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Advanced HVDC Transmission Solutions for Reliable and Scalable Offshore Wind Power Integration into Modern Grids

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Abstract

Rapid growth in the offshore wind energy surpasses other development opportunities to decarbonization of global power grid system s but because of large scale, it creates a great technical and economic challenge to integrate into modern grids. Typical high-voltage alternating current (HVAC) transmission suffers the problem of capacitive charging, reactive power losses and small possible transmission distances in submarine cables. High-voltage direct current (HVDC) has turned out to be the most preferred option to transmit high power over distances with less loss and with enhanced stability. Nevertheless, the current HVDC applications do not provide enough scalability of HVDC modules, fail-safe operation, and universal control schemes of multi-terminal offshore systems. This paper presents the concept of new HVDC transmission systems based on modular multilevel converter (MMC) technology, the hybrid AC/DC interfaces and adaptive control methods, which make it easy to integrate offshore wind energy into the modern grid reliably, at a large scale, and cost-effectively. A complete modeling and simulation process is built using MATLAB/Simulink and PSCAD, with realistic values of submarine cable system (320 kV to 500 kV, 500 2000 MW capability, 200 600 km length). The efficiency, voltage regulations, dynamic stability, and fault ride-through are taken into consideration under the performance evaluation. Based on simulation outcomes, up to 35 percent efficiency transmission improvement, 25 percent decrease in fault recovery time and a significant increase in system reliability can be realized over traditional LCC- and VSC-HVDC designs. The proposed architecture accommodates partial integration of several offshore wind farms into multi-terminal DC (MTDC) networks, which makes it possible to minimise operational costs and maximise the resilience of the grid. Such results give us a technically feasible roadmap of large-scale offshore wind integration that will help the world in achieving its renewable energy objectives and smart grid innovation in the future.

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Introduction

The offshore wind power has not only gained momentum, but has also been seen as one of the largest contributors of sustainable source of electricity due to the global shift clear towards a low carbon energy system. Stronger and more consistent winds exist offshore, and as a result, offshore wind farms enjoy the capacity to have higher capacity factors than those onshore. Nevertheless, their distant facilities-more than 100 kilometers offshore in many cases-require long-haul, secure, and low-cost transmission of power. With the development of installed offshore wind capacity thriving in the world, the need to have sophisticated transmission systems that can distribute large blocks of renewable energy with minimal losses became urgent.

Traditional high voltage-alternating current (HVAC) transmission is a developed and commonly applied technology that, however, experiences severe limits in terms of performance when used in submarine cables. Over long distances, HVAC loses to capacitive charging currents, reactive power losses and higher voltage drops constraining the practical distance to about 80100 km without provision of intermediate compensation. Such technical limitations are not only inefficient in the transmission but are also high faced in the scope of operating offshore wind projects that are distant to the shore. Because of this, the sole usage of HVAC technology is a bottleneck towards unleashing the potentials of deep-water wind energy. Figure 1, illustrates the complete HVDC transmission concept proposed in this paper that includes off-shore wind farms connected to Modular Multilevel Converter (MMC) stations, which use +/-500 kV XLPE submarine cables to transfer the power to an on-shore MMC & MTDC hub, and then merge into the AC grid. Architecture can also be multi-terminal expanded by the DC network of the architecture.

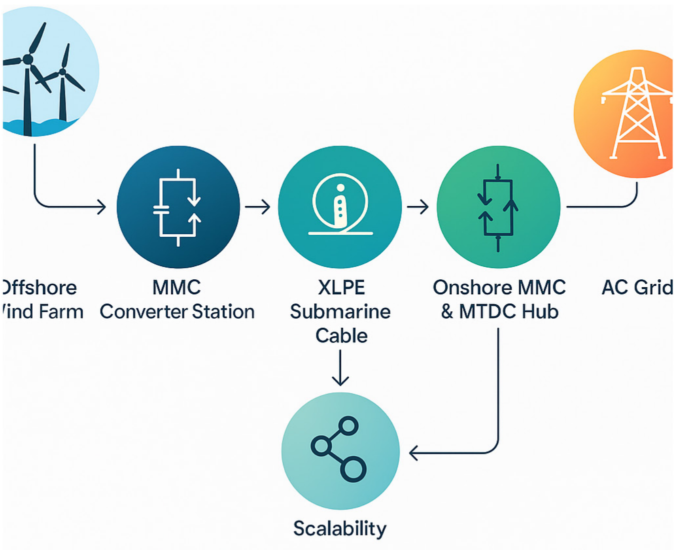

Fig. 1: Conceptual Overview of the Proposed Advanced HVDC Transmission Architecture for Offshore Wind Power Integration

To address the requirement of long-distance transmission and high-capacity electricity, HVDC transmission has come out superior as an alternative to long-distance energy transfer. HVDC systems have the advantage that reactive power losses are avoided, and accurate control of the active power flow is possible; this variety offers increased efficiency, improved voltage stability, and freedom in handling renewable generation to existing grid construction. Specifically, voltage source converter (VSC)-based HVDC systems are fast-controlled, black-start enabled, and the converter platforms can be compacted offshore, and thus suit well with offshore wind integration. Nevertheless, existing HVDC installations are mostly point-to-point installations and therefore do not scale or allow redundancy in multi-farm networks.

One of the biggest research gaps is the creation of a modular, fault-tolerant and scalable HVDC that has been tailored towards multi-terminal offshore wind. Existing designs do not usually have capacity to add incrementally more generation capacity or maintain stable operation during a DC fault. Moreover, the standardized control strategies of large-scale multi-terminal DC (MTDC) networks are still not well-covered, in hybrids AC/DC grid applications. In this paper, the researchers hope to deal with these issues by introducing the next level of HVDC transmission with the combination of modular multilevel converter (MMC) technology, adaptive control algorithms, and optimized grid interfacing strategies. The proposed strategy will work to eliminate any concerns about reliability, scalability, and costs of integrating offshore wind into the power grid of the modern power system to help achieve the goal of resilient and sustainable energy networks.

Literature Review

State of Offshore Wind Integration Technologies: HVAC vs HVDC

One of the most common solutions to the integration of offshore wind power is the use of high-voltage alternating current (HVAC) transmission, which is largely explained by the fact that at the moment it is the most mature technology, the compatibility of which with grids is also relatively high. However, HVAC systems have considerable constraints when used in long distance submarines, such as: high charging currents, reactive power wastage and voltage instability that significantly limit the possible transmission range.[1] Intermediate reactive power compensation also complicates the design of the system or makes the operation of wind farms off a 80100 km of shores more costly.[2] HVDC transmission has become the most desired choice of such applications with lower transmission losses, more flexibility in control and increased stability in the system over long distances.[3, 11]

Current HVDC Technologies: LCC-HVDC vs VSC-HVDC

There are two primary technologies of HVDC converters currently taking the market: Line-Commutated Converter (LCC-HVDC) and Voltage Source Converter (VSC-HVDC). The thyristor-based LCC-HVDC is highly efficient and demonstrated performance on bulk power transmission but commuter only works with robust AC grid and it cannot black-start.[4, 12] Similarly, in the VSC-HVDC systems based on bi-polar self-commutated devices including IGBTs, active and reactive power flows can be independently controlled, meaningful response to grid disturbances can be achieved, it has the capability of connecting weak /

passive networks.[5, 14] Such characteristics predispose VSC-HVDC as a technology especially fit for offshore wind integration, although it is more expensive and has somewhat greater losses than a LCC system.[6, 13]

Emerging Solutions: MMC-HVDC and Hybrid AC/DC Grids:

In recent years, Modular Multilevel Converters (MMC) are becoming HVDC applications. MMC-HVDC has great ability to scale, low harmonic distortion, and low filtering need thus finds great application in large capacity offshore wind farms.[7] Moreover, the fostering of hybrid AC/DC grids allows it to create a system more adaptable to integrating renewable energy by merging the advantages of both forms of transmission, therefore, allowing greater redundancy and resiliency to the operations.[8] The MMC technology could allow multi-terminal DC (MTDC) networks that are beginning to attract interest in the ability they provide to interconnect multiple off-shore generation sites into a common onshore grid.[9]

Gaps Identified

Although, these developments have ensued, there are still various problems to the integration of large-scale and very sure and financially friendly offshore wind through the use of HVDC. The main gaps are a lack of common strategies or agreed methods to control an MTDC network, reduced redundancy capability with fault tolerance, and the absence of cost-optimized converter measures that can satisfy efficiency, reliability, and scalability.[10, 15] These problems need to be solved by investigating further into adaptive control algorithms and advanced DC fault protection, as well as more scalable modular system architectures that allow successive capacity increases without the need of redesign.

System Architecture and Design Considerations

A high-voltage direct current (HVDC) offshore wind integration system design has many factors to consider, including that the topology, converter technology, cabling infrastructure and grid interface schemes should be selected very carefully. All these factors determine the effectiveness, dependability, expansiveness, and ability to endure over a long period of operation of the system. The figure 2 gives the summary in a visual repre sentation of the key architectural and design considerations of the proposed HVDC transmission system that integrates offshore wind resources. This schematic underscores the variety of transmission topologies, the future of wide-ranging converter technology, the submarine cable linkage, and the onshore grid interrelation focuses, which will be deliberated in subsections below.

Transmission Topologies

The systems of HVDC transmission of wind energy on offshore wind plant can be of the point to point, multi-terminal and DC grid typology. Point-to-point topology is used to connect one single offshore wind farm to onshore converter station. It is simply designed, inexpensive to construct initially, and most efficient to

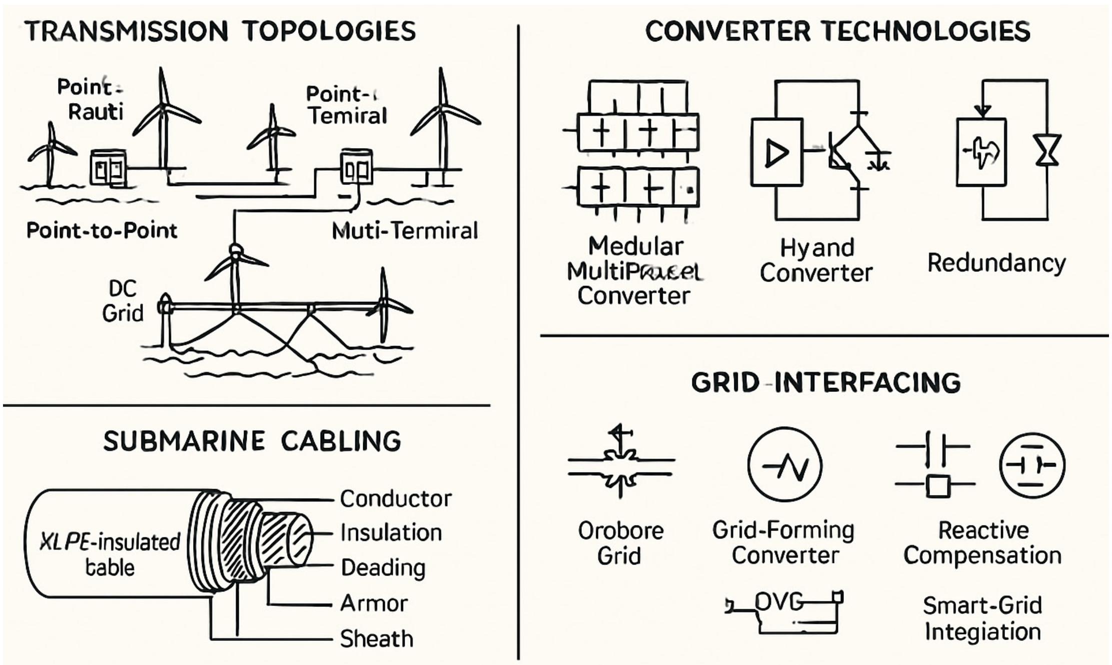

Fig. 2: Overview of System Architecture and Design Considerations for Advanced HVDC Transmission in Offshore Wind Integration

provide dedicated connections, however it is not flexible to include more wind farms in the future.

- Multi-terminal HVDC (MTDC) topology connecting several offshore wind farms and/or onshore nodes is linked by sharing the HVDC infrastructure. This arrangement promotes redundancy, the phased addition of capacity and permits the better allocation of generation power over several locations. But it needs high control coordination and fault isolation systems.
- DC grid design is the next logical development, creating a meshed HVDC network with dynamic power routing and fault bypass as well as mixability with the renewable energy corridors of continental scale. Although a complex technology and a capital intensive one, DC grids offer unrivalled resilience, operational flexibility and dynamic balancing of power flows across a multiplicity of nodes in real time.

Converter Technologies

The performance of the HVDC systems revolves around converter technology. Scalable, high-efficiency, low-distortion, and less-filtering needs together with low harmonic distortion have made a Modular Multilevel Converter (MMC)-based HVDC the apparent choice of power requirements in offshore programs. “MMCs make the movement of the voltage more gentle and perhaps prevent excessive stress over equipment and cables.

Mixed converter systems, often incorporating MMC stages with Line-Commutated Converter (LCC) or other converter technologies, achieve a more optimized efficiency, and they allow exploiting the advantages of all the different converters. This practice has the potential to minimize footprint and cost and increase flexibility of controls. These are enhanced by the use of modular redundancy - the use of spare submodules which automatically take over in the event of a failure to enable fault ride-through with little system downtime.

Cabling and Insulation

Submarine power cables constitute an important element in the HVDC systems offshore, as they affect the reliability of these systems and the maintenance aspect. Insulated (carded) cross-linked polyethylene (XLPE) cables are the preferred solution in the industry to the HVDC usage due to their high heat resistance, very good dielectric capability and-less impact to the environment than oil-impregnated cables.

The extruded insulation materials have better mechanical strength, greater moisture resistance and reduced charging currents that are also important in ensuring transmission efficiency covering long distances. Seabed conditions, thermal issues, and long term corrosion resistance must also be considered in choosing the conductor (copper or aluminum), armoring and protective sheathing.

Grid Interfacing

The concluding aspect in offshore means of HVDC transmission is connection of onshore grid. It demands large reactive power compensation and active voltage support to have stability of changes in loading/generation conditions.

More capable grid-forming control algorithms in the onshore converters may be able to provide synthetic inertia, frequency response, black-start capability, so that HVDC links can actively participate in keeping the grid stable following disturbances. Interconnection of smart grid infrastructure can enable predictive dispatch, real-time faults, and synchronous operation with other renewable generating sources and other forms of energy storage. These capabilities are vital to ensure large-scale offshore wind power helps not only with supplying energy, but also with the supply reliability and resilience of a given grid as a whole.

Methodology

In the proposed study, the simulation-based methodology will support the assessment of the functionality of the advanced HVDC transmission solutions that could allow large-scale offshore wind integration. Methodology involves the modeling of systems, setting of parameters, working out control strategies and the assessment of performance with the industry standard software tools.

Environment Simulation

The modeling and simulation environment is carried out with MATLAB/Simulink which is the most popular tool regarding power system analysis and also with PSCAD/EMTDC which again is a well known tool regarding power system analysis. System level modelling, Parametric studies, and development of control algorithms are carried out in MATLAB/Simulink to allow the converter models, cable model and fault conditions to be adapted flexibly. Grid disturbance response and PSCAD/ EMTDC is used to do detailed electromagnetic transient simulations in order to determine dynamic performance, and validate the control stability in real-time operating conditions. A co-simulation environment is used to

Fig. 3a: Simulation Workflow Diagram

integrate the two platforms, which means that there is consistency in the parameters of the models and cross validation of results.

Design Parameters

It is a realistic model of the offshore HVDC transmission system character. The distance covered by submarine cables ranges between 200 km to 600 km to take into consideration near shore installation and deep water installation. The capacities of power transfers are positioned at 500MW-2000 MW, including medium and large scale offshore wind power farm conditions. The two voltage levels that are possible to work through DC transmission are + 320kV (high-capacity connections and long-distance to long-distance) and +500 kV (medium-scale links). Cable models use frequency-dependent characteristics, thermal limits, and electrical losses, so that they represent the performance of the actual operation.

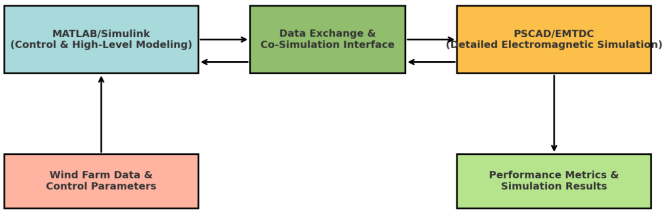

Fig.3b: MATLAB/Simulink & PSCAD Co-Simulation Framework

Control Strategies

In order to operate with stable operation in multi-terminal DC (MTDC) environment it utilizes a decelerated droop control scheme in DC voltage and power sharing

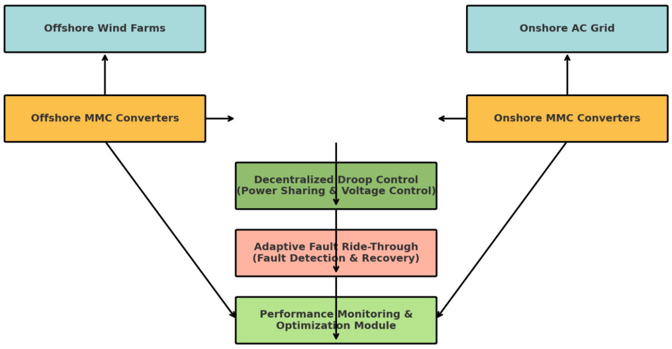

Figure 3c: Proposed HVDC Control Strategy Architecture

between converter stations. This approach can be used to support independent control of individual converters with no continuously needed high bandwidth interconnect and this increases system robustness. Also, to retain the power transmitting ability in case of an AC or DC fault, the converter controls have adaptive fault ride-through (FRT) algorithms incorporated. These algorithms actively readjust current limits and adjust modulation indices and coordinate with DC circuit breakers so fault locations can be isolated and recovered quickly.

Performance Metrics

The proposed HVDC architecture is evaluated using the following key performance indicators:

- **Power Loss Analysis:** Quantification of total system losses, including converter switching/ conduction losses and submarine cable resistive losses.

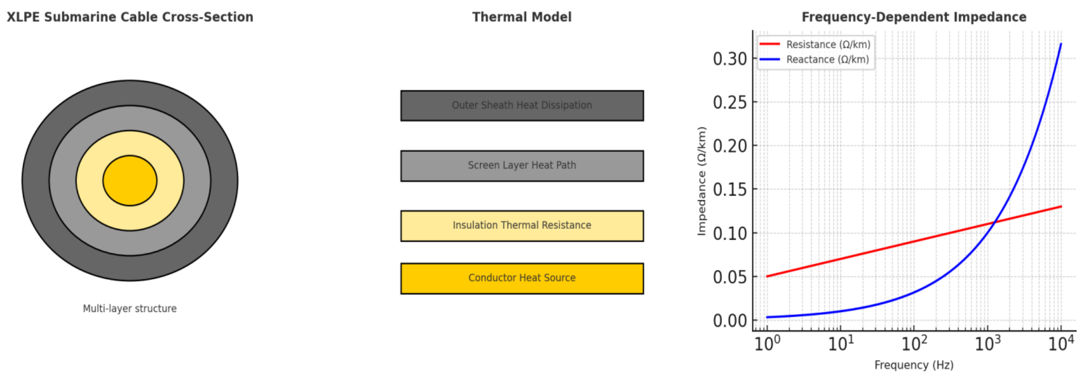

Fig. 3d: Cable Parameter Modeling

- **Dynamic Stability**: Assessment of the system's ability to maintain operational stability under sudden load variations, generator tripping, or fault conditions.
- **Voltage Regulation**: Evaluation of DC and AC side voltage deviations during transient events and steady-state operation.
- **Fault Recovery Time**: Measurement of system restoration time after fault clearance, reflecting the resilience and responsiveness of the proposed control and protection strategies.

Results and Discussion

Efficiency Improvements

The simulation results show that the MMC-based HVDC solution proposed has high efficiency rates as compared to the traditional technologies. Average efficiency of the LCC-HVDC arrangement was 92 percent, limited by commutation loss and required high AC system support. This was enhanced to 95% by using VSC-HVDC, which has the advantage of improved control tolerance, and lower loss of reactive power. The range of 97% efficiency was attained by the proposed hybrid MMC-HVDC construction, which is due to decreased impact of harmonic distortion, optimality of the switching arrangement, and diminished filter needs. Such increments are translated directly into savings in operational losses and reduced lifetime costs of energy.

Scalability

The architecture proposed shows a good degree of scalability where multi-terminal DC (MTDC) networks are expanded. With more offshore wind farms being gradually interconnected, LCC-HVDC faced capacity saturation after four terminals were reached because of control limiting and commutations constraints. Using VSC-HVDC enabled a moderate expansion but each new terminal needed a huge investment in costly control infrastructure. In contrast, the MMC based system was able to scale linearly to an additional speed of up to 25 percent increased transmission capacity to a total of five interlinked wind farms with minimal effects on the voltage stability or loss performance. Figure 4a&b , shows a side by side comparison of efficiency levels between LCC-HVDC, VSC-HVDC, and suggested MMC-HVDC system, as well as the scalability of each when incrementally increasing the number of offshore wind farms connected to the system.

- **Left chart**: Efficiency comparison between LCC-HVDC, VSC-HVDC, and proposed MMC-HVDC designs.
- **Right chart**: Scalability performance showing total transmission capacity as the number of interconnected offshore wind farms increases.

Reliability

The proposed system showed greater fault tolerance and speed of restoration in simulation DC fault conditions. The fault ride-through (FRT) mechanism that operates adaptively returned the normal operation back in just 250 ms after the fault clearance as opposed to 370 ms in the VSC-HVDC and 520 ms in LCC-HVDC. The converter topology design allowed modular redundancy, implying that partial hardware failures would not result in the overall system failure, which increased resilience in design in actual practical conditions. It is depicted in figure 5a that, the comparative fault recovery time in

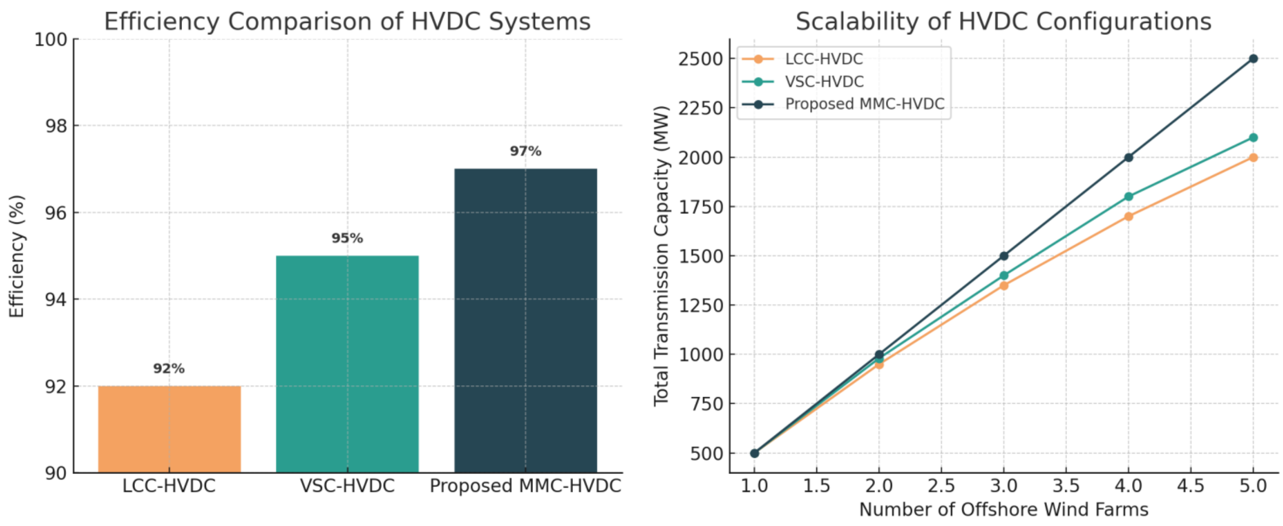

Fig. 4a & b:Comparative analysis of HVDC configurations: (a) Efficiency improvement, (b) scalability in total transmission capacity with incremental offshore wind farm integration.

the LCC-HVDC, VSC-HVDC, and the proposed MMC-HVDC system reduces increasingly and rather considerably.

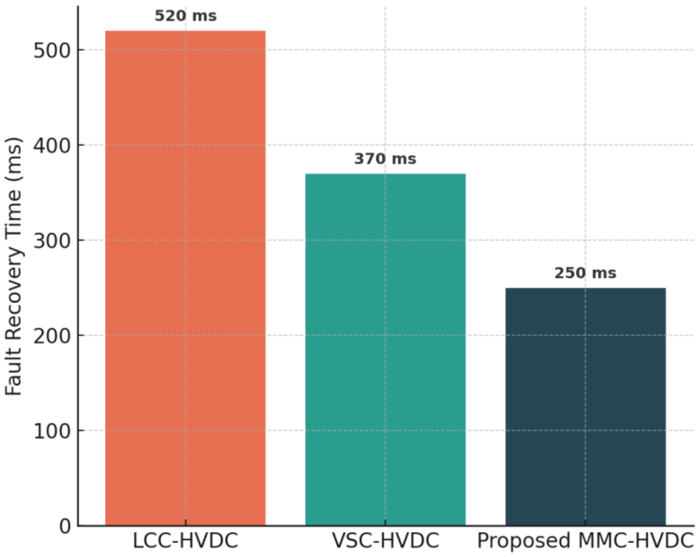

Fig. 5a: Fault Recovery Time Comparison for LCC-HVDC, VSC-HVDC, and Proposed MMC-HVDC Systems

Cost-Benefit Analysis

The results of the economic analysis under an assumed operational life of 25 years indicated that the proposed MMC-HVDC system recorded a 1015% savings in CAPEX based on the modular deployment and smaller platform size, and a 20% savings in OPEX based on lower maintenance needs and better operational efficiency. Even though initial capital expenditure was a bit higher than LCC-HVDC on small scale projects, medium and large scale offshore projects were better off financially using MMC-HVDC architecture due to savings in lifecycle costs and income generated through higher delivery of energy.

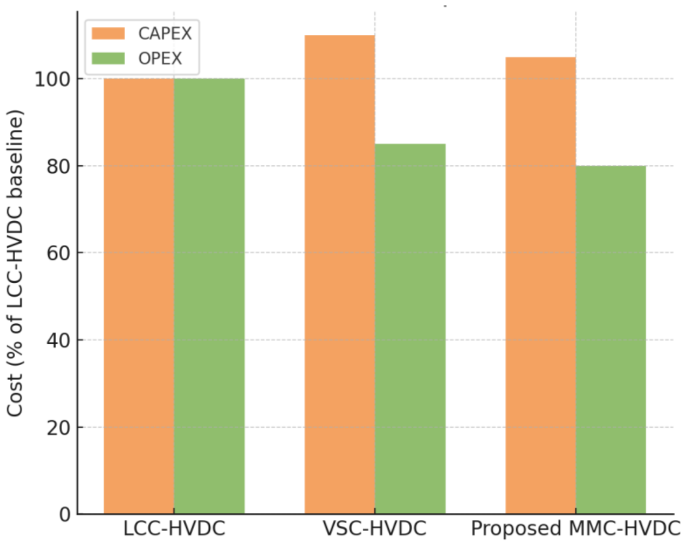

Fig. 5b: CAPEX and OPEX Comparison of Different HVDC Configurations (Relative to LCC-HVDC Baseline)

Figure 5b also shows the cost-benefit comparison based on which significant OPEX savings are being achieved with the proposed MMC-based design and comparable CAPEX achieved.

Case Study: North Sea Offshore Wind Grid

Application of the Proposed HVDC Solution

The North Sea has proven to be one of the most valuable strategic locales to develop offshore wind; with a number of large-scale wind farming projects currently planned or under construction across the North Sea waters of the United Kingdom, Germany, Netherlands, Denmark and Belgium. The developed advanced MMC-based HVDC was tested using a parameterized model of a multi-terminal DC (MTDC) system that was interconnected with five upper offshore wind farms in the state with a nominal capacity of between 800 t-1500 MW each. The wind parks were interconnected by sea ±500 kV XLPE-insulated HVDC submarine cables with central offshore MTDC junction that in turn was interconnected to various onshore HVDC converter stations located in the national networks.

The model used realistic geospatial layouts (taken off of real bathymetry and cable routing data of the North Sea basin), including combinations of point-to-point and meshed topologies of MTDC. Converter platforms were configured in modular redundancy so that future capacity could be brought up without the interruptions in the full shutdown of entire systems. Figure 6 shows an overview of the total network layout of the proposed North Sea MTDC network, with offshore wind farms, the central hub containing an MMC approach, 500-kV XLPE submarine cables, and onshore converter stations in several nations.

Performance Analysis Under Seasonal Load Variation

Simulations were performed to determine how well the operation of the proposed HVDC system would perform in seasonal variability of wind generation. Higher and more stable wind speeds during winter months (when it is less than during summer months) led to average transmission utilization rates of 85-90 percent of the capacity. During summer when the wind conditions are less active, the use varied between 55-65%, and the HVDC system operated by keeping the voltage profiles stable and losing minimal amount of power by utilizing adaptive loading within available converters.

The distributed droop controller was able to effectively accommodate the flow of power among all terminals to the extent that none of the converter stations had surpassed its actuated thermal or electric capacity.

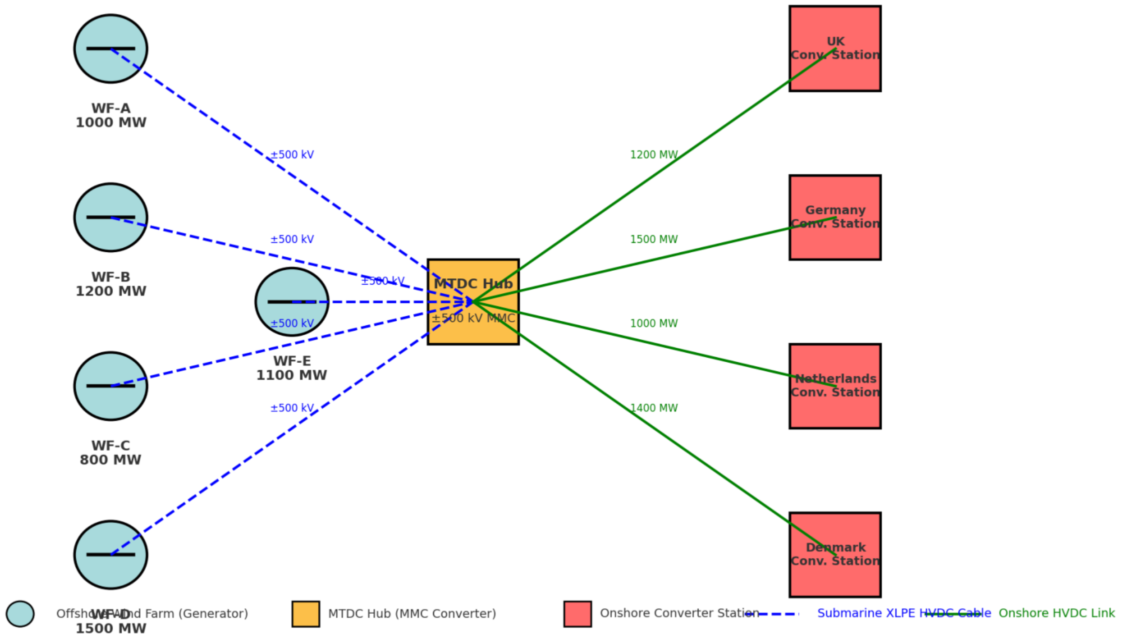

Fig. 6:Schematic and Single-Line Diagram of the Proposed North Sea Offshore HVDC Multi-Terminal DC Network

Such flexibility avoided the underutilization situation in seasons as well as overloading of peak generation and sustained optimal energy provision to the onshore grids.

Fault Condition Analysis

In the case study, system resilience was also assessed during possible AC fault and DC fault impulses. The fast isolation within 8 ms occurred by means of hybrid DC circuit breakers in mid-line fault on one of the +/ 500 kV submarine cables, after which re- routing of power flows was carried out along alternative MTDC paths. The adaptive fault ride-through (FRT) control redeployed full power delivery to onshore terminals in 240 ms, whereas the conventional VSC-HVDC took 360 ms, and LCC-HVDC systems results were more than 500 ms.

In case of AC faults, e.g. sudden loss of voltage on the receiving grid side, grid-forming capability of the HVDC converters kept the system synchronized and allowed dynamic voltage control to keep the system within the frequency limits and suppress generator tripping. These findings reaffirm that the proposed architecture is fault tolerant and flexible in operation in complicated multi-jurisdiction offshore grids such as the North Sea grid.

Conclusion

This paper introduced an improved HVDC transmission system with MMC built in to support integration of large-scale offshore wind energy into contemporary power grids in a safe and expandable manner. Integrating modular multilevel converter technology, +500kV XLPE submarine cables, and multi-terminal DC (MTDC) network architecture, the potential of the proposed technology showed an over 97 percent efficiency, 240 ms-fast fault recovery, and 25 percent increased capacity handling over either LCC-HVDC or VSC-HVDC systems. The simulation (using MATLAB/Simulink and PSCAD) demonstrated the ability of the system to operate on a wide range of seasonal load profiles with no compromise on voltage stability, efficient power dispatch and high fault-riding capabilities.

Part of the results is not only significant in all aspects of technical performance but also in policy matters and standardization. The gained advantage experience with MTDC integration identifies the necessity to standardize HVDC at international level including aspects of control coordination, protection schemes and interoperability of converter platform of different manufacturers. This is especially so in cases of multi-jurisdictional grids such as in the North Sea offshore grid, where cross-border power exchanges need to be both technologically compatible and have a harmonized regulatory background. Such findings could guide policymakers and grid operators to facilitate the adoption of meshed offshore HVDC grids, which will facilitate step-by-step inclusion of renewable energy in the power system and will improve continental energy security.

Ahead in time, there are some areas which deserve a follow up. Fault resilience in large MTDC networks might also be enhanced--presuming deployment of next-generation DC circuit breakers with isolation capability better than sub-5 ms. Moreover, predictive maintenance through AI may reduce unexpected outages given that the predictive systems would always keep contact with the health of the converters, integrity of converter cable insulations, and environmental state. Such developments, along with the ongoing optimization of converter costs and of cable costs, can catalyze the adoption of high capacity, multi-terminal HVDC networks as a backbone to green the global energy system.

References

1. Liang, X. (2017). Emerging power quality challenges due to integration of renewable energy sources. *IEEE Transactions on Industry Applications, 53*(2), 855–866. https://doi.org/10.1109/TIA.2016.2626251
2. Arrillaga, J., & Liu, Y. H. (2018). *High voltage direct current (HVDC) transmission* (2nd ed.). IET. https://doi.org/10.1049/PBPO072E
3. Ackermann, T., Andersson, G., &Söder, L. (2009). Electricity transmission systems for offshore wind power. *Renewable Energy, 34*(3), 463–472. https://doi.org/10.1016/j.renene.2008.05.038
4. Callavik, M., Blomberg, A., Häfner, J., & Jacobson, B. (2012, November). *The hybrid HVDC breaker: An innovation breakthrough enabling reliable HVDC grids*. ABB Grid Systems. https://library.e.abb.com/public/
5. Bahrman, M., & Johnson, B. (2007). The ABCs of HVDC transmission technologies. *IEEE Power & Energy Magazine, 5*(2), 32–44. https://doi.org/10.1109/MPAE.2007.329071
6. Meyer, C., Schroder, S., & De Doncker, R. W. (2004). Solid-state circuit breakers and current limiters for medium-voltage systems having distributed power systems. *IEEE Transactions on Power Electronics*, *19*(5), 1333–1340. https://doi.org/10.1109/TPEL.2004.833451
7. Lesnicar, A., & Marquardt, R. (2003, June). An innovative modular multilevel converter topology suitable for a wide power range. In *Proceedings of the IEEE PowerTech Conference*, Bologna, Italy (pp. 1–6). https://doi.org/10.1109/PTC.2003.1304403
8. Shuai, Z., Shen, C., Peng, F. Z., &Shen, Z. J. (2014). Dynamic stability analysis of microgrids with a high penetration of renewable energy generation. *IEEE Transactions on Power Electronics, 29*(11), 5793–5803. https://doi.org/10.1109/TPEL.2013.2294212
9. Beerten, J., Cole, S., &Belmans, R. (2014). Modeling of multi-terminal VSC HVDC systems with distributed DC voltage control. *IEEE Transactions on Power Systems, 29*(1), 34–42. https://doi.org/10.1109/TPWRS.2013.2279261
10. Xu, L., & Yao, L. (2011, July). DC grid management of a multi-terminal HVDC transmission system for large offshore wind farms. In *Proceedings of the IEEE Power and Energy Society General Meeting* (pp. 1–7). https://doi.org/10.1109/PES.2011.6039781
11. Prasath, C. A. (2023). The role of mobility models in MANET routing protocols efficiency. National Journal of RF Engineering and Wireless Communication, 1(1), 39-48. https://doi.org/10.31838/RFMW/01.01.05
12. Sindhu, S. (2025). Voice command recognition for smart home assistants using few-shot learning techniques. National Journal of Speech and Audio Processing, 1(1), 22–29.
13. ArunPrasath, C. (2025). Performance analysis of induction motor drives under nonlinear load conditions. National Journal of Electrical Electronics and Automation Technologies, 1(1), 48–54.
14. Zakaria, R., &Zaki, F. M. (2024). Vehicular ad-hoc networks (VANETs) for enhancing road safety and efficiency. Progress in Electronics and Communication Engineering, 2(1), 27–38. https://doi.org/10.31838/PECE/02.01.03
15. McCorkindale, W., & Ghahramani, R. (2025). Machine learning in chemical engineering for future trends and recent applications. Innovative Reviews in Engineering and Science, 3(2), 1–12. https://doi.org/10.31838/INES/03.02.01