Voltage-Source-Converter-Based High Voltage Direct Current Transmission System

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Long-distance offshore wind power transmission systems utilize multi-terminal high voltage direct current (MT-HVDC) connections based on voltage source converters (VSCs). In addition to having the potential to work around restrictions, the VSC-based MT-HVDC transmission system has significant technical and economic merits over the HVAC transmission system. Offshore wind farms (OWFs) will inevitably grow because of their outstanding resistance to climate change and ability to provide sustainable energy without producing hazardous waste. Due to stronger and more persistent sea winds, the OWF often has a higher generation capacity with less negative climate effects. The majority of modern installations are distant from the shore and produce more power than the early OWF sites, which are situated close to the shore.

Keywords: HVDC ; LCC ; offshore ; onshore ; VSC ; renewable energy

1. Introduction

High voltage direct current (HVDC) systems play a vital role in facilitating the transfer of huge amounts of electrical power generated by offshore wind farms (OWFs) to the grid. To link offshore wind power (OWP) to the local grid, multi-level voltage source converter (MVSC) topologies have gained increased attention in recent years [1]. An HVDC system with quick and flexible power flow regulation ensures electrical grid reliability and security. Furthermore, OWFs are typically placed far from the local grid. As a result, OWFs require long transmission lines (TLs) to transport the generated electricity to consumers. The adoption of high voltage alternating current (HVAC) technology for such an offshore grid is not feasible, since the reactive power flow increases with transmission distance due to line capacitances, resulting in large line losses. As a result, HVDC TLs are regarded as critical technologies for this purpose. The capacity to independently control active and reactive power flow in each of the AC grids is the key feature of the VSC-HVDC transmission system [2][3].

Power is typically transported from the generation side to the main grid. HVAC and HVDC are two methods for transmitting power to the national grid. In comparison to HVAC, HVDC is considered to be suited for transporting bulk power over vast distances. HVDC TLs based on line-commutated converters (LCCs) or voltage source converters (VSCs) are both thought to be more practical than HVAC. Furthermore, due to technological advancements and long-distance cost comparison, HVDC networks are regarded as economically sustainable [4]. The distance between WFs and coastal areas is also rapidly increasing. Some offshore wind power plants (OWPPs) that are currently operational use underwater cables that extend up to 200 km. According to available studies, HVDC and HVAC cost the same over a distance from 150 to 200 km. HVDC becomes more cost-effective as transmission distance rises. HVAC undersea cables' cumulative capacitive current also limits their use in long-distance transmission. As wind farms migrate further away from coastal locations, HVDC becomes the only viable option [5][6][7]. Despite the rapid improvement of OWP, it is currently confronted with issues such as WT noise and land availability [8]. OWFs have sparked global interest due to the vast untapped wind potential and improved wind regimes. Currently, OWFs are evolving toward high-capacity and long-distance transmission, while the connection of OWFs to the grid has introduced new difficulties for technology and the economy. As a result, appropriate power transmission systems that can connect big OWFs to onshore power grids over long distances must be investigated [9]. Various transmission schemes for massive OWF integration have been developed and discussed over the last 20 years, with the majority of research focusing on the operational viability and economics of each transmission system [10]. **Figure 1** depicts a scenario of a distinctive HVDC system utilized to connect an OWPP with the onshore power infrastructure. Because the larger transformer's voltage perspective is too huge to fit within a cross-section of a tower, WT transformers normally increase the voltage from 690 V to 25,000–40,000 V. The turbine side converter typically has a power rating from 5 to 10 MW. The majority of collection systems use 33 to 36 kV AC to capture WF energy [11][12]. The offshore platform and the WT output are connected by high-voltage undersea cables. An HV transformer at the OWF elevates the collecting system voltage level from 132,000 to 150,000 V in preparation for the transmission and connection to the onshore grid using a DC line, which is usually 320,000 V [13][14][15].

Figure 1. Typical scenario for using HVDC technology to connect offshore wind power to the main AC network.

Despite the steady advancement of HVDC technology over the last decade, it has to be tailored to the unique requirements of offshore projects. HVDC has additional issues, particularly for OWF grid integration, for instance:

(1) **Efficiency:** Offshore projects can be more affordable, minimizing power losses in the system.

(2) **Harsh environment:** There is only restricted maintenance access.

(3) **Footprint:** The size and weight of HVDC stations have a substantial impact on the costs of investment.

(4) **Reliability:** The cost of unharvested energy due to transmission system outages can be critical in determining the viability of an offshore project [16].

In contrast, many existing power grids throughout the world, especially in Europe, find it difficult to accommodate 8000×10^6 W DC electricity at AC grids' single point via LCC HVDC. Future VSC HVDC lines of this rating, on the other hand, are more capable of connecting to weak networks [12].

The gas-insulated line (GIL), as derived from geographic information system (GIS), requires only the basic performance of the electrical grid, i.e., there is no switchgear, dynamic thermal stability, and insulation; hence, it has observable consistency merits over both overhead lines with a high capability for power transmission and long-distance lines. The high prices and technical requirements of the manufacture design, as well as the protracted project term, are significant difficulties for the actual project. A new hybrid DC transmission model in China combines the improved performance of VSC-HVDC and LCC-HVDC technologies while being less expensive than current VSC HVDC transmission [17]. However, the existing transmission power is decided by the VSC HVDC side, and power flow reversal is difficult to achieve because of the voltage polarity that must be altered in the LCC converter station [12]. Nonetheless, it is a new trend of innovation that is becoming an alternative to OWP transmission, though it has not been used due to a lack of research, except in China.

2. HVDC Converter Technology

Due to its inherent drawbacks, such as the inability to change voltage without transformers, the need for conversion equipment, the requirement for reactive power, harmonics, and the complexity of control, direct current transmission has only recently found widespread application [18]. However, due to the development of remote wind energy technology and the need for linking isolated asynchronous HVAC systems, HVDC transmission is currently regaining prominence [19][20][21][22][23][24]. HVDC transmission installations are happening more quickly than ever before. The following are just a few possible advantages of HVDC transmission:

- Compared to AC cables, DC cables do not exhibit the skin effect or the proximity effect.
- Notably, in long-distance, high-voltage applications, transmission losses are reduced by a DC cable's lack of a large reactive charging current.
- Due to the substantial transmission loss, it is challenging for an AC system to utilize distant resources like offshore wind generation.
- Effective active power control is present in DC systems [25].

Because they may be utilized to connect several AC grids [26] using DC networks, VSC-HVDC systems enable us to take advantage of a multidirectional power flow [27][28]. Since HVDC systems have several advantages over HVAC schemes, including the asynchronous connection of multiple independent AC networks, the absence of reactive power in the DC link, and lower power losses [29][30], they can help to build a more dependable power network and smarter grids [31][32]. Compared to MVAC systems, DC-collecting systems provide more benefits. DC cables lead to reduced losses and do not require reactive power correction, as was previously indicated for HVDC transmission. The substitution of large, heavy, low-frequency transformers with DC to DC converters outfitted with lighter, smaller, and medium-frequency transformers has another benefit [33]. The possible reduction in weight and size is crucial in applications of offshore wind, since this is somewhere where supporting structures and storage space for the equipment are expensive and limited. Although there are currently no fully operating all-DC wind power plants (WPPs) with collection of the DC systems deployed, the introduction of DC technology still faces many hurdles [34][35].

2.1. LCC

LCC, often known as “classical HVDC”, are the “oldest” and most used thyristor-based systems [36]. The well-known and advanced LCC converter technology is depicted in **Figure 2**. LCC converters have the advantage of having a lot of operating expertise and being reasonably priced. The high voltage of up to 600 kV and high power ratings of thyristor-based converters are their distinguishing features. Active power control and a robust AC grid were necessities for the thyristor technology. Transistors were widely used, which changed HVDC technology and made LCC less practical for use in offshore applications.

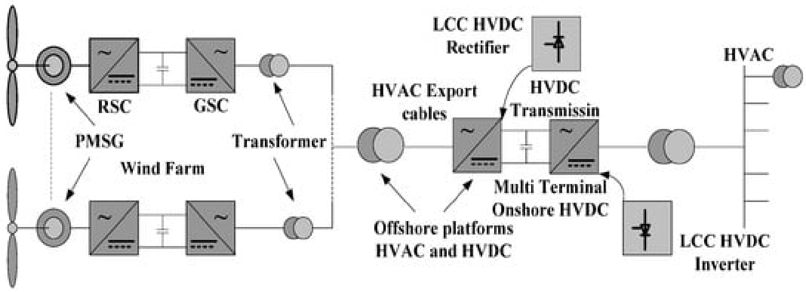

Figure 2. Schematics for the transmission of offshore wind energy in detail using LCC HVDC technology [25].

2.2. VSC

The VSC using IGBT transistors has been a common terminal for HVDC since 1999. This approach was used in the first HVDC commercial project using an OWF [37][38]. The numerous benefits of the VSC technology used in the HVDC systems depicted in **Figure 3** include compactness, the ability to join the weak AC system, separate regulation of reactive and active power, and black start capabilities [39][40][41][42][43].

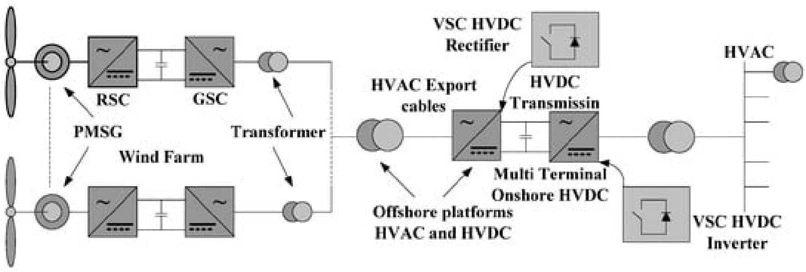

Figure 3. Transmission of offshore wind energy in detail using VSC-based HVDC technology [5].

2.3. Offshore Turbine Converter Topologies

Many turbine topologies have been suggested to fit the series architecture, which is divided into two categories as follows [5]:

(1) LCC-based turbine converters or CSC with PWM.

(2) Interface DC/DC buck between an HVDC system and turbine VSC

DC/DC buck interface between the turbine VSC and HVDC system.

3. VSC-HVDC vs. LCC-HVDC

Current-source converters (CSCs), as well known as the LCC-utilizing thyristor, and VSC HVDC, using IGBT transistors, are now the two main HVDC technologies. Both are suited for a variety of applications. CSC-HVDC technology outperforms conventional AC alternatives in terms of efficiency and power transfer capacity for long-distance, high-capacity TSs. VSC-based HVDC is the preferred technology for power transmission (PT) from OPPs with constrained space because it offers superb reactive and active power regulation capabilities. Mercury-arc valves, a technology predominantly developed in Sweden and Germany during the 1930s, are a component of modern HVDC systems. In the past, there have been commercial uses for an HVDC system between Moscow and Kashira in the Soviet Union in 1951, and a 20 MW, 100 kV link between the island of Gotland and the Swedish mainland [44]. Since the 1970s, thyristor valves have only recently been utilized in HVDC applications. The mercury-arc technology has largely overcome its drawbacks. The Eel River Converter Station in Canada became the first LCC-HVDC to be operational in 1972. The IGBT valves used in VSCs provided an upgrade over thyristor valves. The first commercial VSC HVDC connection between the Gotland Islands and mainland Sweden was launched by ABB in 1999. It was made up of underwater cables with a 50 MW rating and an 80 kV rating [45][46].

4. VSC-Based HVDC Scheme

The IGBT technology is used by VSC. Rainer Marquardt developed this idea in 2003 [47]. In the event of a black start, it generates its AC voltages, enabling the current to be turned on and off as necessary regardless of the AC voltage. Its converters use pulse width modulation, which allows for simultaneous amplitude and phase angle modification while maintaining a constant voltage. Due to its high level of flexibility and inherent capacity to adjust both its reactive and active power, it is more beneficial in locations with metropolitan power networks. The majority of converter stations for the VSC-HVDC technology employ multilayer converter circuits [48][49], as seen in **Figure 4** and **Figure 5** [50].

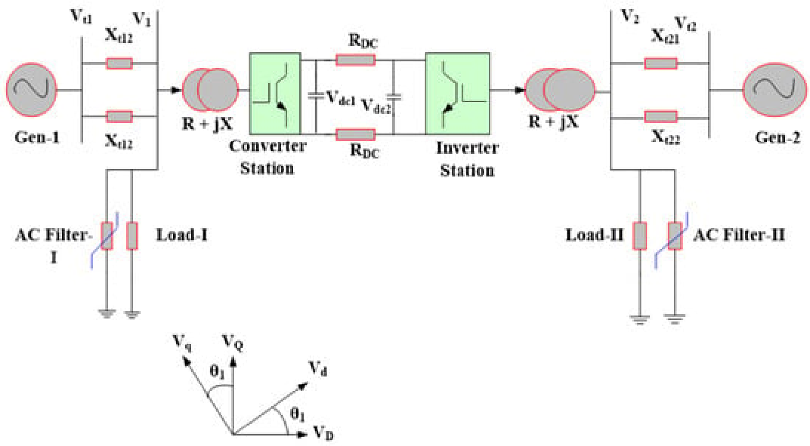

Figure 4. Design of a VSC-HVDC system.

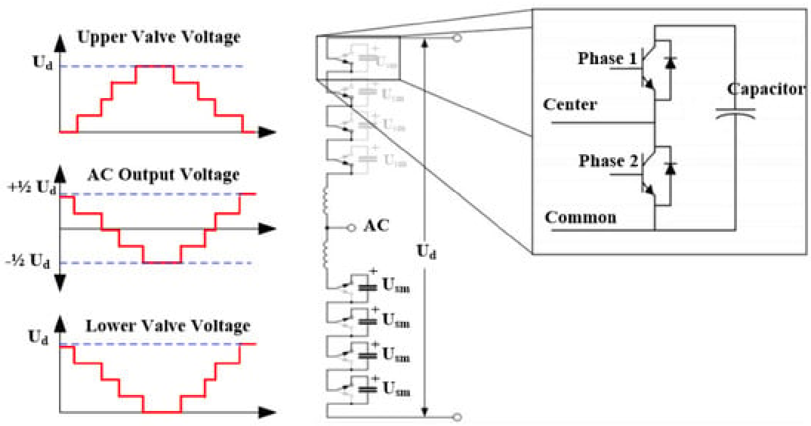

Figure 5. Modular multilevel converter.

VSC-Based HVDC for OWFs

One of the solutions to the problem of fulfilling rising urban and industrial demands is offshore wind energy systems [23][51][52]. OWFs can generate more power and operate more consistently than land-based systems because they have more consistent characteristics and stronger winds than on land [53]. Larger wind tribunes are brought on by the viability of

OWFs, but the complexity of maintenance and high installation costs present challenges to reducing O&M expenses [53][54][55]. With growing distances from the shore, wind turbine technology is facing additional difficulties like long-distance HVDC undersea cables and the security of turbine equipment [56].

5. MT-HVDC Transmission Systems

Several converters are coupled to a single HVDC circuit to form a VSC-based MT-HVDC system [57]. Squirrel cage induction generators (SCIGs) [58] are examples of central power converters used for a group of WTs, while double-fed induction generator (DFIG) WFs use individual power converters in each WT [59][60]. The so-called WF rectifiers are used to link WFs to the shared HVDC circuit. Through grid-side inverters, the HVDC circuit power is introduced into the terrestrial AC grid [61]. The MT DC system's single-line diagram is depicted in **Figure 6**. The system includes two grid-side VSCs (GSVSC) and four terminals with wind farm VSCs (WFVSC). The suggested MT DC system, however, can be used with any quantity of terminals and any mix of GSVSCs and WFVSCs. Although other WT technologies, such as those based on the PMG, can also be employed, the two wind farms that are being discussed here are all based on DFIGs and separated from one another. The four terminals are connected at a single point in **Figure 7**, but other connection patterns are equally applicable.

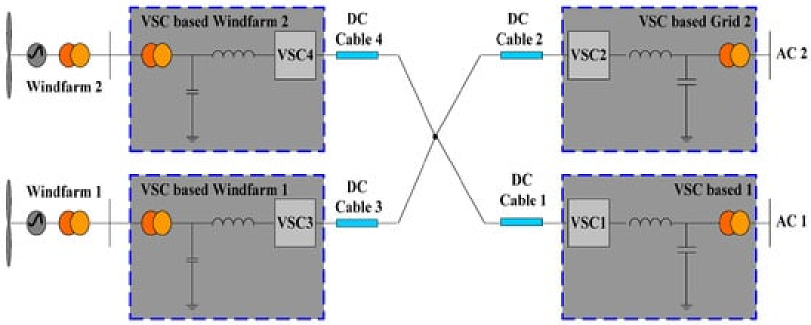

Figure 6. MT VSC HVDC system integration with a single-line diagram.

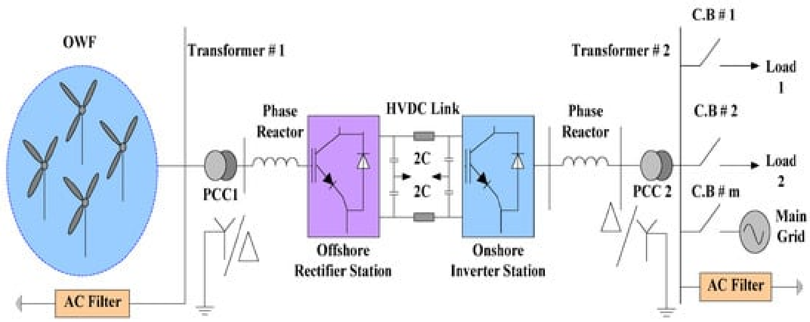

Figure 7. OWPP grid integration schematic using VSC HVDC.

Energy from the WFs is gathered and converted to DC by the WF VSCs. DC wires are then used to deliver the DC power to the GSVSCs. The two WFVSCs also regulate the respective wind farm networks' AC voltages and frequencies. According to a predetermined arrangement, the two GSVSCs convert the DC power back to the respective AC grid.

6. Economic Assessment of HVDC OWFs

The objective of the calculation of cost is to evaluate the capital expenditure (CAPEX) for the configurations under investigation. OWFs are made up of a sizable number of parts. Only the major cost drivers are taken into account when estimating CAPEX. These are the onshore substation, the collection cables, the offshore substation with transformers and switchgear, the high-power converters (HPEs), the export cables, and the wind turbines, including the drive train and foundation. Reactive compensation is necessary for all AC wind farms, and expenses also included are any extra platforms and shunt reactors. All cost data must be normalized because they are accessible for multiple years and are provided in different currencies. The usual interchange rate from the beginning of the year, as acquired from the cost data, is used to convert currencies.

6.1. Operational Costs

Based on the indicated median values, the yearly operational cost (OPEX) of every component was calculated as a percentage of the CAPEX. The net present value of the OPEX is obtained by applying the equation to discount the yearly OPEX over the lifetime of the wind farm (WF) [62].

$$\mathrm{Opex_{NPV}} = \frac{\sum_{n=1}^{N} \mathrm{O_n}}{\mathrm{d}}\left(1 - \frac{1}{(1+\mathrm{d})^{\mathrm{L_T}}}\right) \tag{1}$$

where On is the yearly OPEX of component n,d is the concession rate, LT is the lifetime in existence, and OpexNPV is the net present value of the operational costs. A concession charge of 6% and a lifespan of 324.222 months are taken into account in the basic scenario [62][63].

6.2. VSC-Based HVDC Transmission Cost Calculation

Regarding VSC-based HVDC transmission, the calculation performed to gain an idea of the overall cost of KVSC consists of Kcap(VSC) for capital expenditures, Kopex(VSC) for operation and maintenance, and Kloss(VSC) for less cost [63].

$$\mathrm{K_{VSC}} = \mathrm{K_{cap(VSC)}} + \mathrm{K_{opex(VSC)}} + \mathrm{K_{loss(VSC)}} \tag{2}$$

6.2.1. Capital Costs

Kcap(VSC) is made up of two costs: Kstation(VSC) for the foundation of the converter station and Kcable(VSC).

$$\mathrm{K_{cap(VSC)}} = \mathrm{K_{station(VSC)}} + \mathrm{K_{cable(VSC)}} \tag{3}$$

6.2.2. Operation and Maintenance Costs

Equation (3), which is used in the study, yields the Kopex(VSC); the B of the DC submarine cable equals 0.5%, I is 5%, and n is 240 months.

6.2.3. Cost of Losses

The converter station loss Ksub(loss)

and line loss Kline(loss) make up the loss expenses for the Kloss(VSC) loss rate for converter stations. Psub loss measures how much of the transmitted power is lost at the station. Two converter stations' Psub(loss) ranges from 1.6 to 2.4%, and Zhen notes that Psub(loss)
is between 1 and 2 percent [64].

6.2.4. Foundation Costs for Converter Stations

The entire infrastructure investment for each converter station is the VSC-based converter station cost. In addition, the expected additional expenses for IGBT technology are the converter station layout's civil construction costs, the converter station's DC capacitor and AC filter costs, and the converter station's converter controller and reactor costs. The cost of a converter station based on VSC is then calculated as a percentage of the capacity of each converter station, denoted by P.

$$\mathrm{C_{station(VSC)}} = \mathrm{C_{perMW}}.\,2\mathrm{P} \tag{4}$$

6.2.5. Cost of Cable Installation and Foundation

The DC cable's VSC-based cost is determined by transmission distance, much like the cost for the HVAC cable is.

$$\mathrm{C_{cable(VSC)}} = 2\left(\mathrm{P_1} + \mathrm{P_2}\right)\mathrm{L} \tag{5}$$

where P1 and P2 represent the cost and installation expenses for a DC cable per kilometer [19]. Since the DC voltage waveform is not susceptible to peak/effective ratio underutilization, the cost of the cables in the VSC-HVDC option is significantly lower than that of AC alternatives. The transmission capability ratio of DC cables to AC cables can be calculated using Equation (6).

$$\frac{\mathrm{P_{max.-DC}}}{\mathrm{P_{max.-AC}}} = \frac{2\mathrm{V_{dc}I_{dc}}}{3\mathrm{V_{ac}I_{ac}pf}} = \frac{2\sqrt{2}\mathrm{V_{ac}I_{ac}}}{3\mathrm{V_{ac}I_{ac}pf}} = \frac{2\sqrt{2}}{3} \approx 1 \tag{6}$$

As observed in (6), DC solutions only require two polar wires for a given power transmission, but AC solutions require three. Compared to AC choices, the cost of the cable would be substantially lower with VSC-HVDC. This benefit might be more apparent if the reactive power and skin impact are factored, as in the work of Xiang [65].

6.3. An Economic Comparison of HVAC and HVDC Systems

Since every project has unique situations and features, including line distance, rated power, topography, and utilized technology, it is challenging to estimate the accurate price of HVDC. On the other hand, a broad estimate can be derived using the information from earlier initiatives. The DC grid interconnection back-to-back plan of Chongqing-Hubei in China was the first clarified VSC HVDC line, encompassing a total distance of 1711 km with a maximum voltage capability of 420,000 V and a main power transmission capacity of 5000×106 W [66].

Three cost factors come into play when comparing HVAC and HVDC economically:

- Cost of line;
- Cost of losses;
- Cost of terminal.

The overall cost is split into two parts: the expense of building the infrastructure and the expense of maintaining the system once it is operational. This considers the cost of the investment, the cost of the poles, wires, insulation, converter stations, and the use of the right of way. Financial losses are specifically included in the operating cost. Given that both AC and DC use the same types of insulation and conductors, AC requires three conductors while DC just requires two [67]. DC poles become a less costly route as a result, using less conductor and insulator material [68]. Calculations for AC and DC transmission line losses look like this:

$$\text{Power Transmitted by DC} = \mathrm{V_d I_d} \tag{7}$$

$$\text{Power Transmitted by AC} = 3\mathrm{V_a I_a}\cos\theta \tag{8}$$

$$\text{DC Power Loss} = 2\mathrm{I_d^2 R} \tag{9}$$

$$\text{AC Power Loss} = 3\mathrm{I_a^2 R} \tag{10}$$

By combining Equations (9) and (10) we obtain Equation (11).

$$2\mathrm{I_d^2R} = 3\mathrm{I_a^2R}, \mathrm{I_a I_d} = \sqrt{\frac{2}{3}} \tag{11}$$

If three-phase AC is substituted with DC, the same power transfer, conductor size, and power loss are assumed [69][70].

7. Summary

Offshore wind farms must comply with safety limits to ensure the stable operation of the system. The IEC and IEEE have established standards for the integration of offshore wind farms into electrical power systems. These standards cover a range of topics including design, installation, operation, and maintenance of OWFs. Additionally, the safe distance between WTs and the coast, shipping lanes, and other infrastructure are considered in the design process.

Some specific safety and performance standards for offshore wind farms include:

- IEC 61400-3 [71], which provides guidelines for the design, installation, operation, and maintenance of WT generators and WF control systems.
- IEEE 1547 [72], which covers the interconnection and interoperation of distributed energy resources within the electric power system.
- IEEE P2450 [73], which provides guidelines for the planning, design, installation, operation, and maintenance of WT generator systems, including the wind turbine, electrical equipment, and the wind farm control system.
- IEC 62271-110 [74], which covers the HVDC systems used to transmit power from OWFs to the onshore electrical grid.

It is important to note that compliance with these standards is not mandatory, but it is highly recommended as it ensures the safety of the equipment and the people who operate it, and also helps in the integration of the WFs into the existing power grid.

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