RECENT ADVANCES IN TRANSMISSION TECHNOLOGIES FOR OFFSHORE WIND INTEGRATION

Abstract: The expansion of offshore wind farms has increased the demand for transmission technologies that can reliably deliver large-scale renewable power to the grid. This paper reviews recent advances in high-voltage direct current (HVDC) systems, dynamic line rating (DLR), advanced conductors, and energy storage systems (ESS). Multi-terminal HVDC networks provide controllable, long-distance transmission with reduced curtailment, while DLR improves utilization of existing infrastructure through real-time capacity adjustments. Advanced conductors such as ACCC increase ampacity, reduce line losses, and enhance wildfire resilience, and ESS technologies stabilize the grid by providing frequency regulation, black start capability, and cost reductions. Together, these innovations strengthen wind energy transmission and enable a more resilient and sustainable power system.

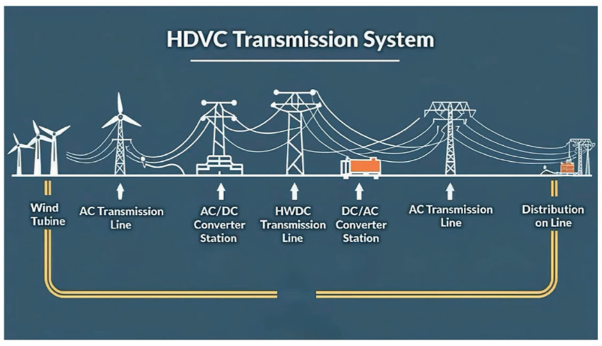

Figure 1: HVDC Transmission System. AC/DC Converter Station (Rectifier), DC/AC Converter Station (Inverter)

Introduction

As the world shifts towards renewable energy driven by climate change and sustainability targets by governments and regulatory bodies, it has increased the demand for efficient transmission of wind energy. Therefore, over the past three years, there have been significant advancements in wind transmission technologies, such as HVDC transmission systems, Dynamic Line Rating (DLR), advanced conductors like ACCC, and Energy Storage Systems (ESS). These technologies have substantially improved the efficiency and reliability of wind energy transmission, especially in Offshore Wind Farms (OWFs). This paper will review these recent innovations, emphasizing their technological benefits and current real-world applications.

1. Multi Terminal HVDC Systems

Why HVDC for OWFs:

In recent years, developers have built larger OWFs to increase renewable electricity generation, taking advantage of the stronger and more consistent wind conditions found at sea and the flexibility of open ocean space. However, OWFs are far away from shore, making traditional High Voltage Alternating Current (HVAC) transmission inefficient, as long AC cables face issues like cable skin effects, stability limits, reactive current loss, and require frequency synchronization with the grid [1].

High Voltage Direct Current (HVDC) transmission systems overcome these limitations. In a HVDC transmission system, an offshore converter called a rectifier converts the wind farm's AC input to DC current, which then passes through the HVDC transmission line and converts back to AC current using the inverter [2].

The comparisons between HVDC and HVAC transmission systems are shown in table 1, using metrics that are limitations in HVAC transmission systems:

HVDC transmission systems eliminate the skin effect and reactive current losses, while offering controllable power flow and asynchronous grid interconnection. These features make HVDC the most efficient and reliable choice for delivering future large scale offshore wind power over long distances.

Types of HVDC technology:

There are two types of HVDC technologies: Line commutated converter (LCC) and Voltage source converter (VSC) systems.

LCC HVDC transmission systems use thyristor valves (current-controlled switches) that can be arranged in six or twelve pulse bridge configurations to convert AC to DC and back.

Commutation is the transfer of current from one thyristor valve to the next and is driven by the AC system voltage. Key components in a LCC HVDC system include thyristor valve bridges, high harmonic transformers, smoothing reactors,

Table 1: Comparing HVDC and HVAC Systems [3],[4].

Metric	HVAC Transmission System	HVDC Transmission System	Reasoning
Skin effects	Significant – AC currents can flow on the "skin" of thick conductors, limiting capacity	Negligible – DC distributes evenly through the conductor	Eddy currents induced by changing magnetic fields in AC causes currents to crowd at surface for cables >1 in, whereas DC has no alternating fields to induce them.
Stability	Less controllable — power follows path of least impedance, which can create loops and oscillations	Controllable — operator sets exactly how much power flows and where	Unequal flows in the AC system can cause stability issues.
Reactive Current Loss	High — reactive charging currents in long AC cables can add losses and require reactive support	Very Low — no reactive charging, only active power carried (DC).	AC cables suffer capacitive charging currents that do not transmit usable power. DC currents have no phase shifts or capacitance charging over long lines
Frequency Synchronization	Must remain synchronous, AC links require same frequency on both ends	Can connect asynchronous systems — DC decouples frequency between two AC networks	HVDC converters vary frequencies, so asynchronous operation is possible.
Cost	Lower terminal cost, but high cable cost over long distances. Efficiency lost as distance grows	Higher terminal converter cost, much lower cable cost over distance	HVDC substation costs eleven more times compared to HVAC due to expensive equipment like thyristors and insulated gate bipolar transistors (IGBTs). However, the cost of HVDC cable is much lower than the cost of HVAC cable, and at a critical distance of about 500 miles, HVDC transmission projects are cheaper.

reactive power compensators, and high pass filters [4]. The high harmonic transformer is designed to withstand high AC and DC voltage stress and harmonic currents. A smoothing reactor, typically in the range of 0.1-0.5 H, is installed on the DC side to maintain steady current flow [4]. Additionally, because thyristors inherently consume reactive power, reactive power compensators are required. These power compensators are often rated at 60% converter capacity to balance the reactive power demand [4]. Finally, high pass filters are used to suppress switching and harmonic currents to ensure power quality [4].

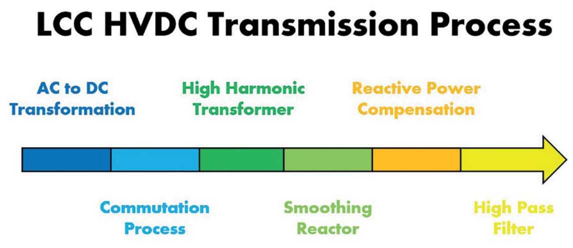

Figure 2: LCC HVDC Transmission System Process [4].

Because LCCs draw reactive power and depend on a strong AC grid for commutation, they require external reactive compensations like capacitor banks or synchronous condensers. They have high power and voltage ratings, however, have limited flexibility at low loading and cannot black start weak grids.

VSC transmission systems use self-commutating, voltage-controlled switches called insulated-gate bipolar transistors (IGBT) which enable conversion between AC and DC. The IGBT valve modules, operating with pulse width modulation (PWM), allow for a fully controlled AC voltage. In addition, a harmonic filter is included, which serves the same role as in a LCC system, but requiring a much smaller and more cost-effective design.

Despite LCC HVDC transmission systems being able to deliver large power transfers with high efficiency, there are some constraints of LCC systems compared to VSC systems. Metric comparing VSC HVDC and LCC HVDC systems are shown in table 2:

In the context of offshore wind farm integration, VSC HVDC transmission system has emerged as the preferred transmission technology because its self-commutation IGBTs and high frequency PWM not only enable cost effective long distance links but also fully satisfy grid requirements like black start capabilities, independent voltage/reactive power support and rapid fault ride through and synthetic inertia for remote wind farms. Moreover, VSC's converters and voltage source behavior support the creation and implementation of VSC systems in multi terminal networks.

Table 2: Comparing VSC and LCC HVDC transmission systems [4],[5].

Metric	VSC-HVDC	LCC-HVDC
Active and Reactive Power Control	PWM driven IGBT bridges can regulate real (P) and reactive (Q) power independent and instantly, without relying on AC voltage	Draws reactive power (50-60%) of active power and must use external compensation such as capacitor banks or synchronous condensers
Black Start Capability	The self-commutation IGBTs allows converter to black start the system without external support	Depends on AC system voltage for commutation and cannot black start a grid without external voltage sources
Power Reversal	Reverses power flow supply by changing the phase angle reference, so swapping the DC cable polarity is not necessary	Must reverse DC voltage polarity at each converter station, adding switching stress.
Grid Operation	Can operate into very weak or passive AC networks because it does not depend on grid voltage for commutation	Needs a minimum grid strength to commutate thyristors, limiting deployment at remote or weakly connected sites.
Filters and Reactive Equipment	The high switching frequency of the IGBTs and PWM reduces harmonic current, so AC side filters and transformers in the VSC system can be smaller, lighter, and lower power loss.	Use lower frequency switching (50-60 Hz), requiring large smoothing reactors, harmonic filters, and transformers to handle harmonics.
Dynamic Response and Fault Tolerance	High frequency PWM control and self-commutated IGBTs provides synthetic inertia, frequency support, and fault ride	Reliance on grid strength limit fault ride capabilities and reduce system response
Multi Terminal and Offshore Integration	Modular voltage-controlled converters simplify mesh or multi terminal HVDC networks, which are ideal for large offshore wind clusters and future HVDC grids	The series connected thyristor bridges and commutation requirements makes future multi terminal schemes complex and expensive

Table 3: Comparing P2P vs MTDC transmission system [8].

	P2P HVDC	MTDC
Configuration Redundancy	Single path, if either end fails, link is lost. Unserved load reduction 6.7 % only	Meshed paths, power can be rerouted around outrages. Built in redundancy translates to less unserved load, up to 8.6 % reduction
Operational Flexibility	No rerouting options if the only path is down. Reduced total generation cost by only 5.9 %	Meshed topology allows operators to shift power to multiple sources, enabling dynamic rerouting. Reduced total generation cost by 6.4 %
Reduced Curtailment (loss of excess energy)	Can only evacuate surplus wind energy from the single wind farm connected to the converter. If the converter hits the maximum capacity, extra generation faces AC network limits and must be curtailed. Reduce curtailment by 41.8%.	By being able to collect output from multiple wind farms, MTDC can carry away surplus generation of wind energy to terminals that are least congested. Reduce curtailment by 50.3%.

Figure 3: North Sea Wind Power Hub projected location and architecture [28].

Point to point to multi terminal grids:

There are many configurations to HVDC systems, such as a monopolar link, bipolar link, and back-to-back, but this paper will only review multi terminal configurations.

Multi terminal HVDC (MTDC) systems exceed the basic two terminal point to point (P2P) HVDC concept by interconnecting three or more converter stations on a common DC network. Instead of a single rectifier inverter pair, MDTC networks allow any terminal to inject or extract power that can connect several OWFs and onshore grids across borders [6],[7].

The comparison of MTDC systems and HVDC systems under a simulation of extreme conditions (heatwaves, wildfires, etc) are shown in a table:

While MTDC systems may be more complex than traditional P2P systems, their flexibility and cut in curtailment make them the technology for gathering power from multiple OWFs and delivering to shore. The flexibility and reduced curtailment help stabilize grids, reduce costs by just adding another terminal to connect more farms, and poses a potential solution as more wind farms are being built.

There have been recent adoptions of MTDC systems including the Shetland HVDC project and the in-development phase of the North Sea Wind Power Hub, shown in figure 3.

The Shetland HVDC project connects the 443 MW Viking Wind Farm to the GB grid via a 260km subsea cable, featuring a three terminal configuration that splits energy flow from Shetland to Spittal and Blackhillock [9]. As a result, the system can transmit power from the offshore Viking Wind Farm, capable of generating 1.8 TWh annually, powering nearly 500,000 homes [10]. In addition, the Shetland HVDC project connection with the Viking Wind Farm would also support 35 permanent roles and contribute £70 million to the local economy [10].

The North Sea Wind Power Hub is an international MTDC project to connect OWFs across multiple countries including Denmark, Netherlands, Germany, and Norway [11]. The projected benefits of this project based on studies indicate that the transmission asset lifecycle costs could be reduced by 30% over a full 180 GW offshore wind roll out compared to radial connections. Additionally, the project is expected to increase social welfare by €1.0-1.7 billion per year and projected a 4% reduction in CO2

Table 4: Comparing SLR and DLR [12],[13]

Feature	SLR	DLR
Weather basis	Assumed worst case (fixed)	Measured in real time (tension sensors), allowing proactive load adjustments to prevent overheating and excessive sag
Congestion Relief	No dynamic congestion mitigation, underutilization of existing transmission lines	Enables active congestion relief by leveraging temporary capacity gains to redirect load
Integration in Wind Energy	Limits wind generation	Supports higher wind integration (e.g. increase of 2 feet per second in wind speed can increase ampacity of transmission line by 15%)
Transmission Efficiency	Fixed rating, suboptimal asset use	Optimizes utilization of transmission network, and boosts power capacity of existing grids by 10-30% for most of the time.

emissions for Europe's power sector by 2040. [11].

These projects prove that the MDTC technology for wind energy transmission is not only feasible, but also economically advantageous for large scale renewable energy integration.

2. Dynamic Line Rating (DLR)

DLR advantages:

Conventional Static Line Rating (SLR) are determined using conservative, "worst case" weather assumptions (e.g. 40 C ambient, zero wind, high solar loading) [12]. Under SLR, the ampacity (maximum allowable current) is chosen so that, even in the hottest, no wind, high sun conditions, the conductor won't overheat or sag beyond safe levels. But often actual weather is milder, resulting in SLR underutilizing transmission assets.

Therefore, Dynamic Line Rating (DLR) is introduced as it continuously adjusts a conductor's allowable current in real time by measuring tension, which reflects the combined effects of conductor heating, sag, wind cooling, ambient temperature, and solar radiation. Tension based DLR systems can send live ampacity updates, enabling operators to use temporary increases in capacity when weather conditions permit.

Table 4 will compare SLR and DLR systems incorporated in wind energy transmission.

DLR continuously adapts conductor ampacity to actual weather and operating conditions. By leveraging real time tension measurements, DLR reduces curtailment of wind generation and smooths power flow, valuable for OWFs. For OWFs, adding new cables or towers may be expensive, so DLR poses an alternative that delivers immediate efficiency and enhances grid stability.

Although DLR technology poses an alternative that advances with wind transmission, there are some concerns on data accuracy, cybersecurity, and communication complexities. The Electric Reliability Organization (ERO) emphasizes that the reliability of DLR depends on accurate sensor and weather data, and the need for a cyber secure system to maintain real time data integrity [14]. In addition, the ERO mentions that by utilizing DLR systems, it requires secure communication integration infrastructures to have coordination among operators (transmission owners, operators, and reliability coordinators) for real time DLR data to be integrated smoothly into control rooms and reliability frameworks.

Real world adoptions:

There have been recent adoptions of DLR such as AEL/LineVision 2023 collaboration and National Grid/LineVision 2022 collaboration on UK Offshore Wind Integration.

The AEL/LineVision demonstration deployed DLR on five transmission circuits (including a 345 kV line in Indiana and a 69 kV line in Ohio). There has been data from October 2023 - March 2024 showing the results of the implementation on the 345 kV line [15]:

- Peak DLR reached 4931 A, which is a 141% increase over the static line value of 2043 A.
- Average DLR was 3294 A, which is a 61% increase from static line and the median DLR value was 3279 A, which is a 60% increase over static line.
- There are also other line ratings used like Ambient Adjusted Rating (ARR), however it only averaged 2687 A, only 32% above static line.

The National Grid and LineVision 2022 collaboration utilized LineVision sensors on critical double circuits exporting energy from offshore wind sites to England and Wales [16]. The key findings of implementing these sensors include [17]:

- DLR averaged 29-33% above post fault static ratings across autumn, winter and spring. This results in an additional 900 A of uplift.
- DLR has a higher rating compared to static rating for 96% of hours (meaning that the ampacity limit of DLR is always greater than static lines)
- Daily forecasts delivered consistent 9% ampacity uplift, which resulted in a 19% increase in boundary capacity on the SSHARAN B7a interface (corridor where power flows via the circuit).
- DLR would have avoided ~£14.25 million of payments during 2022 outrages.

By these recent implementations of DLR, it shows that DLR can result in dramatic increases in ampacity resulting in cheaper energy and reducing wind curtailment risk. This signifies that while the DLR field is still growing, the future of DLR in wind energy transmission is crucial.

3. AVCR, ACSS, and ACCC conductors

ACCC advantages:

Conventional Aluminium Conductor Steel Reinforced (ACSR) conductors consist of one or more layers of cold drawn aluminum strands helically wound around a galvanized high steel core. The steel core gives the high tensile strength, while aluminum strands provide good conductivity.

There have been two other types of conductors called Aluminum Conductor Steel Supported (ACSS) and Aluminum Conductor Composite Core (ACCC) conductors that have better performance compared to ACSR. ASCC consists of annealed aluminum strands helically wound around a steel core and ACCC consists of a lightweight, hybrid carbon fiber reinforced polymer core and uses annealed trapezoidal aluminum strands.

Table 5 shows the results of the data when ACSR, ACSS, and ACCC conductors are tested:

While ACCC conductors are significantly more expensive than ACSR and ACSS conductors, their minimal sag, reduced tension loss, and lowest 10-year creep strain combine to deliver up to twice the ampacity and achieve far better performance. This capability enables wind farm operators to increase export capacity without the expense of installing additional cables or towers. By having the ability to run at higher temperatures with minimal sag, it ensures a reliable power delivery, especially for environmental stresses in OWFs.

Table 5: Comparing metrics of ACSR, ACSS, and ACCC conductors [18].

Metric	ACSR	ACSS	ACCC
Max Operating Temperature	~75-100 ºC	~200-210o C	210 ºC
Degree of Sag at 180 C	~222 cm	~241 cm	~101 cm
Tension loss at 180C	~74%	~60%	~50%
10 Year Creep Strain	0.047%	0.051%	0.035%
30 Year Total Cost Efficiency	Lowest ampacity and highest losses	Moderate ampacity	Highest ampacity
Ampacity Increase vs ACSR	—	~1.2x	~2x
Relative Initial Cost Upfront	1x	~1.1-1.5x	~5-7x

Real world adoptions:

Adoptions of ACCC have been demonstrated in several major transmission projects, including American Electric Power's (AEP) 345 kV reconductoring project, Greece's Peloponnese 400 kV line, and California's Transmission Plan, which features projects such as Julian Hinds–Mirage. In AEP's project, two 120-mile ACSR lines were replaced with ACCC, resulting in doubled capacity (greater ampacity), a 30% reduction in power losses, and $15 million in energy savings [19]. While data from the more recent Greece and California projects is not yet available, ACCC is expected to deliver similar benefits, including higher ampacity, reduced line losses, and enhanced wildfire resilience [19],[20]. These real-world applications highlight how advanced conductors like ACCC can provide a cost-effective and efficient solution for wind energy transmission.

4. Energy Storage

Types of ESS and ESS advantages:

Energy Storage systems (ESS) store energy for later use, balancing supply and demand in power grids. The integration of energy storage systems is crucial for renewable energy sources like wind power by storing excess energy when generation exceeds demand and releasing energy during shortages to stabilize the grid.

Ullah et al. categories ESS technologies into different sections, including electrochemical (batteries), mechanical (hydro, compressed air, flywheels, supercapacitors), and chemical (hydrogen) storage [21].

The overview of main ESS types and how they operate are shown in Table 6:

There are many benefits of using Energy Storage Systems for wind farms. These benefits include:

- Frequency Regulation & Inertia Support: ESS can inject/absorb power to counteract frequency derivations caused by wind variability. ESS can also match inertia responses of synchronous generators by injecting large amounts of power to the grid, contributing to grid stability [21].
- Smoothing Power Output & Reducing Curtailment: ESS can store excess power during high wind periods and release it during lulls to smooth power output over minutes to hours, while reducing curtailment (losing energy during low demands) [22],[23].
- Improved Economic Viability and Cost Reduction: By reducing curtailment and providing frequency regulation, ESS can contribute to a lower levelized cost of energy (LCOE) despite the added cost of the ESS itself, giving an economic benefit of using ESS [24].
- Enhanced Reliability & Black Start Capability: Grid forming battery systems can enable OWFs to blackstart and operate on an islanded mode during disturbances without reliance on external voltage sources [25].

With these benefits, ESS technology poses an effective solution for solving wind transmission issues. As ESS technology continues to mature and become more advanced, it will increase the scale potential of offshore wind farms.

Real world adoptions:

There have been adoptions of energy storage systems for wind transmission systems seen by the incorporation of lithium-ion BESS with the Hornsdale Wind Farm in South Australia. Initially commissioned in 2017 with a capacity of 100 MW / 129MWh, the project was expanded to 150 MW / 194 MWh. According to the Hornsdale Power Reserve Year 1 Technical and Market Impact Case Study, the battery is capable of injecting 100 MW within 150 ms, providing Fast Frequency Response (FFR) services [26]. In an August 25, 2018, event, the BESS delivered 84 MW almost instantly, preventing under frequency load shedding which could have led to a statewide blackout [26]. Apart from stability benefits, the BESS also delivered significant economic benefits. In the second year with the incorporation of the BESS, the average Regulation Frequency Control Ancillary Services (FCAS) costs reduced from $470/MWh to only $40/MWh, contributing to $116 million in total FCAS savings [27]. These outcomes show that modern energy storage systems are enhancing the stability and efficiency of wind energy transmission.

Table 6: Different ESS types and their functions [21]

Storage Type	What it is	How it works
Battery ESS (BES)	Electrochemical cells (e.g. Li-ion, lead acid)	Charges the battery by converting excess wind generation into chemical energy; discharge by reversing the reaction to supply power
Supercapacitor ESS (SCES)	Double layer capacitors or pseudocapacitors (store energy using oxidation/reduction reactions)	Stores energy electrostatically between charged plates and discharges by releasing stored ions
Flywheel ESS (FES)	Rotating mass (rotor) coupled to motor or generator	Electrical energy spins up rotor gaining kinetic energy and generator extracts the energy by slowing down rotor
Superconducting Magnetic ESS (SMES)	Superconducting coil maintained below critical temperature	Electrical current circulates indefinitely in the coil, storing energy in the magnetic field. Power electronics interface control charge/discharge
Hydrogen ESS (HES)	Electrolytic hydrogen production and storage	Surplus energy goes to an electrolyzer that splits water into hydrogen (H2) and oxygen (O2). H2 stored and later reconverted to electricity by fuel cells or turbines
Hybrid ESS (HESS)	Combinations of two or more ESS technologies	Each subsystem will operate within its optimal range

Figure 4: Regulation Frequency Control Ancillary Services costs with BESS versus without BESS [27].

Conclusion:

The transition to renewable energy requires transmission systems that can reliably deliver large scale offshore wind power to the grid. Recent innovations like MTDC HVDC networks, DLR, advanced conductors like ACCC, and ESS address the technical and economic challenges of wind transmission. These technologies not only improve efficiency and reliability but also reduce curtailment, enhance grid stability, and lower overall system costs. As more real-world adoptions continue to emerge, these advancements show a clear path towards building more interconnected, resilient, and sustainable transmission infrastructures capable of supporting the global shift to clean energy.

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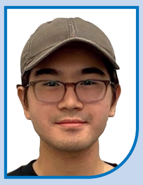

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