for 500 MW and 1000 MW offshore wind farms at different distances from shore. The analysis considers both Line Commutated Converter (LCC) and Voltage Source Converter (VSC) HVDC technologies, comparing them against conventional HVAC transmission systems. Key parameters examined include cable losses, converter losses, and reactive power compensation requirements.

The findings reveal that HVDC systems become increasingly advantageous as transmission distance increases, with the break-even point occurring at approximately 50-70 km for VSC-HVDC and 60-80 km for LCC-HVDC systems. For shorter distances, HVAC transmission remains more cost-effective due to lower infrastructure requirements. The study demonstrates that converter losses in HVDC systems are partially offset by reduced cable losses, especially in submarine applications where reactive power compensation becomes significant.

This research established fundamental guidelines for transmission technology selection in offshore wind projects and has influenced industry standards for decades. The loss evaluation methodology presented has become a benchmark for subsequent studies, providing essential insights for project developers, grid operators, and policymakers in the renewable energy sector.

3. Short-term frequency regulation and inertia emulation using an MMC-based MTDC system (E. Leon, 2017)

This paper addresses the critical challenge of maintaining grid stability as conventional power plants are displaced by converter-interfaced renewable energy sources, which inherently provide less system inertia. The research proposes an innovative control strategy for multi-terminal DC (MTDC) systems based on modular multilevel converters (MMCs) to enhance short-term frequency regulation and provide virtual inertia support.

The proposed control methodology enables MTDC systems to independently support both primary frequency regulation and system inertia emulation by utilizing the capacitive energy stored in MMC converter stations. This approach is particularly valuable when MTDC systems cannot access power reserves from connected AC systems or offshore wind farms. The control strategy coordinates reactive power management across converter stations to improve damping of low-frequency electromechanical oscillations, enhancing overall system stability.

The paper presents comprehensive analyses including transient stability studies and small-signal stability assessments to validate the proposed control scheme. Simulation results demonstrate the system's ability to provide rapid frequency response comparable to conventional synchronous generators. The research shows that coordinated control of onshore wind farms and MTDC systems can significantly improve frequency regulation performance.

The findings indicate that this enhanced frequency control can increase system reliability, reduce spinning reserve requirements, and lower operational costs while enabling higher penetration of renewable energy sources. The work represents a significant contribution to grid integration technologies, offering practical solutions for maintaining power system stability in renewable-dominated grids. This research has important implications for future grid codes and the design of HVDC networks supporting large-scale renewable energy integration.

4. Control of offshore wind turbines connected to diode-rectifier-based HVDC systems (Bidadfar et al., 2020)

This research addresses the control challenges associated with diode-rectifier-based HVDC (DR-HVDC) systems, which represent a promising low-cost solution for connecting remote offshore wind farms to onshore power systems. Unlike conventional HVDC systems, DR-HVDC systems lack active control of DC voltage, requiring fundamental changes in wind turbine control philosophy from grid-following to grid-forming operation.

The paper proposes a novel grid-forming control strategy for offshore wind turbine converters connected to DR-HVDC systems. The control architecture employs two sequential control loops: the first regulates active power mismatches by converting them to voltage angle deviations that induce frequency changes, while the second adjusts the alternating voltage magnitude to counteract these frequency variations. An internal current control loop provides fault current limitation and eliminates high-frequency resonances.

The proposed control system enables wind turbines to maintain stable offshore AC network voltage and frequency without relying on external grid-forming devices. This capability is essential for DR-HVDC systems since diode rectifiers cannot provide the voltage and frequency support typically available from conventional HVDC converters.

Extensive electromagnetic transient simulations validate the control strategy under various operating conditions, including fault-ride-through scenarios, wind turbine power changes, reactive power disturbances, and wind turbine outages. Results demonstrate robust performance and stable operation across all tested conditions. This research contributes significantly to the commercial viability of DR-HVDC technology, offering a path toward more cost-effective offshore wind farm connections while maintaining grid stability and reliability requirements essential for industrial deployment.

5. Distributed voltage and frequency control of offshore wind farms connected with a diode-based HVDC link (R. Blasco-Gimenez et al., 2010)

This pioneering paper introduces a distributed control strategy for maintaining voltage and frequency stability in offshore wind farms connected to onshore grids through diode-based HVDC transmission systems. The research addresses fundamental control challenges arising from the unidirectional power flow characteristics of diode rectifiers, which cannot provide the bidirectional power control capabilities of conventional HVDC systems.

The proposed distributed control approach assigns specific roles to individual wind turbines within the offshore network to collectively maintain system stability. The control strategy divides wind turbines into different operational modes: some provide voltage regulation, others handle frequency control, and additional units manage reactive power compensation. This distributed architecture ensures redundancy and improved system reliability compared to centralized control approaches.

The paper presents detailed mathematical modeling of the offshore AC network and diode rectifier system, establishing the theoretical foundation for the control strategy. The control algorithm coordinates wind turbine converters to regulate offshore grid voltage and frequency while maximizing power extraction from available wind resources. Special attention is given to handling variations in wind conditions and maintaining stability during transient events. Simulation results demonstrate the effectiveness of the proposed control system in maintaining stable operation under various scenarios, including wind speed fluctuations, load changes, and fault conditions. The research shows that properly coordinated wind turbine converters can successfully replace conventional grid-forming devices in offshore applications. This work laid important groundwork for subsequent developments in DR-HVDC technology and has influenced modern approaches to offshore wind farm control. The distributed control philosophy presented continues to be relevant for current and future offshore wind integration projects.

6. Novel energisation method for offshore wind farms connected to HVDC via diode rectifiers (O. Saborío-Romano et al., 2019)

This paper presents an innovative solution to one of the most challenging aspects of diode-rectifier-based HVDC (DR-HVDC) systems: the energisation of offshore wind farms. Unlike conventional HVDC systems, diode rectifiers cannot control DC voltage or provide grid-forming capabilities during startup, making the initial energisation process particularly complex and requiring novel approaches.

The proposed energisation method utilizes the full-scale power converters of individual wind turbines as temporary grid-forming voltage sources, coordinated to energise the offshore network in a carefully orchestrated sequence. The process involves selecting one wind turbine converter to operate in grid-forming mode, initially energising the wind turbine busbar, then progressively energising offshore AC cables and auxiliary loads. Other wind turbines remain disconnected during each energisation stage to prevent parallel operation complications.

The sequential approach ensures controlled voltage and current levels throughout the energisation process, avoiding potentially damaging inrush currents and overvoltages that could occur with conventional energisation methods. The method eliminates the need for additional offshore auxiliary power supplies or external voltage sources, reducing system complexity and costs.

Comprehensive electromagnetic transient simulations validate the proposed method using a benchmark offshore wind farm test system. Results demonstrate robust performance across various parameter uncertainties and transient events, with voltage and current remaining within safe operational limits throughout all energisation stages. The research proves that the method can reliably achieve complete system energisation using only the wind turbines' built-in converters. This breakthrough enables the practical implementation of DR-HVDC systems, offering a cost-effective solution for offshore wind farm connections while maintaining operational safety and reliability standards.

7. Hybrid topology of a diode-rectifier-based HVDC system for offshore wind farms (Y. Chang and X. Cai, 2018)

This paper introduces a hybrid HVDC topology that combines the cost advantages of diode rectifiers with the control flexibility of voltage source converters (VSCs) for offshore wind farm applications. The hybrid approach aims to optimize the trade-off between system cost, controllability, and operational flexibility in offshore wind power transmission systems.

The proposed hybrid topology integrates diode rectifiers for the main power transmission path with strategically placed VSC modules that provide essential control functions. This configuration maintains the low-cost benefits of diode rectifiers while addressing their inherent limitations in power flow control and grid support capabilities. The hybrid system can provide reactive power support, voltage regulation, and enhanced fault-ride-through capabilities that pure diode-rectifier systems cannot achieve.

The paper presents detailed analysis of the hybrid system's operational characteristics, including power flow control, fault response, and interaction with offshore wind farm controls. The topology allows for optimized power extraction from wind turbines while providing the grid services required by modern transmission system operators. Mathematical modeling and control design methodologies are developed specifically for this hybrid configuration.

Extensive simulation studies validate the hybrid topology's performance under various operating conditions, including normal operation, fault scenarios, and wind variability. Results demonstrate superior performance compared to conventional diode-rectifier systems in terms of controllability and grid integration capabilities, while maintaining cost advantages over full VSC-HVDC systems. The research contributes to the evolution of HVDC technology for offshore applications, offering a practical compromise between cost and functionality. This hybrid approach represents an important step in the commercialization of cost-effective offshore wind transmission systems, potentially accelerating the deployment of large-scale offshore wind projects**.**

3. Methodology

The integration of multi-megawatt offshore wind turbines with power grids is a critical issue in the renewable energy sector. One of the primary challenges is to achieve high voltage direct current (HVDC) transmission with minimum power losses. The modular multilevel converter (MMC) is a promising technology for interfacing offshore wind turbines with HVDC grids due to its high efficiency, modularity, and scalability. In this literature review, we will explore the recent developments in interfacing multi-megawatt offshore wind turbines with MMCs.

The MMC is a type of power converter that can generate high-quality AC voltages and currents with low harmonic distortion. The MMC consists of multiple series-connected sub-modules that are individually controlled to generate the desired voltage waveform. The voltage waveform generated by the MMC can be easily adjusted by varying the modulation index of each sub-module.

Recent studies have shown that MMCs can be used to interface multi-megawatt offshore wind turbines with HVDC grids. The MMC can act as a voltage source converter (VSC) or a current source converter (CSC) depending on the control strategy used. The VSC-based MMC is commonly used for interfacing offshore wind turbines with HVDC grids because it can provide voltage control and support reactive power compensation. The CSC-based MMC is typically used for interfacing offshore wind turbines with AC grids because it can provide high-quality AC voltages with low harmonic distortion.

Several control strategies have been proposed for interfacing offshore wind turbines with MMCs. The most common control strategy is the current control strategy, where the MMC is controlled to maintain a constant current output. Other control strategies include the voltage control strategy, the power control strategy, and the impedance control strategy.

Studies have also investigated the impact of MMCs on the dynamic performance of offshore wind turbines. The MMC can provide a fast response to changes in wind speed and can improve the stability of the wind turbine system. However, the use of MMCs can also lead to increased harmonic distortion and electromagnetic interference, which can affect the reliability and performance of the wind turbine system.

4. Conclusion

In conclusion, the integration of multi-megawatt offshore wind turbines with MMCs is a promising technology for achieving high-efficiency HVDC transmission. The control strategy used for interfacing offshore wind turbines with MMCs plays a critical role in the dynamic performance and stability of the wind turbine system. Further research is needed to optimize the design and control of MMC-based offshore wind turbine systems.

The simulation of the wind energy electrical system is carried out using MatLab Simulink.The simulation model contains permanent magnet synchronous generator (PMSG) andtwo MMC’s, one at generator side and one at the grid side control of the generator and the converter. compare the obtained results during simulations with the already existing topologies

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