Key Issues and Challenges in Generation, Integration and Control of Offshore Wind Energy Conversion System

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Abstract
Offshore wind generation is gradually gaining importance in this green energy era. Its installation and controlled integration with grid pose several challenges. This paper comprehensively highlights the key issues and challenges related to the above problems as well as to the contingency concerns keeping in view of the pertinent grid-code requirements.
Keywords: High voltage AC (HVAC) or DC (HVDC), Line commutated converters (LCC), Voltage source converters (VSC), Multi-terminal VSC-HVDC (VSC-MTDC), Doubly Fed Induction Generator (DFIG).

Introduction

The wind power generation has become the fastest developing non-conventional energy resource over the last 20 years. Wind power leads in the transition away from fossil fuels and continues to be the most proficient source in terms of price, performance, and reliability. It is in a speedy evolution on the path of becoming a fully commercialized, unsubsidized technology. The commercial wind power installations have tremendously increased by around 40 times, with annual installations increased up to 63 GW in the year 2015 in eighty different countries and the overall generation capacity increased to 433 GW. The environmental benefits of wind power generation do not cause air pollution and CO_2 emission. Offshore became a new interest in wind energy generation. The statistical analysis reflects that offshore wind energy will increase from 3 GW to 75 GW by 2020 [1]. Offshore wind farms are planned for capacities above 1000 MW in a present scenario. Many countries in Europe, Asia and North America are ahead in this industry.

As per the report of Global Wind Energy Outlook [1], twenty-eight countries have greater than 1 GW installation capability, including seventeen in Europe, four in Asia-Pacific (China, India, Australia, and Japan), three in Latin America (Brazil, Chile, and Uruguay), three in North-America (Canada, Mexico and United States), and one in South Africa. Out of eighty countries, eight countries have more than 10 GW installed capacity. In the year 2017, China was having the largest market in terms of the annual installations of wind energy with 188,392 MW, out of which 28,259 MW (15%) was through offshore wind farms. Second in number was the US with 89,077 MW of wind generation. Next, Germany with 56,132 MW of which 15998 MW (28.50%) was offshore based. It was ranked second in offshore installation. Figure 1 depicts the country-wise wind energy installation capacities in MW.

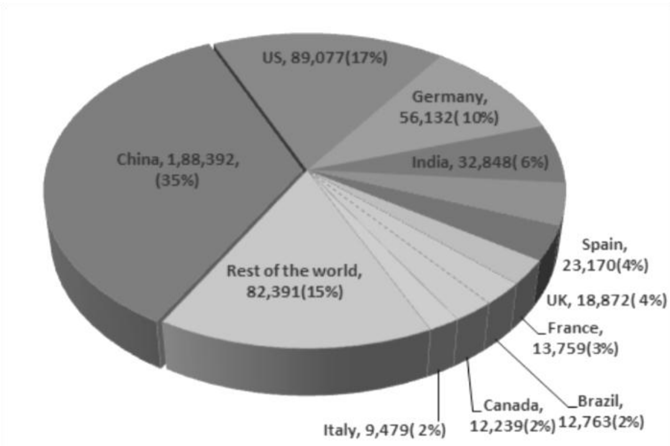

Figure1: Cumulative Annual Installation Capacity of wind energy in MW [1].

European Union plays a major role in offshore wind energy market having its first offshore installation in Denmark in the year 1991. Figure 2 represents the annual installation of wind energy in the European Union showing the share of offshore wind energy generation [1]. The maximum, newly grid-connected offshore capacity of 4,334 MW, was added in the Year 2017.

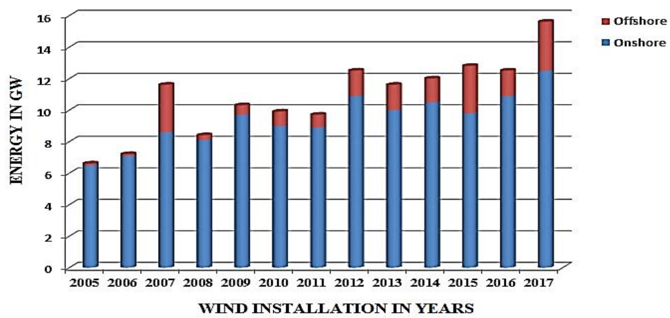

Figure2: Annual Installed Wind Energy Capacity in the European Union in Years 2005-2017(GW)

Installation

Installation of an offshore wind farm is a big challenge and the installation of wind turbine structure is completed in two stages, namely, foundation installation and turbine installation. Both are installed at different times. Initially, the construction of the foundation needs to be completed. Thereafter, turbine installation, including tower, nacelle, and rotor etc. are done. Installations are extremely dependent on the site parameters like water depth, wind speed, and sea-bed conditions. Site bathymetry (water depth), however, is the most important factor for offshore installation. Water depth can affect the project time duration and cost implication. For the existing or under construction offshore projects, the average water depth is up to 40 meters in the North Sea, Baltic Sea, and the Irish Sea region [2].

Sea-bed condition around the turbine location is also important because the poor sea-bed condition can cause sliding of legs and penetrate into the sea-bed which can spoil the whole offshore wind turbine structure. Environmental conditions are also taken into consideration for installation High wind speed, gust, snow, ice, ambient temperature, inadequate water depth, poor seabed conditions, visibility, and sea state are a few parameters which can affect the installation of an offshore wind energy system [2].

Foundation technology plays an important role in offshore wind farm design. Foundation installations are commonly designed according to sufficient and maximum wind speed, wind waves, water depth, and soil properties. Generally, mono-piles and gravity based structures are used in offshore wind farms. However, they become costlier with an increase in depth. Floating supported structures are more beneficial because they have better flexibility in construction and installation [3].

Wind Generation System

Generally, there are two types of wind generation system namely, fixed speed and variable speed wind generation system. Fixed speed wind turbines are simple and cheaper. But these turbines have to be more robust mechanically due to high structural loads. In fixed speed turbine, variation in wind speed can directly affect its drive train torque because its rotor speed cannot be varied. This result in power fluctuations and grid voltage fluctuations. Hence, variable speed wind generation systems become a viable industrial option [4].

In variable speed wind generation system, it is necessary to produce constant frequency electrical power from a variable speed source. Doubly fed induction generator (DFIG) is widely used in case of variable speed wind turbine system. DFIG wind energy system needs to employ power electronic based back to back converters to connect the generator rotor to the grid which controls reactive power and its real power oscillations under a grid fault which is lower in comparison to other wind energy generators. DFIG is much superior from conventional synchronous generators in terms of rotor angle stability. The use of back to back PWM converters and pitch control of rotor blades enables the variable speed operation. The variable speed wind turbine can generate 20-30% more power in comparison with the fixed speed wind turbine (FSWT) [5]. Direct-driven permanent magnet synchronous generator (PMSG) can also be used for generation in a wind energy system. PMSG does not require a gearbox system but the drawback of the direct drive PMSG is that its design is large and costly. It employs huge power electronic converters [4].

Grid Integration Methodology

It is noted that offshore wind farms are connected to the onshore electric grid radially via high voltage AC (HVAC) or DC (HVDC) via marine offshore cables. AC cables cannot be technically managed due to pre-dominant capacitance effect. For grid-connected offshore wind farm with capacities above 500 MW and the distance greater than 50 km, HVDC links are the most economical and preferable solution [6].

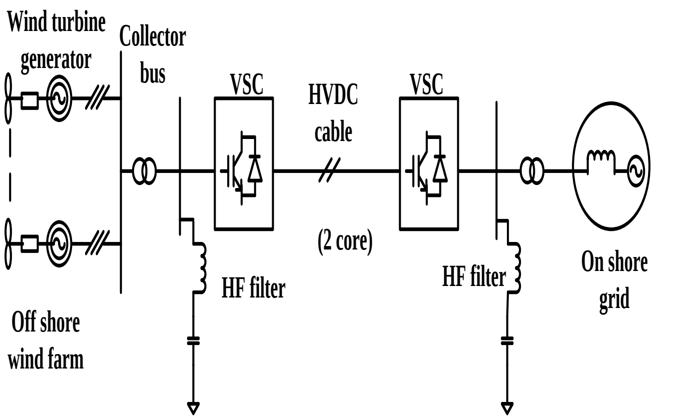

Figure3: Grid connected Offshore Wind farm using VSC HVDC Link

Voltage Source Converters (VSC) and Line Commutated Converters (LCC) are the most extensive and well-known technologies used in marine HVDC links. VSCs are based on Insulated Gate Bipolar Transistors (IGBTs), Gate Turn Off thyristors (GTOs) and can control active and reactive power independently. VSCs do not have commutation failure problems, however; they are about 60% greater in size compared to LCC station [7, 8].

For power capacities above 400MW, LCCs are more favorable due to their better power rating and minimal power losses. The Power handling capability of thyristor used in LCC-HVDC is greater in comparison to that of IGBT power devices used in VSC-HVDC. LCCs are the preferred solution in case of higher power losses and are less expensive compared to VSC-HVDC. But with the use of thyristor in LCCs some drawbacks arise in terms of reactive power consumption, commutation failure and large short-circuit capacity [9].For offshore wind farms, specifically, VSC offers a significant advantage over LCC because there is no need for an external commutation voltage during operation. LCC HVDC and VSC HVDC require huge offshore platform which is fed by a wind generator, ac-dc transmission converters, and step up transformer. This type of system has a disadvantage of high installation and servicing cost [10].The novel interconnecting approach for the offshore wind farm with series connected Pulse Width Modulated (PWM) based Current Source Converters (CSC) on generator and grid side are discussed in [12]. Series connections of CSCs are suitable for build-up of transmission voltage and it eliminates the need for offshore step-up transformer and HVDC transmission converters. This PWM CSC can offer a sinusoidal current with a fully controlled power factor. Protection from short circuit fault is provided by the dc link reactor of CSC. Today, the development of multi-terminal HVDC grids is the biggest challenge due to issues related to its operation, control, coordination and protection [12]. A hybrid configuration with the combination of conventional LCC -HVDC and the VSC is also used for the integration of offshore wind farms [9]. By the proposed approach, a fault can be handled by LCC rectifier and due to this VSC can overcome the stability problems easily.

Control Strategy

In this section control strategy of segregated components of a grid integration is discussed. Generally, DFIG driven wind turbine works on vector control concept. A stator flux field oriented scheme regulates the rotor current of DFIG through which the power flow to the grid is controlled. Combined control of an offshore wind farm connected with HVDC system is analysed by using an uncontrolled diode rectifier in [11] and [16]. The uncontrolled offshore rectifiers can produce grid forming capabilities. It can minimize losses and cost of offshore wind energy system by eliminating the STATCOM and transformer tap changers. But these rectifiers have some disadvantages that they cannot be used for longer to control the HVDC link current under grid faults.

The power-reduction control strategy with cluster technology for offshore wind farms is proposed in [12]. The dc grid of offshore wind farm consists of numerous clusters in which many wind turbines having dc output are connected parallel to each other. An offshore dc/dc converter collects the output of these clusters. This brings up the voltage to a level for transmission through HVDC link connected to the onshore ac grid.

HVDC-VSC with control strategy, comprising of two subsystems and a DC voltage controller, is discussed in [13] which can improve the fault ride through capability of the wind farm. The additional proposed dc controller is able to maintain the dc voltage of the HVDC link at a constant value of 150V. The AC voltage controller can support the grid voltage during faults. It also improves the fault ride through capability in steady state. Modulation index and shift angle are provided by AC and DC voltage control loops. This additional dc voltage control strategy has the ability to regulate the generator speed along with ac voltage of wind farm under the variation of wind speed.

Non-linear controller for improvement in the controlling action of VSC-HVDC transmission system is proposed in [15]. The input-output linearization and feedback linearization is based on nonlinear differential geometric techniques which can eliminate the non- linearity of the system and decouples the input control variables. It is noted that Digital Signal Processor (DSP) controller produces the sampling and control delays due to which the dynamic performance of the VSC is affected. So, a predictive current controller is used in [15] to eliminate the static and discretization errors. The predictive current controller can eliminate the sampling and control delays. It can also improve the current response and speed and reduces the input current harmonics in the offshore wind energy system. This predictive input-output linearization current controller [15] shows better performance in comparison of a traditional PI controller.

Sliding mode control scheme along with feedback linearization for VSC HVDC transmission link has been proposed in [17]. This control scheme can be considered for resilient AC system where voltage and frequency are constant. Sliding mode control scheme is a robust control approach having a fast-dynamic response and has ability to solve tracking and stabilization problems in nonlinear systems. This approach has an invariance property for parametric uncertainties. It provides damping to the generator oscillation and reduces the overshoot for an operating condition.

In [14], an AC-AC matrix converter is used in place of conventional back to back converter to control the DFIG wind energy system. This matrix converter topology provides bi-directional power flow in a single stage. It can provide sinusoidal input and output currents and unity power-factor. Use of this AC-AC matrix converter excludes the need of huge DC link capacitors.

Control of Multi-terminal Offshore Wind Farm

Due to the limited power exchange and based on the advantages of HVDC VSC technology, MTDC transmission system has gained popularity during recent years [18]. It facilitates the transnational exchange with high-cost efficiency. Central master controller and local terminal controllers are used to controlling the Multi-terminal VSC-HVDC (MTDC). Master controller provides a minimum set of functions for coordinated operation of terminals. The master controller includes start and stop and provides a reference for active and reactive power. The terminal controller controls active and reactive power along with dc and ac voltage regulation [18].

In [18], various circuit topologies of multi-terminal VSC-HVDC linked transmission systems for offshore wind farms and on-shore ac grid integration are discussed. MTDCs are generally used to control active power, reactive power, and voltage regulation. These controllers are also used when a fault occurs and have the capability to recover the network automatically when the fault clears.

Control of multi-terminal offshore wind farm consists of two control methods: Master-Slave and Coordinated control.

MASTER-SLAVE CONTROL METHOD

The master controller is used to provide the main control to start or stop the operation. It provides active and reactive power references to the terminal controllers. The direction of power flow is also decided by this controller. The local control parameters are controlled by terminal controllers (A, B, C) which can control the active and reactive power, DC and AC voltages. Figure 4 shows the control scheme of Master-slave by using voltage margin approach [19]. It is important that MTDC link has one of the terminals configured in constant DC voltage control mode. Among the two of the VSCs of Master-slave control system, one provides a Vdc reference which controls the DC bus voltage while the other VSC controls the active power by giving power reference point [20].

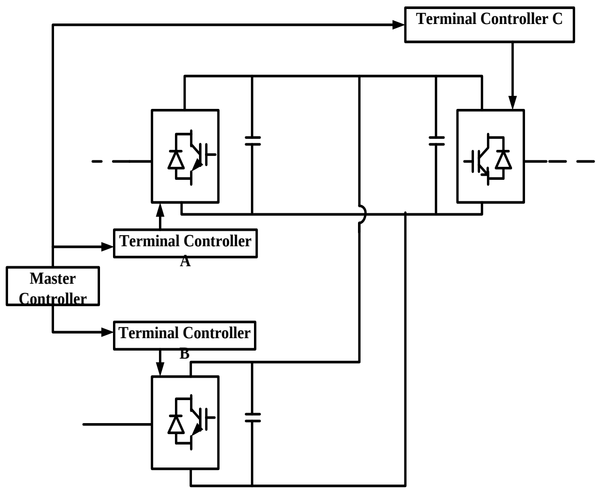

Figure4: Master Salve Control in Multi-terminal Offshore Wind Farms

COORDINATED CONTROL

Different coordinated control strategies, for the cluster of offshore wind farms, connected with MTDC are deliberated in many literatures. The coordinated strategy is established between the real and reactive powers, produced by offshore wind farms, and the DC voltage at terminals of MTDC, under grid-frequency variation [21]. DC voltage and power generated are controlled in a coordinated way by VSCs of MTDC. This coordinated control can enhance the steady state, dynamic voltage profile and regulation ability of HVDC transmission grid. Droop-based technology with coordinated control is proposed in [22]. This coordinated control strategy is reliable against the other control strategy. It allows the different converters to maintain power flow and at the same time regulating the dc voltage. In a droop control scheme, each VSC shows a directly proportional relationship between DC voltage and incoming power or dc current as shown in figure5.

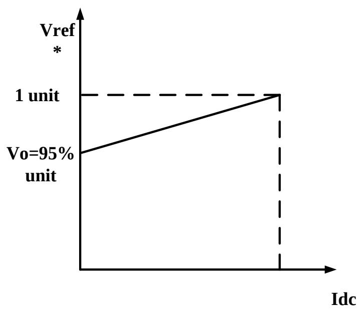

Figure5: Droop control scheme

This droop-based control strategy does not need any additional communication system. But they require an optimum operation point of the overall system caused by the variation of currents and voltages in the MTDC. But highly complex MTDC system requires communication system with coordinated control. A modified approach named master - auxiliary control strategy with dc voltage- margin control and dc voltage droop control are used in MTDC which can reduce the requirement of communication system [21].

Contingent Effects In Offshore Wind Energy Conversion System

Overvoltage is one of the major problems in off-shore wind farms connected to the grid by long AC marine cables which can affect the transient stability of the system. When the output power is low in an offshore wind farm, the capacitance reaction of no-load lines can create overvoltage. The overvoltage depends upon operation mode, cable type, and its length. Overvoltage is caused by an increase of asymmetric short circuit when the length of offshore submarine cable is increased up to 30 km. To overcome this problem, an arrester and high voltage shunt reactor are connected in transmission lines [23].

Improper design of controller can excite resonance in offshore as well as in onshore wind energy system due to HVDC filter/ transformers, and AC submarine cables. This can create a serious harmonic stability problem which can damage equipment. HVDC controller is used with a resonance suppression control by means of disturbance rejection techniques to overcome this problem, as discussed in [26].

To enhance the LVRT capability and transient stability of grid-connected DFIG offshore and onshore wind energy system, the combination of superconducting magnetic energy storage (SMES) and the fault current limiter (FCL) is discussed in [27]. This combination has a common superconducting coil which behaves as a short circuit current limiter. Optimized control of converters and tuned superconducting coil inductance can minimize the voltage deviation of DFIG terminal and power fluctuation during faults. The stored energy and a coil inductance (L) can be diminished using Fault Current Limiter (FCL) in the SMES-FCL whose combination uses lower power to stabilize the wind energy system in comparison to the SMES alone [24-25].

Some of the literature contributes the idea towards stabilizing the grid by introducing additional virtual inertia. This strategy lays emphasis on short-term energy storage in the power electronic inverter and converter which provides virtual inertia to the system by emulating the action of a synchronous generator. This virtual inertia concept is also called as the virtual synchronous generator (VSG) or virtual synchronous machine (VISMA). This control concept can regulate the magnitude and phase of VSC's output voltage with reference to active and reactive power errors. Controlling of stator power (active and reactive power) of WECS is done by a new optimal preview control (OPC) using linear quadratic regulator (LQR) approach as proposed in [28].

In [29] VSG control strategy is used in VSC-MTDC of offshore wind energy system to enhance its transient stability. This control strategy can damp out the low-frequency oscillations. It eliminates the need for a communication system because it relies on local measurement equipment.

Grid Code Requirements

Grid code requirements can vary between countries and its severity depends upon the penetration level of wind power. It also depends upon the strength of the grid system. It provides a standard for installation and enlargement of wind turbine technology. It aims at the normal operation of wind farms within the voltage, current, and frequency variation limits [32].

In FSIG, there are problems in meeting grid code requirements because they absorb a large amount of reactive power and also lack in control of torque due to small changes in speed [30]. DFIG has become more viable industrial option in the megawatt range. It has the ability to control the torque of the machine under variable speed conditions. It can also decrease the cost of inverter along with the increase in efficiency of wind energy extraction. In a fault condition, DFIG has fast voltage recovery because it has ability to control the reactive power. However, it has a disadvantage in case of voltage dips at stator terminals. Under these circumstances, DFIG wind farms are allowed to disconnect from the grid [31].

The grid code requirement especially reactive current due to voltage dips produces a great impact on offshore multi-terminal VSC-HVDC systems. Offshore MTDC system's development depends on its reliable control and performance under normal and contingency situations [33].

Conclusion

This paper has presented an overview on offshore wind energy system comprising of installation and generation issues with challenges. It has discussed different control aspects of the segregated component of grid integration. The control of multi-terminal VSC-HVDC offshore wind farm with master-slave and coordinated control strategies are also discussed along with contingency concerns.

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