electronics

Review

A Comparison Review on Transmission Mode for Onshore Integration of Offshore Wind Farms: HVDC or HVAC

Syed Rahman [1], Irfan Khan [2,*], Hend I. Alkhammash [3] and Muhammad Faisal Nadeem [2,4]

1. Department of Electrical and Computer Engineering, Texas A&M University, College Station, TX 77843, USA; smz_909618@tamu.edu
2. Clean and Resilient Energy Systems (CARES) Lab, Texas A&M University, Galveston, TX 77553, USA; faisal.nadeem@uettaxila.edu.pk
3. Department of Electrical Engineering, College of Engineering, Taif University, Taif 21944, Saudi Arabia; khamash.h@tu.edu.sa
4. Department of Electrical Engineering, University of Engineering and Technology Taxila, Taxila 47080, Pakistan

* Correspondence: irfankhan@tamu.edu; Tel.: +1-409-740-4549

Abstract: The development of offshore wind farms (WF) is inevitable as they have exceptional resistance against climate change and produce clean energy without hazardous wastes. The offshore WF usually has a bigger generation capacity with less environmental impacts, and it is more reliable too due to stronger and consistent sea winds. The early offshore WF installations are located near the shore, whereas most modern installations are located far away from shore, generating higher power. This paradigm shift has forced the researchers and industry personnel to look deeper into transmission options, namely, high voltage AC transmission (HVAC) and high voltage DC transmission (HVDC). This evaluation can be both in terms of power carrying capability as well as cost comparisons. Additionally, different performance requirements such as power rating, onshore grid requirements, reactive power compensation, etc., must be considered for evaluation. This paper elaborately reviews and explains the offshore wind farm structure and performance requirements for bulk offshore power transfer. Based on the structure and performance requirements, both HVDC and HVAC transmission modes are compared and analyzed critically. Finally, a criterion for selection and increasing popularity of HVDC transmission is established.

Keywords: HVDC transmission; HVAC transmission; offshore wind farms; offshore grid integration; reactive power compensation

check for updates

Citation: Rahman, S.; Khan, I.; Alkhammash, H.I.; Nadeem, M.F. A Comparison Review on Transmission Mode for Onshore Integration of Offshore Wind Farms: HVDC or HVAC. *Electronics* **2021**, *10*, 1489. https://doi.org/10.3390/electronics10121489

Academic Editor: Zhiwei Gao

Received: 15 May 2021
Accepted: 15 June 2021
Published: 20 June 2021

1. Introduction

Fossil fuels are usually considered a major cause of global greenhouse gas emissions, and they are mostly consumed in the transportation and power generation sectors. In the last two decades, the consumption of fossil fuels was significantly reduced because of greater research and investment in developing renewable energy resources-based alternatives for transportation and power generation sectors. The new installations of power plants over the last few years show an increasing share of renewable energy sources, exceeding 60% in 2018 [1]. Solar and wind energy are among the two most promising renewable technology options available in current times [2]. Among these, wind energy is installed in a larger generation capacity. Wind energy is more reliable, due to its availability for 24 h. With advanced power electronic technology and control algorithms, wind energy can be integrated into the utility grid without heavily relying on battery energy storage. The wind energy reliability further increases for offshore WF [3–5].

Control of wind generation and its integration into the utility grid has drastically improved in the last few decades. Initial wind power generators are based on fixed-speed squirrel cage induction generators (SCIG). A gearbox is generally employed for matching the speed between turbine and generator. Although this solution is simple and economical, it results in lower operating efficiencies, needing capacitor banks for reactive power, and variation in wind speeds are reflected in grid frequency. For addressing this concern, semi-variable speed control mechanisms based on a Wound rotor induction generator (WRIG) and doubly-fed induction generator (DFIG) are introduced. WRIG uses rotor resistance for controlling turbine speed up to 10% of rated speed, whereas DFIG employs a partial rated power electronic converter on the rotor side. With DFIG, speed control up to 30% is possible. With this control approach, advanced features such as maximum power point tracking, improved dynamic performance, and partial fault ride-through capability are also achieved. However, the bulky and costly gearbox is still employed. Most optimal performance can be achieved using full-speed control. Here, a power converter rated for 100% of generation capacity is used for controlling the power generation from SCIG or permanent magnet synchronous generator (PMSG) or wound rotor synchronous generator (WRSG). The gearbox can be eliminated here by using a higher number of poles. Currently, semi-variable and full-variable speed control wind turbines are employed in almost all onshore and offshore installations [6–10].

This advancement in wind generation is also reflected in the increasing percentage share of wind energy from 1.7% to 6% of total energy in the last 8 years [1]. However, onshore generation is currently leading with a 96% share. Onshore generation is preferred due to minimal installation and maintenance cost, lower carbon emissions, and the most economical power generation (among renewable sources) [11–14]. However, it suffers from high variability, low operating efficiency, and undesirable effects on human and animal life [14,15]. To address this and to harness stronger winds, offshore generation has evolved as an optimal solution. Higher generation capacity, improved reliability, and remote location are the significant benefits. Due to these factors, offshore wind generation has increased 8 folds in the last decade. As these facilities are located deep in the ocean, this type of wind generation suffers from higher wear and tear (due to stronger winds), high installation and maintenance cost resulting in a higher cost of generation [15–21]. With further improvement in technology, its cost is projected to decrease significantly in the coming decades. By 2050, offshore wind generation is projected to account for 20% of total wind generation [1], as shown in Figure 1.

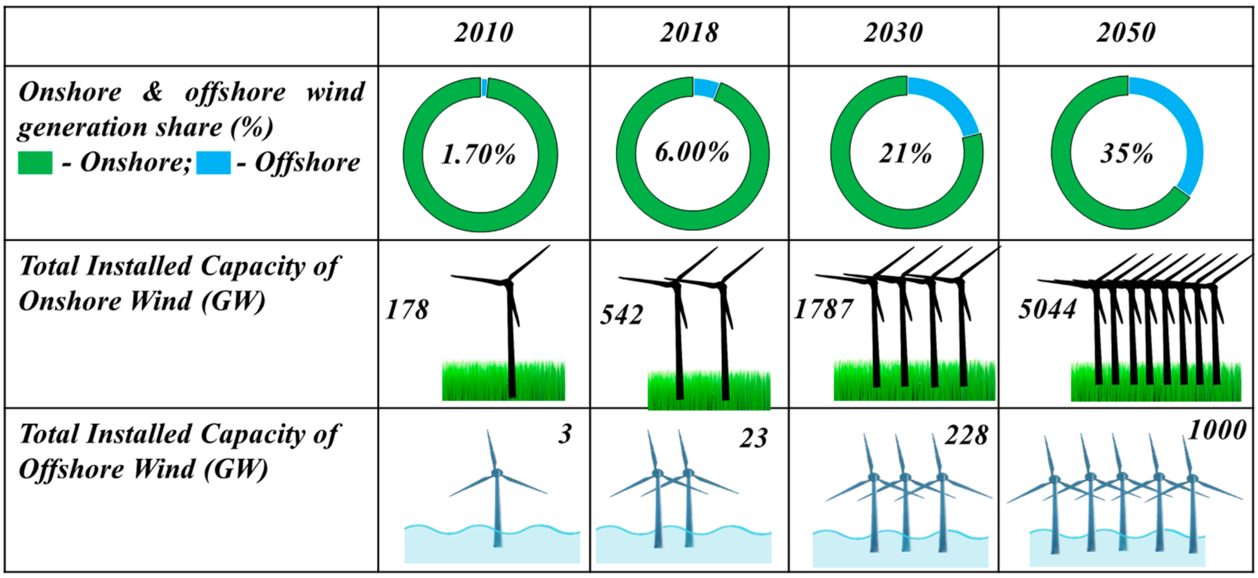


Figure 1. Growth and prediction of wind generation share over 40 years.

Initially, most offshore WF used to transmit generated power via HVAC transmission. Power electronic circuitry connected to the wind turbine converts the generated highly-variable AC power into constant power AC voltage. This AC voltage is transmitted to onshore without using any expensive offshore and onshore side converter stations. This results in the most economical transmission options with abundant experience of design/diagnostics/protections majorly attributed to its land transmission system. However, offshore WFs are now going deeper into the ocean for utilizing far stronger winds. This increasing offshore distance and power rating must impact the transmission mode. For larger distances, transmission voltage levels must be increased, which results in higher cable losses and increased reactive power compensation. This severely limits the active power transmission capability for lengths greater than 100–150 km in overhead lines and 50 km in submarine transmissions [22,23]. With the improvement in semiconductor technology, these concerns can be addressed using the HVDC transmission option. In this technology, an AC voltage is rectified to DC and then transmitted. This theoretically eliminates the issues related to reactive power compensation. However, the offshore and onshore converter stations are complex. Although a power electronics-based converter station is an additional cost, the benefits obtained compensate for it.

An apt comparison to this problem can be the railroad system running primarily on the AC power supply. Performance requirements dictate the line voltage be maintained within a permissible limit. However, the voltage drop due to line inductance needs distribution transformers to be installed at short intermediate distances. This results in extra cost. To alleviate this issue, an AC voltage is provided at a low operating frequency resulting in lower voltage drops, and thus, reduced distribution transformer requirement. Using low-frequency AC voltage (LFAC) transmission can also be a good alternative when compared to HVAC and HVDC. In 2014, CIGRE general meeting suggested minimization of components in the converter stations to achieve minimal cost and lower footprint [24]. By altering the power electronic circuitry on the wind turbine side, it is possible to generate and transmit low-frequency high voltage AC power to the onshore grid. Improvements in semiconductor technology and enhanced computational capabilities also provide opportunities for improving both the cost, performance, and footprint of the transmission technology [24,25].

Along with these opportunities, there are also changes in the grid codes provided for offshore WF integration. Capability to black-start, voltage stability, and reactive power capability are some of the major requirements which must be conveniently met. Thus, there is a need to evaluate different transmission modes for given grid requirements along with cost constraints. This paper presents an overall comparison among different transmission modes.

The rest of the paper is organized as follows. Section 2 details the layout of HVAC and HVDC transmission-based offshore WFs. This section helps in identifying the major elements in the system. Section 3 details the grid code requirements of the offshore wind integration. Section 4 details the different offshore wind transmission configurations discussed in the literature and used in commercial installations. Section 5 presents a comparison of the two transmission methods. Section 6 concludes the paper.

2. Power Layout for Integration of Offshore Wind Farm

Power generating offshore WFs consist of clusters of wind turbines connected in series and parallel. Each turbine is provided with its power electronics and control. This circuitry remains the same irrespective of the mode of transmission. As power generation from a wind turbine is highly variable, power electronic circuitry is exceedingly important to filter out the power generation ripple in the grid frequency. To achieve this, two options are available. The first option is to be employed doubly-fed induction generators capable of achieving continuous and ripple-free power up to ±30% speed variation. In this system, the power converter circuitry is placed on the rotor side of the generator, whereas the stator is connected to the AC grid via a step-up transformer. Another popular configuration is to place the power converter on the stator side and rate it for 100% of the turbine power rating. This helps in achieving synchronized grid operation for full variation of turbine speed. The major drawback here is the higher power rating of power circuitry compared to the previous case [6,7].

Power electronic circuitry on the turbine side consists of a rectifier followed by a full-wave inverter. Different configurations such as diode rectifier with inverter or PWM rectifier with inverter are typical examples. This helps in removing the variability in generated voltage frequency. The generated voltage level is collected using an AC collector system. The local AC collector system is interconnected using a step-up transformer. The entire power generated is collected at the onshore station and then transmitted to the offshore station. As offshore WF generates power at a distant location from land, the transmission of generated power heavily relies on power rating and offshore distance from the nearest onshore grid connection. AC and DC configurations of transmission are shown in Figure 2.

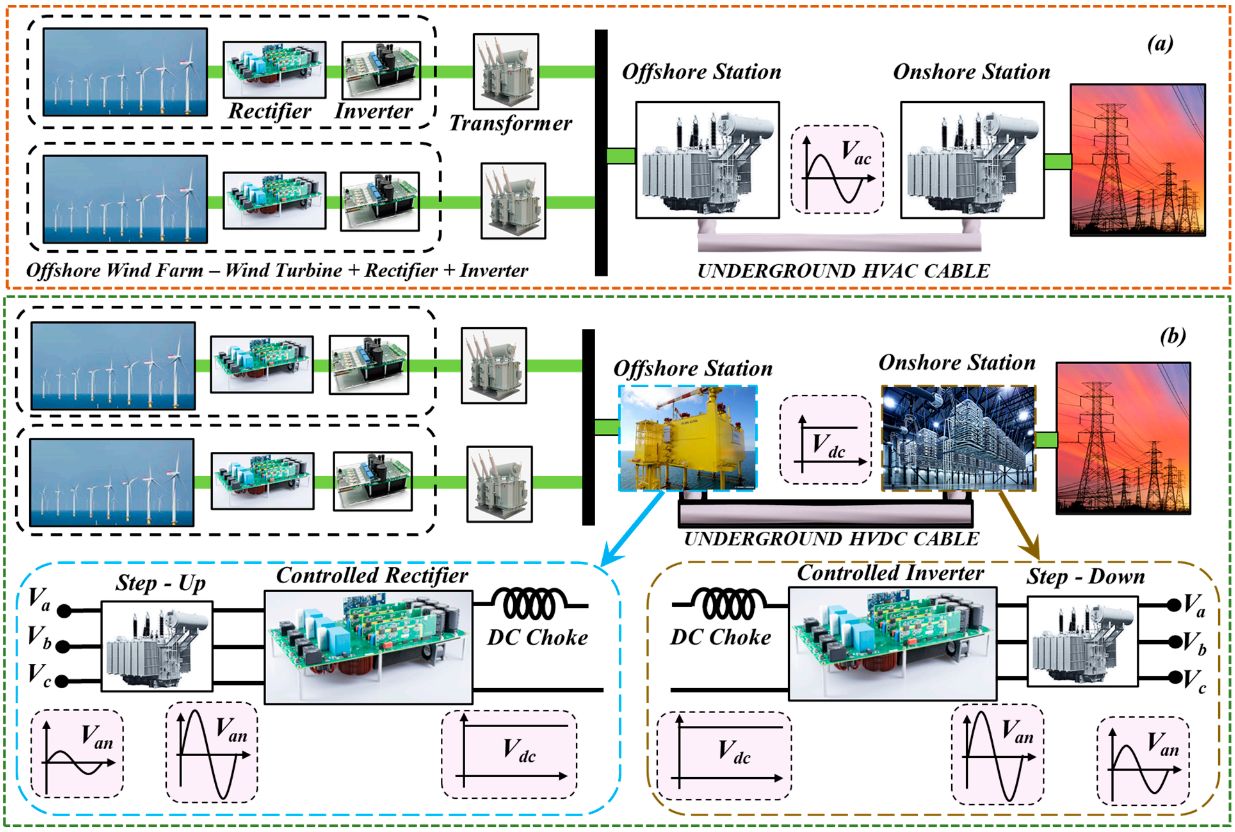


Figure 2. Offshore wind power plant layout for (**a**) HVAC and (**b**) HVDC transmission.

HVAC transmission is characterized by simple yet highly mature technology. The entire transmission and receiving station apparatus would consist of AC cables, transformers, and reactive compensation elements. Since power generation is alternating in nature, using a simple step-up transformer, generated voltage level can be increased to the required transmission level. Thus, there is no requirement for any power electronics converter. On the other hand, in HVDC transmission, the generated power is converted from AC to DC power using a converter station. Each converter station consists of a step-up transformer and power electronic converter followed by DC choke. Functions of the converter transformer are: (a) to provide cancellation of lower order harmonics by supplying required phase shift between the two AC circuits, (b) to provide galvanic isolation thereby acting as a barrier by preventing any DC side fault from penetrating on the AC side (c) to limit the short circuit current with its reactive impedance (d) to provide required transformation for DC voltage level transmission and (e) to contribute in fine adjustment of supply voltage using tap chargers [26]. On the onshore station, the converter employed is a rectifier, which converts the AC voltage to DC voltage, whereas, on the offshore station, the inverter is employed. The structure of both converters is identical in nature, but a different control methodology is employed to control the direction and magnitude of power transfer. Due to bulk power transmission, DC voltage levels are maintained at around ±500 kV. For achieving these voltage levels, each converter system employs a large number of switches and requires an extensive cooling mechanism. This reflects as high converter station installation cost.

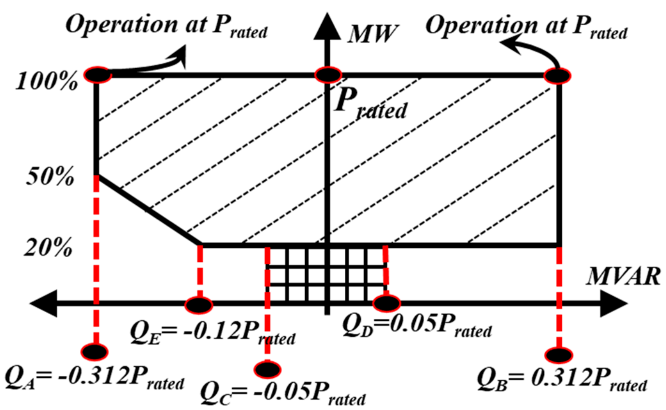
3. Grid Side Requirements of Offshore WF

There are grid codes that must be considered for wind power plants (including both onshore and offshore WFs). For explanation, grid codes of [27] are considered here.

3.1. Voltage or Reactive Power Control Capability

The voltage at the point of common coupling (PCC) must be controlled to achieve power flow and system stability. In offshore wind turbine systems operated with fixed-speed induction generators, no capability of voltage control of reactive power management is possible. To achieve this capability, additional capacitor banks, VAR compensators, or STATCOM are required. However, with the latest HVDC technology employing Voltage Source Converters (VSC), it is possible to control active and reactive power utilizing pulse–width modulation switching [24]. The reactive power requirement as a function of active power injection is shown in Figure 3a. It is explained for five operating points [27]. Points on the left (A, E, C) indicate operation at leading power factor. When the power factor is at 0.95 leading (A) or 0.95 lagging (B), rated operation at 1 p.u of active power can be achieved. However, when operated at points (C) and (D), the MVAR capability is 5% of the active power. Point E indicates that approximately 12% of active power is now available for reactive power management [28]. In the case of a fault, the grid codes dictate that the system must start pumping reactive power into the system.

This pumping of reactive power facilitates the recovery of system voltage. For a 1% drop of system voltage (in 50–90% range), 2% of reactive power must be provided. This means, at 50% of rated system voltage, the wind system must be pumping reactive power (capacitive) equal to its rated MW capacity. Additionally, this transition must be achieved in 20 ms (i.e., from normal operation to FRT operation).



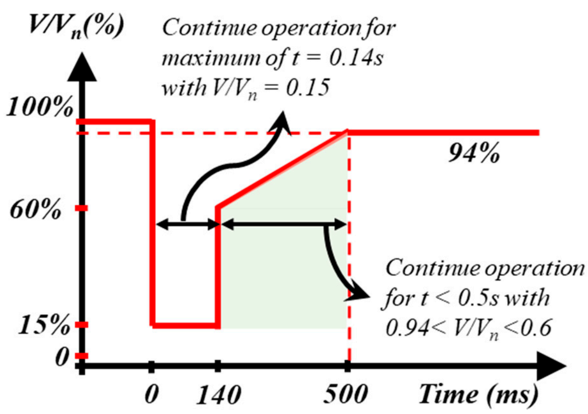
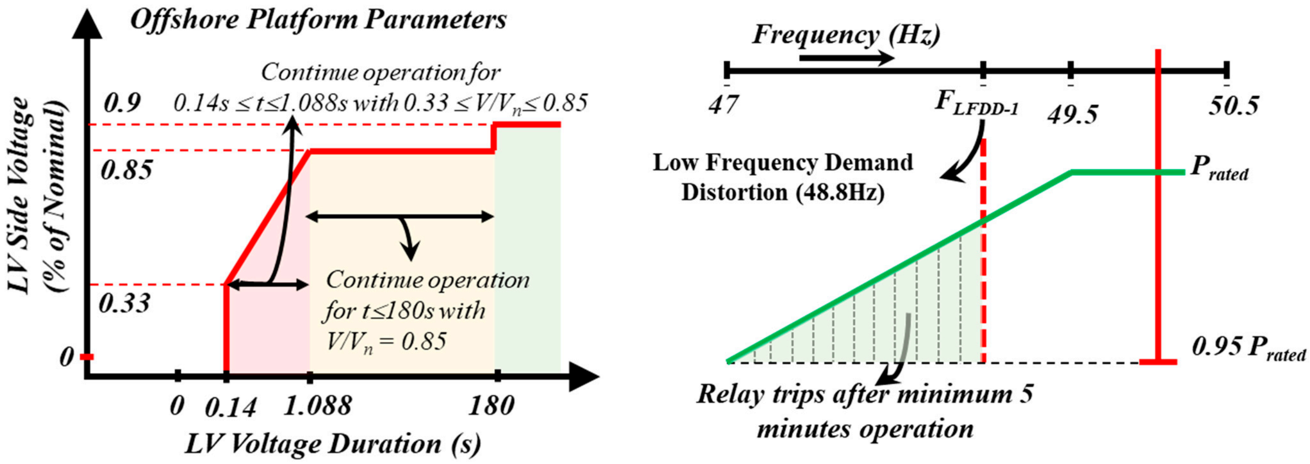


Figure 3. *Cont.*



(**c**) (**d**)

Figure 3. (**a**) Reactive power requirement as a function of active power to achieve wind farm integration in Great Britain [29]. (**b**) Requirement of withstanding voltage dips on the LV side of the offshore platform [28,29]. (**c**) Requirement of LV voltage sag duration requirement [28]. (**d**) Frequency requirement for wind farm integration in Great Britain [29].

3.2. Fault Ride-Through (FRT) Capability

During periods of voltage sag (i.e., low voltage durations) synchronizing and continuous operation requirements for the low voltage side of offshore wind turbines are shown in Figure 3b [29]. For a period of 140 ms, the offshore wind system must remain connected and operate even with voltage dipping to approximately 15% of the rated value. The purpose is to support the onshore transmission system during low voltage duration (caused by faults on the AC grid) or the fault occurring on the offshore platform (low voltage side winding) [27,30–33].

Moreover, the offshore wind turbine must supply active power output (for voltage dip duration >140 ms) in addition to the maximum reactive current capability. This reactive power injection would help in the improvement of the voltage profile of the system. The timespan for recovery of voltage sag is 1 s. The detailed requirement of the system is given in Figure 3c [28].

Apart from this, the High Voltage Ride Through (HVRT) capability of the system must also be achieved along with low and zero voltage through. As per requirement, the system must operate at rated power from 0.9 to 1.1 pu voltage level. However, if the system voltage rises to 1.2 pu, the system must stay connected and operate for at least 100 ms. Resultantly, FRT capability (Zero Voltage Ride Through (ZVRT), Low Voltage Ride Through (LVRT), and High Voltage Ride Through (HVRT)) is one of the most stringent requirements among the existing wind turbine control and operation [28,29,34].

3.3. Active Power vs. Frequency Control

Continuous operation of the WF must take place in the frequency range of 47–52 Hz. For frequency range of 49.5 Hz to 50.5 Hz, rated operation, i.e., constant active power, must be injected. However, for frequency in the range of 49.5 Hz to 47 Hz, WF output must not decrease by more than 5%. Detailed requirement is given in Figure 3d.

Other requirements of the system include the following [28,29,34,35]:

- DC faults must not completely disrupt the entire system.
- Voltage stabilization and frequency support must be provided by the offshore system to the onshore AC grid.

3.4. Black Start Capability

The occurrence of a fault on the onshore grid can sometimes result in blackout operation. During this condition, offshore power generation and transmission must be stopped.

However, when the onshore grid is back online, the offshore must be reconnected. This means, that the power generation and transmission must be resumed normally. For HVDC transmission, the offshore system must be capable of resuming operation without any support from the onshore structure. This means, that the converter system must employ switches that are independent of AC grid for the commutation process. This reason dictates self-commutated semiconductor devices instead of line-commutated devices [8,36,37].

4. Different Topologies for Offshore Wind Farm

Different configurations of offshore wind turbine systems with different converters and transmission mechanisms are shown in Figure 4 [15,34,38,39].

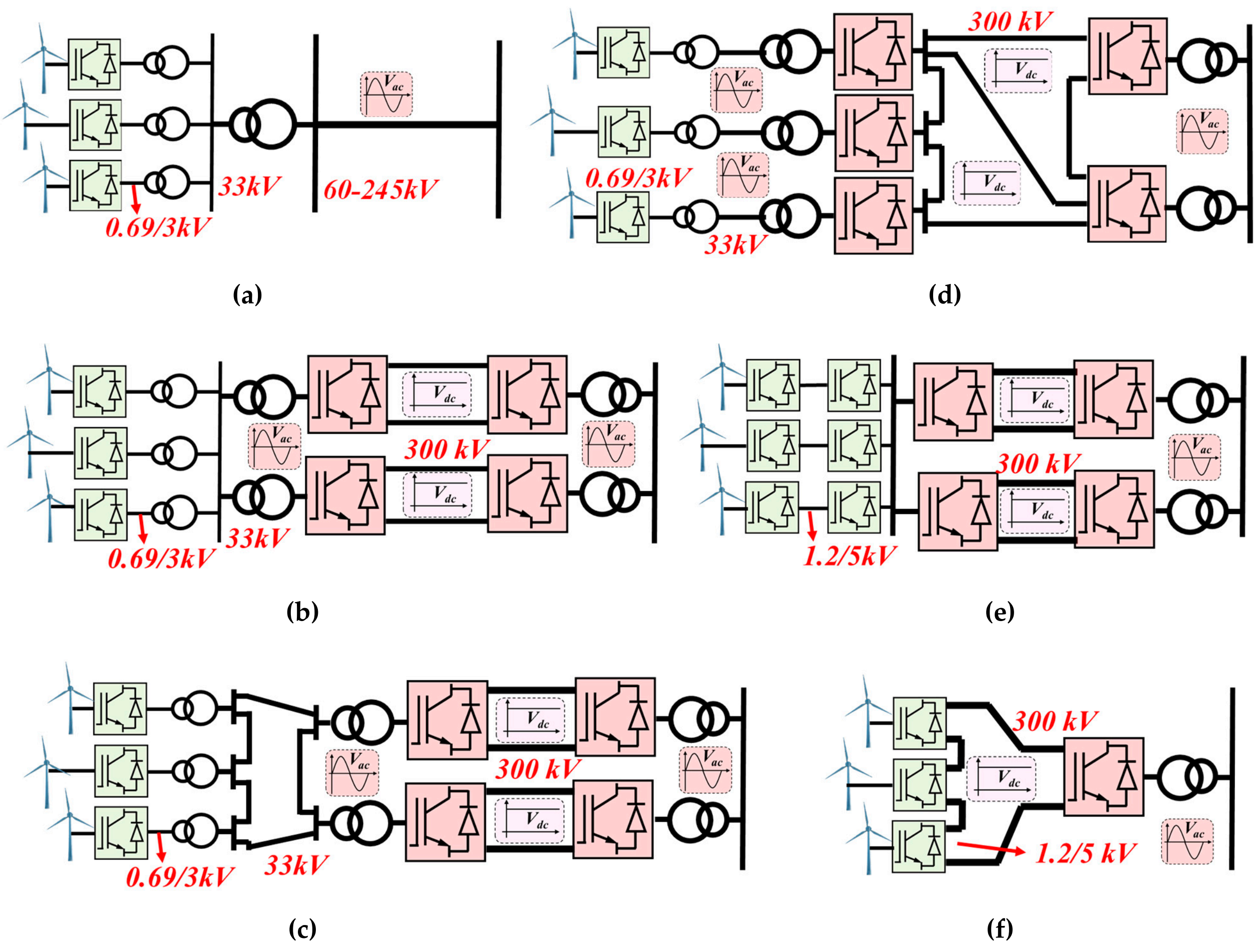


Figure 4. (**a**) Parallel AC connected system with HVAC based transmission system. (**b**) Parallel AC connected system with HVDC transmission. (**c**) Mesh connected AC system with mesh connected HVDC transmission. (**d**) Multi-terminal DC grid-based mesh structured HVDC transmission. (**e**) Parallel AC connected system with medium frequency transformer embedded HVDC based transmission system. (**f**) Series DC connected system with HVDC transmission system.

Type–1: In this configuration, wind turbines, along with the power converter, are connected in parallel, as shown in Figure 4a. Each unit has a step-up transformer which steps up the voltage from 0.69/3 kV to 33 kV. AC collector system collects the power from all the WFs (which are connected in parallel) by forming an AC voltage bus. This voltage is further increased to higher voltage levels such as 60–245 kV depending upon the distance of wind turbines from the shore [16,40]. However, this aspect of power transfer is dependent upon the transmission distance, i.e., when distance increases, reactive power compensation required also increases. This limits the power transferring capability over long distances. This problem can be addressed by operating at a lower frequency. However, it results in greater transformer size, which leads to increased cost [24]. Another improvement would incorporate a reactive power compensation platform between the onshore and offshore platforms. This would increase power capability, although it will result in higher costs [41].

Type–2: This is the most popular offshore/onshore wind turbine configuration, as shown in Figure 4b. Here, same as type-1, power is collected in parallel and then boosted to higher voltage levels. To overcome the power limitations of AC transmission systems, the HVDC transmission system is employed. Boosted AC voltage is rectified by using AC–DC converters. Step-up transformer and converter systems are placed in an offshore converter station.

With this configuration, it is possible to achieve higher voltage and power transmission levels along with more distant locations from shore. In this configuration, depending upon the converter type selection (discussed in Section 5), additional reactive power compensation may be required [34].

Type–3: This configuration is almost like the previous configuration, except that the AC collector system is now connected in mesh instead of parallel (as shown in Figure 4c). This helps in improving the reliability of the system on the collector side [38].

Type–4: In this configuration, AC power generated is first stepped up to 33 kV and then transmitted to multiple converter stations (as shown in Figure 4d). These converter stations step up the AC voltage and then convert it to a DC voltage of 300 kV. To increase the reliability of the system, the HVDC grid is connected to the mesh structure. Failure of any one cable will not reduce the power transfer capability of the system, although the cost incurred would be higher compared to other systems [38].

Type–5: In this configuration, the collector system is DC in nature, and the wind turbines are connected in parallel (as shown in Figure 4e). The generated voltage level is first rectified to reach a voltage level of 1.2–5 kV, and then, this voltage level is further boosted to 30–50 kV by the high gain DC–DC converter. As no transformer is used in the collector system, higher insulation levels are required both in the converter system and wind turbine. However, here, a medium or high-frequency transformer embedded in a DC–DC converter is used, which helps in reducing the footprint and weight of the offshore converter station. Due to wide research on the solid-state transformer in the field of traction drives and renewable energy, this configuration has attracted a lot of research interest [42,43]. This topology is specifically being developed for offshore WFs.

Type–6: This is the simplest offshore WF configuration shown in Figure 4f. Here, the generated power is rectified to give a DC output voltage of 1.2–5 kV (depending upon the turbine generation level). These individual modules are then connected in series to reach the desired voltage level of 300 kV for HVDC transmission. This configuration eliminates the offshore converter station, and the losses incurred would be the least due to the usage of the least component implementation. Each series unit is provided with a bypass switch in case of any failure or scheduled maintenance. However, the failure of a greater number of individual units would lead to a complete shutdown of the transmission system (as the required transmission voltage level is not maintained, and there is no intermediate platform to mitigate this issue) [44,45].

5. AC Vs DC Transmission Choice for Offshore Wind Farm

5.1. Technology Comparison

In HVAC transmission mode, power converter circuitry is dedicatedly placed on the turbine side. However, the AC voltage level is stepped up for transmission. This forces the offshore grid to perfectly synchronize with the onshore utility grid. This means the voltage capability/reactive power compensation/fault-ride through capability becomes an objective of the control algorithm of the turbine side power circuitry. However, this results in a complex algorithm, which makes it extremely hard to realize. To alleviate this, additional hardware such as reactive power compensators or voltage boosting hardware is provided at intermediate stages. This also adds up to the installation and maintenance cost. However, protection and diagnosis methodologies are well defined with a high volume of experience in high power control and operation. This maturity in operational experience and bulk manufacturing helps in an improved design [43,46].

HVDC technology attracted a lot of attention with its lesser conductor requirement, theoretically no transmission distance limit (leading to higher power ratings), and most importantly the additional flexibility obtained by decoupling the onshore and offshore AC grids. This also enhances the grid stability in case of power blackout [39,47,48]. Initial HVDC installations were dominated by thyristor-based Line Commutated Converters (LCC). For achieving higher voltage and power levels, thyristor valves are employed. Each valve consists of many thyristors connected in series and parallel. However, they are all switched at the same time instant, thereby behaving as a single unit. However, additional hardware is required to suppress transients due to manufacturing level non-idealities in the thyristors. Mostly, a 12-pulse rectifier is employed for transmitting bulk power. On the inverter side, the power transmission is controlled at larger firing angles (>90°). This results in higher reactive power requirements, along with threats of semiconductor failure due to repeated commutation failure. On the DC side, bulky DC filters are employed to provide constant DC voltage along with suppression of current transients. Due to these features, converter stations are usually bulky with the bandwidth of control operation restricted to line frequency [34,49,50].

With the advent of larger voltage and power rated semiconductor devices such as power IGBTs, this controlled switches-based HVDC technology has seen immense development in the last two decades. Initial technology relies heavily on a two-level Voltage Source Converter (VSC), where, similar to LCC, IGBTs are stacked in series and parallel. However, they are switched at a switching frequency of 2 kHz, resulting in higher switching losses [51]. Additionally, voltage/power ratings of IGBTs is comparatively lower compared to thyristors. This results in amplications of the series/parallel problems. However, due to controlling feature and fast switching frequency, the quality of the waveform obtained is improved compared to LCC, thereby minimizing the filtering requirement on both AC and DC sides. Additionally, the control algorithm provides the capability of decoupled active and reactive power control. This almost eliminates the need for any external hardware requirement for providing reactive power compensation. The latest development in this area is the introduction of IGBT switches rated for 4.5 kV/6.5 kV. This minimized the number of series/parallel switches required to realize a switch valve. Issues of paralleling or series connection of switches in terms of reliability and performance are well documented in literature.

An improvement over VSC technology is the introduction of Modular Multilevel Converter (MMC) technology. Here, instead of placing the switches in series and parallel, a modular design approach is followed. For achieving the required voltage/power, based on switch ratings, the number of MMC modules is decided. MMC modules can be either half-bridge or full-bridge configuration depending upon the performance requirement. Half-Bridge topology consists of two switches and one DC link capacitor, whereas full-bridge topology consists of four switches and one DC link capacitor. Each module is controlled to contribute to output voltage step along with control of DC link capacitor voltage. This module based control, although possesing control challenges, helps in further improvement of waveform quality, control capability, switching losses, and thermal design. However, the control algorithm is highly complex. In most of the recent installations, MMC is being used as the favourite installation option [34,49,51].

5.2. Conductor Configurations for HVAC and HVDC Systems

HVAC: For transmission of bulk power, either single or double circuit lines can be employed. With a single circuit line, three conductors are placed for three phases. In this case, the power per conductor is high, and thus, charging reactive power requirement is pretty high. In the case of double circuit lines, six conductors are placed on the same poles, with two parallel lines. This decreases the line impedance and thus the reactive power requirement. For meeting the reactive power requirements for longer distances

(0.95 lagging to 0.95 leading), additional reactive power compensation devices are needed. For the underground cabling in HVAC transmission, usually, single circuit lines are employed due to higher reliability and lower failure rate compared to overhead transmission lines [34,52,53].

HVDC: There are three basic configurations available for HVDC power transmission. They are classified based on no. of conductors and use of ground return. In Monopole, only one conductor runs throughout the line with the ground considered as the other line. In a bipolar system, a pair of conductors with opposite high voltage polarity (with respect to ground) constitute the transmission system. Although this system is costly compared to a monopole, it offers advantages such as higher power transmission capability along with increased reliability. In a homopolar system also, two similarly polarized high voltage conductors transmit power. This configuration decreases the installation cost, but the return metallic wire compensates the obtained advantage. Overall, most recent HVDC installations employ bipolar HVDC systems with voltage ratings up to ±500 kV [54–57].

Compared to the land counterparts, the most significant change in the offshore transmission mode is the extensive use of underground/sub-marine cables. Overhead transmission lines design is comparatively simple with requirements such as power/voltage/ampacity, mechanical strength to withstand wind pressure, etc. However, in a submarine environment, there are additional requirements such as long continuous lenghts, higher reliability, excellent corrosion and abrasion resistance, and minimized water penetration and environmental impacts [58]. All these requirements reflect as additional costs both in manufacturing and installation. However, they do not need intermediate supporting poles for avoiding sagging of transmission lines. A comparison of losses with HVAC and HVDC for same voltage rating and equal length is given in Table 1.

Table 1. Comparison of HVAC and HVDC power transmission cables [58].

	Length (km)	Power (MW)	Voltage (kV)	Losses (%)
AC	1000/2000	3000	800	6.7/10
DC	1000/2000	6400	800	3.5/5

Performance comparison of HVAC and HVDC transmission is given in Table 2.

Table 2. Performance comparison of HVAC and HVDC transmission modes [34,49,51,59,60].

Parameter/Feature	HVAC	HVDC
No. of conductors	3 (single circuit), 6 (double circuit)	2 (bipolar) with metallic return
Power transmission capability	Lower	Higher
Transmission capability	Limited by the distance	Independent of distance
Offshore/Onshore Station	Low-frequency transformer	Power electronic converter system
Losses for 1200 MW rating [59] (2004)	Conversion losses—0%, line losses—1.2%	LCC:Conversion losses—1.4%, line losses—0.5%; VSC: Conversion losses—0%, line losses—1.2%
Space requirements	Small	Larger
Control capability	Depends entirely on the turbine side converter	An additional degree of freedom provided by the converter stations
Black start capability	Yes	LCC based system—No, VSC based HVDC—Yes
Reactive power compensation	Requires additional hardware	LCC requires lower compensation, VSC does not require any compensation
Active and reactive power control	Dependent on load current and line impedance	Independent of each other for VSC based HVDC system
Offshore and onshore utility grid	Both grids are coupled	Both grids are completely decoupled
Technology maturity	Highly matured	Relatively inexperienced
Skin effect	Occurs	Absent
Corona losses	Higher	Lower
Voltage regulation	Relatively poor	Better
Interference with the communication line	Higher	Lower

5.3. Cost Comparison

HVAC: In this transmission mode, low-frequency transformers are employed on both onshore and offshore stations. This greatly helps in reducing the installation and maintenance costs. It is always the simplicity, ease of operation, and the high operational reliability of line-frequency transformers that led to popular bulk power transmissions. However, increasing the voltage level leads to other problems related to non-ohmic losses in the transmission lines, i.e., reactive losses (losses occurring in cable capacitance or overhead transmission lines inductance) [47]. Moreover, the installation cost of three HVAC cables is higher compared to the monopolar or bipolar configuration of HVDC requiring one or two conductors, respectively.

HVDC: In this transmission mode also, onshore and offshore converter stations are employed. However, each converter station consists of additional components compared to the low-frequency transformer. Power converters for rectifying the collected AC voltage level into a DC voltage. On the onshore side, DC voltage is converted to AC voltage. The cost of HVDC transmission is heavily dictated by the HVDC technology employed. When thyristors-based LCC is employed, the reactive power compensation relies heavily on the firing angle. To compensate for this reactive power, additional hardware is installed. Fault detection and its mitigation require protection equipment, which is costlier and needs more maturity when compared to AC transmission [34,61,62]. On the other hand, employing controlled semiconductor-based HVDC technology, namely, VSC or MMC, active and reactive power can be effectively and independently managed. This eliminates the need for extra reactive power compensation hardware. However, the cost of switches and gate driving circuits adds up significantly to the installation cost. Additionally, the cost of filtering elements is also reduced as high quality of the waveform is obtained (with both rectifier and inverter). Due to modular design, semiconductor failure results in the loss of relatively lower generation capacity at the converter station. This improves the overall reliability, operating cost, and reduced backup capacity [34,63,64].

Selecting between the two transmission modes depends upon power rating, cost of installation/operation of transmission, and offshore distance. Studies have been presented in the literature that show break-even distance as a function of power rating and HVDC technology employed. For example, for offshore WF power rating of 400 MW, breakeven distance when comparing HVAC and HVDC LCC is 52 km whereas this distance between HVAC and HVDC VSC becomes 85 km [65]. Although, cost of installation of different equipments can be fairly estimated, operation cost of the transmission mode is determined by estimating the annual losses. Comparison for the same transmission distance of 750 miles for HVDC and HVAC is shown in Table 3 [66].

Table 3. Cost comparison of HVAC and HVDC transmission modes.

	Parameter	HVDC (Bipole)	HVAC (Double Circuit)
Transmission System Details	Rated power (MW)	3000	3000
	Transmission voltage level (kV)	500	500
	Distance in miles	750	750
Cost Breakdown	Station cost (including Q compensation) (M$)	420	542
	Transmission line cost (M$/mile)	1.6	2
	Total Transmission line cost (M$)	1200	2400
	Total cost (M$)	1620	2942
	% losses at full load	6.44%	6.93%
	Capitalized cost of losses at $1500/kW (M$)	246	265

Another interesting study is presented in [67], where evaluation of annual losses with both AC and DC configuration is provided for 100 and 300 MW transmission of offshore WF. In both these transmission modes, subsea cabling and tramsisison system is used. The annula loss comparison considers all the components from the wind turbine output to the onshore utility grid. It can be observed here that with DC transmission, line losses are significantly reduced as shown in Table 4.

Table 4. Annual Energy losses and costs of components in the two offshore transmission modes [67].

	AC Configuration (100 MW, 300 MW)	DC Configuration (100 MW, 300 MW)
	Annual Energy losses	
Collection Cables (%)	0.05, 0.06	0.03, 0.04
Transmission lines (%)	0.36, 0.30	0.27, 0.23
Power electronics including transformers (%)	3.39, 3.39	3.46, 3.47
Total energy losses (%)	3.8, 3.75	3.77, 3.75
	Cost Analysis	
OPEX Cost (million$)	5.71, 17.17	6.37, 18.98
CAPEX Cost (million$/20 years)	300.59, 903.88	335.01, 998.72

Note: OPEX refers to Annualized Operational Expenditures (including operational, maintenance, administrative, insurance, and royal costs), and CAPEX refers to Total Capital Expenditures (including turbine cost, support system cost, electrical system cost, project development cost) [67].

6. Conclusions

For increasing the energy contribution of offshore generation, offshore wind farms are now located deeper into the ocean. Increasing the power rating and distance affects the conductor configuration and transmission mode. For HVAC transmission mode, robust and simple hardware and control structures result in lower installation and maintenance costs. Another benefit is the technical maturity due to the existence of vast and bulk power transmitting land version of overhead transmission lines. However, additional hardware is required for meeting reactive power compensation and voltage regulation requirements. These requirements exceed the HVDC system cost after the break-even distance. HVDC system, although having higher operating losses, is a transmission mode that seems to be more appropriate for meeting the stringent grid code requirements. With features such as independent active–reactive power control, decoupled onshore and offshore grid, increased flexibility, voltage boosting capability, etc., HVDC seems to be a better alternative for bulk offshore power transmission.

With the introduction of MMC technology, HVDC-based transmission has drastically improved the performance thereby eliminating any reactive power or harmonic filter requirements. Moreover, relatively lower loss of system due to component failure contributes to its improved reliability compared to HVAC systems. Hybrid transmission systems consisting of different HVDC technologies or a combination of HVAC and HVDC systems are being developed for addressing cost and reliability constraints. Another area of active research includes the development of diagnosis and protection of large DC currents.

Future directions of work for offshore wind turbines include (a) development of higher power rated wind turbines for withstanding higher wind speeds installed deeper into the ocean, (b) integration with other renewable source such as wave energy converter, (c) improvement in performance and control by utilizing state-of-the-art power electronics and advanced control techniques, and (d) realization of reliability and cybersecurity aspect of these offshore renewable energy sources.

Author Contributions: Writing—original draft preparation: S.R.; formal analysis, visualization: M.F.N.; methodology, funding: H.I.A.; conceptualization, writing—review and editing, supervision: I.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. IRENA. Deployment, investment, technology, grid integration and socio-economic aspects. In *Future of Wind*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2019.
2. Panwar, N.; Kaushik, S.; Kothari, S. Role of renewable energy sources in environmental protection: A review. *Renew. Sustain. Energy Rev.* **2011**, *15*, 1513–1524. [CrossRef]
3. Billinton, R. Bagen Reliability Considerations in the Utilization of Wind Energy, Solar Energy and Energy Storage in Electric Power Systems. In Proceedings of the 2006 International Conference on Probabilistic Methods Applied to Power Systems, Stockholm, Sweden, 11–15 June 2006; pp. 1–6.
4. Yang, Y.; Bremner, S.; Menictas, C.; Kay, M. Battery energy storage system size determination in renewable energy systems: A review. *Renew. Sustain. Energy Rev.* **2018**, *91*, 109–125. [CrossRef]
5. Keck, F.; Lenzen, M.; Vassallo, A.; Li, M. The impact of battery energy storage for renewable energy power grids in Australia. *Energy* **2019**, *173*, 647–657. [CrossRef]
6. Chen, Z.; Guerrero, J.M.; Blaabjerg, F. A review of the state of the art of power electronics for wind turbines. *IEEE Trans. Power Electron.* **2009**, *24*, 1859–1875. [CrossRef]
7. Blaabjerg, F.; Liserre, M.; Ma, K. Power Electronics Converters for Wind Turbine Systems. *IEEE Trans. Ind. Appl.* **2012**, *48*, 708–719. [CrossRef]
8. Yaramasu, V.; Wu, B.; Sen, P.C.; Kouro, S.; Narimani, M. High-power wind energy conversion systems: State-of-the-art and emerging technologies. *Proc. IEEE* **2015**, *103*, 740–788. [CrossRef]
9. Erlich, I.; Shewarega, F.; Feltes, C.; Koch, F.W.; Fortmann, J. Offshore Wind Power Generation Technologies. *Proc. IEEE* **2013**, *101*, 891–905. [CrossRef]
10. Gao, Z.; Liu, X. An Overview on Fault Diagnosis, Prognosis and Resilient Control for Wind Turbine Systems. *Processes* **2021**, *9*, 300. [CrossRef]
11. Kaldellis, J.; Apostolou, D. Life cycle energy and carbon footprint of offshore wind energy. Comparison with onshore counterpart. *Renew. Energy* **2017**, *108*, 72–84. [CrossRef]
12. Anuta, H.; Ralon, P.; Taylor, M.; La Camera, F. *Renewable Power Generation Costs in 2018*; IRENA: Abu Dhabi, United Arab Emirates, 2019.
13. Watson, S.; Moro, A.; Reis, V.; Baniotopoulos, C.; Barth, S.; Bartoli, G.; Bauer, F.; Boelman, E.; Bosse, D.; Cherubini, A.; et al. Future emerging technologies in the wind power sector: A European perspective. *Renew. Sustain. Energy Rev.* **2019**, *113*, 109270. [CrossRef]
14. Sun, X.; Huang, D.; Wu, G. The current state of offshore wind energy technology development. *Energy* **2012**, *41*, 298–312. [CrossRef]
15. Anaya-Lara, O.; Tande, J.O.; Uhlen, K.; Merz, K. *Offshore Wind Energy Technology*; Wiley: Hoboken, NJ, USA, 2018.
16. Ahmad, H. *Offshore Wind Park Connection to an HVDC Platform, without Using an AC Collector Platform*; Gotl Univ Sweden; 2012; Available online: http://www.diva-portal.org/smash/get/diva2:617719/FULLTEXT01.pdf (accessed on 1 March 2021).
17. Ackermann, T.; Ancell, G.; Borup, L.; Eriksen, P.; Ernst, B.; Groome, F.; Lange, M.; Mohrlen, C.; Orths, A.; O'Sullivan, J.; et al. Where the wind blows. *IEEE Power Energy Mag.* **2009**, *7*, 65–75. [CrossRef]
18. Bilgili, M.; Yasar, A.; Simsek, E. Offshore wind power development in Europe and its comparison with onshore counterpart. *Renew. Sustain. Energy Rev.* **2011**, *15*, 905–915. [CrossRef]
19. Gonzalez-Rodriguez, A.G. Review of offshore wind farm cost components. *Energy Sustain. Dev.* **2017**, *37*, 10–19. [CrossRef]
20. Snyder, B.; Kaiser, M.J. Ecological and economic cost-benefit analysis of offshore wind energy. *Renew. Energy* **2009**, *34*, 1567–1578. [CrossRef]
21. Bórawski, P.; Bełdycka-Bórawska, A.; Jankowski, K.J.; Dubis, B.; Dunn, J.W. Development of wind energy market in the European Union. *Renew. Energy* **2020**, *161*, 691–700. [CrossRef]
22. Tang, L.; HVDC Technologies & ABB Experience. DOE Workshop—Applications for High-Voltage Direct Current Transmission Technologie. Available online: https://fdocument.org/document/le-tang-abb-april-22-2013-hvdc-technologies-abb-technologies-abb-experience.html (accessed on 12 May 2021).
23. Ryndzionek, R. Sienkiewicz, Łukasz Evolution of the HVDC Link Connecting Offshore Wind Farms to Onshore Power Systems. *Energies* **2020**, *13*, 1914. [CrossRef]
24. Ruddy, J.; Meere, R.; O'Donnell, T. Low Frequency AC transmission for offshore wind power: A review. *Renew. Sustain. Energy Rev.* **2016**, *56*, 75–86. [CrossRef]
25. Qin, N.; You, S.; Xu, Z.; Akhmatov, V. Offshore wind farm connection with low frequency AC transmission technology. In Proceedings of the 2009 IEEE Power & Energy Society General Meeting, Calgary, AB, Canada, 26–30 July 2009; pp. 1–8.
26. Sharifabadi, K.; Nee, H.; Norrga, S.; Teodorescu, R.; Harnefors, L. Design and Optimization of MMC-HVDC Schemes for Offshore Wind-Power Plant Application. In *Design, Control and Application of Modular Multilevel Converters for HVDC Transmission Systems*; Wiley: Hoboken, NJ, USA, 2016; pp. 283–304.
27. Nasiri, M.; Milimonfared, J.; Fathi, S. A review of low-voltage ride-through enhancement methods for permanent magnet synchronous generator based wind turbines. *Renew. Sustain. Energy Rev.* **2015**, *47*, 399–415. [CrossRef]

28. Wu, Y.-K.; Chang, S.-M.; Mandal, P. Grid-Connected Wind Power Plants: A Survey on the Integration Requirements in Modern Grid Codes. *IEEE Trans. Ind. Appl.* **2019**, *55*, 5584–5593. [CrossRef]
29. Giddani, O.A.; Adam, G.P.; Anaya-Lara, O.; Burt, G.; Lo, K.L. Control strategies of VSC-HVDC transmission system for wind power integration to meet GB grid code requirements. *SPEEDAM* **2010**, 385–390. [CrossRef]
30. Lu, S.-D.; Wang, M.-H.; Tai, C.-Y. Implementation of the Low-Voltage Ride-Through Curve after Considering Offshore Wind Farms Integrated into the Isolated Taiwan Power System. *Energies* **2019**, *12*, 1258. [CrossRef]
31. Xie, Z.; Zhang, X.; Zhang, X.; Yang, S.; Wang, L. Improved ride-through control of DFIG during grid voltage swell. *IEEE Trans. Ind. Electron.* **2014**, *62*, 1. [CrossRef]
32. Liu, X.; Li, X.; Jiao, D. Theoretical Study on Control Strategy of Grid-Connected High Voltage Ride Through in Doubly-Fed Wind Farm. *IEEE Access* **2019**, *7*, 107453–107464. [CrossRef]
33. Kyaw, M.M.; Ramachandaramurthy, V. Fault ride through and voltage regulation for grid connected wind turbine. *Renew. Energy* **2011**, *36*, 206–215. [CrossRef]
34. Dragan, J.; Khaled, A. *High. Voltage Direct Current Transmission: Converters, Systems and DC Grids—Dragan Jovcic, Khaled Ahmed*; John Wiley & Sons: Hoboken, NJ, USA, 2015.
35. Li, P.; Hu, W.; Hu, R.; Huang, Q.; Yao, J.; Chen, Z. Strategy for wind power plant contribution to frequency control under variable wind speed. *Renew. Energy* **2019**, *130*, 1226–1236. [CrossRef]
36. Perveen, R.; Kishor, N.; Mohanty, S.R. Off-shore wind farm development: Present status and challenges. *Renew. Sustain. Energy Rev.* **2014**, *29*, 780–792. [CrossRef]
37. Blasco-Gimenez, R.; Añó-Villalba, S.; Rodríguez-D'Derlée, J.; Bernal-Pérez, S. Diode based HVDC link for the connection of large off-shore wind farms with self start capability. In Proceedings of the 2011 14th European Conference on Power Electronics and Applications, Barcelona, Spain, August 30 –1 September 2011; pp. 1–9.
38. Cheah, M. Offshore Wind Integration through High Voltage Direct Current Systems. Available online: https://orca.cf.ac.uk/101463/1/2016CheahMPhD.pdf (accessed on 5 April 2021).
39. Korompili, A.; Wu, Q.; Zhao, H. Review of VSC HVDC connection for offshore wind power integration. *Renew. Sustain. Energy Rev.* **2016**, *59*, 1405–1414. [CrossRef]
40. Ibrahim, A.O.; Nguyen, T.H.; Lee, D.-C.; Kim, S.-C. A Fault Ride-Through Technique of DFIG Wind Turbine Systems Using Dynamic Voltage Restorers. *IEEE Trans. Energy Convers.* **2011**, *26*, 871–882. [CrossRef]
41. Jerkø, A. Reactive Power and Voltage Control of Offshore Wind Farms. 2014 MS Thesis, published by NTNU-Trondheim. Available online: https://ntnuopen.ntnu.no/ntnu-xmlui/bitstream/handle/11250/257852/745186_FULLTEXT01.pdf?sequence=1 (accessed on 10 January 2021).
42. Robinson, J.; Jovcic, D.; Joos, G. Analysis and Design of an Offshore Wind Farm Using a MV DC Grid. *IEEE Trans. Power Deliv.* **2010**, *25*, 2164–2173. [CrossRef]
43. Chen, W.; Huang, A.Q.; Li, C.; Wang, G.; Gu, W. Analysis and Comparison of Medium Voltage High Power DC/DC Converters for Offshore Wind Energy Systems. *IEEE Trans. Power Electron.* **2012**, *28*, 2014–2023. [CrossRef]
44. Veilleux, E.; Lehn, P.W. Interconnection of Direct-Drive Wind Turbines Using a Series-Connected DC Grid. *IEEE Trans. Sustain. Energy* **2014**, *5*, 139–147. [CrossRef]
45. Guan, M. A Series-Connected Offshore Wind Farm Based on Modular Dual-Active-Bridge (DAB) Isolated DC–DC Converter. *IEEE Trans. Energy Convers.* **2019**, *34*, 1422–1431. [CrossRef]
46. Bidadfar, A.; Saborío-Romano, O.; Sakamuri, J.N.; Akhmatov, V.; Cutululis, N.A.; Sørensen, P.E. Coordinated Control of HVDC and HVAC Power Transmission Systems Integrating a Large Offshore Wind Farm. *Energies* **2019**, *12*, 3435. [CrossRef]
47. Renaudin, F. Integration and stability of a large offshore wind farm with hvdc transmission in the norwegian power system. Available online: https://ntnuopen.ntnu.no/ntnu-xmlui/bitstream/handle/11250/256606/348739_FULLTEXT01.pdf?sequence=2 (accessed on 3 April 2021).
48. Kirby, N.M.; Luckett, M.J.; Xu, L.; Siepmann, W. HVDC transmission for large offshore windfarms. In Proceedings of the Seventh International Conference on AC and DC Transmission, London, UK, 28–30 November 2001.
49. Jallad, J.; Mekhilef, S.; Mokhlis, H. Frequency Regulation Strategies in Grid Integrated Offshore Wind Turbines via VSC-HVDC Technology: A Review. *Energies* **2017**, *10*, 1244. [CrossRef]
50. Watson, N.R.; Watson, J.D. An Overview of HVDC Technology. *Energies* **2020**, *13*, 4342. [CrossRef]
51. Flourentzou, N.; Agelidis, V.G.; Demetriades, G.D. VSC-Based HVDC Power Transmission Systems: An Overview. *IEEE Trans. Power Electron.* **2009**, *24*, 592–602. [CrossRef]
52. Alekseeva, N.; Bubnova, A.; Chudny, V.; Tikhodeev, N. Reliability analysis and comparison of long-distance HVAC and HVDC power transmission lines. *Proc. Int. Conf. Power Syst. Technol.* **2003**, *1*, 375–379.
53. Dziendziel, A.; Kocot, H.; Kubek, P. Construction and Modeling of Multi-Circuit Multi-Voltage HVAC Transmission Lines. *Energies* **2021**, *14*, 421. [CrossRef]
54. Kalair, A.; Abas, N.; Khan, N. Comparative study of HVAC and HVDC transmission systems. *Renew. Sustain. Energy Rev.* **2016**, *59*, 1653–1675. [CrossRef]
55. Alassi, A.; Bañales, S.; Ellabban, O.; Adam, G.; MacIver, C. HVDC Transmission: Technology Review, Market Trends and Future Outlook. *Renew. Sustain. Energy Rev.* **2019**, *112*, 530–554. [CrossRef]

56. Kamalapur, G.D.; Arakeri, K. A Comparative Study of Monopolar and Bipolar HVDC Transmission Systems. *Eur. J. Adv. Eng. Technol.* **2020**, *7*, 21–26.
57. Warnock, J.; McMillan, D.; Pilgrim, J.; Shenton, S. Failure Rates of Offshore Wind Transmission Systems. *Energies* **2019**, *12*, 2682. [CrossRef]
58. Ardelean, M.; Minnebo, P. HVDC submarine power cables in the world. *Jt. Res. Cent.* **2015**, 1–79. [CrossRef]
59. Walling, R.A. *Preliminary Evaluation of the System Compatibility of an HVDC Transmission Alternative for the Beseck-East Devon Segment of the Middletown-Norwalk Transmission Project*; GE Energy: Schenectady, NY, USA, 2004; pp. 1–19.
60. Ackermann, T. *Wind Power in Power Systems*; Wiley Online Library: Chichester, UK, 2005.
61. Saad, M. Challenges of HVDC Transmission Systems for Large Offshore Wind Power Plants. *SSRN Electron. J.* **2017**. [CrossRef]
62. Oni, O.E.; Davidson, I.; Mbangula, K.N. A review of LCC-HVDC and VSC-HVDC technologies and applications. In Proceedings of the 2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC), Florence, Italy, 7–10 June 2016; pp. 1–7.
63. Dorn, J.; Huang, H.; Retzmann, D. *Novel Voltage-Sourced Converters for HVDC and FACTS Applications*; Siemens AG: München, Germany, 2007.
64. Alyami, H.; Mohamed, Y. Review and development of MMC employed in VSC-HVDC systems. In Proceedings of the 2017 IEEE 30th Canadian Conference on Electrical and Computer Engineering (CCECE), Windsor, ON, Canada, April 30 –3 May 2017; pp. 1–6.
65. Lazaridis, L. Economic Comparison of HVAC and HVDCSolutions for Large Offshore Wind Farms under Special Consideration of Reliability. Available online: https://www.diva-portal.org/smash/get/diva2:609080/FULLTEXT01.pdf (accessed on 5 December 2020).
66. Bahrman, M.P.; Johnson, B.K. The ABCs of HVDC transmission technologies. *IEEE Power Energy Mag.* **2007**, *5*, 32–44. [CrossRef]
67. Kucuksari, S.; Erdogan, N.; Cali, U. Impact of Electrical Topology, Capacity Factor and Line Length on Economic Performance of Offshore Wind Investments. *Energies* **2019**, *12*, 3191. [CrossRef]