

Overview of offshore wind farm configurations

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Abstract. Offshore wind energy has been attracting great attention. Compared with onshore wind power systems, offshore wind power applications present significantly greater economic challenges mainly due to the required bulky and costly offshore substation. To lower the cost of offshore wind power systems, various configurations are proposed in both industry and academia. The present work investigates existing offshore wind farm configurations.

1. Introduction

Offshore wind energy has been attracting increased attention [1]. There are generally two types of configuration for wind energy conversion systems (WECS), namely, fixed-speed and variable-speed configurations [1]. In the case of fixed-speed system, generator terminals are connected to the grid with no power converter being required. On the contrary, variable-speed system employs power converters for adjusting the generator speed to capture the maximum power from the wind. The variable-speed system features higher energy efficiency and lower mechanical stress, thus becoming the dominant technology in WECS [1].

In general, the whole offshore wind farm consists of two parts. One is the power generation system. The other is the power transmission system. Offshore wind farms are usually located far from the onshore grid connection point. To transmit the power of the offshore wind farm from the offshore collection point to the onshore collection point, both high voltage alternating current (HVAC) and direct current (HVDC) transmission links are used in practice, though with different features. HVAC is the simplest and most economic connection method when the distance between offshore and onshore connection points is less than 50 km. HVDC, on the other hand, is dominating the market when the distance is above 50 km [2].

Figure 1 shows the basic structure of a typical offshore wind farm where only main electrical components are considered [2]. As shown in figure 1, the output of turbine-generator-converter system, that is normally 690 V, is stepped up to 33 kV by a transformer. The 33-kV collection system is then transformed to an HVAC level by another transformer. The HVAC level is then transformed to an HVDC level by a centralized AC/DC power converter (modular multilevel converters (MMC) is dominating the market) [3]. The total captured wind power is then delivered to the onshore collection point by the transmission system. All the transformers, HVDC AC/DC converters, compensators, and energy storage components, if any, are housed in an offshore substation. The offshore substation is very bulky and costly.



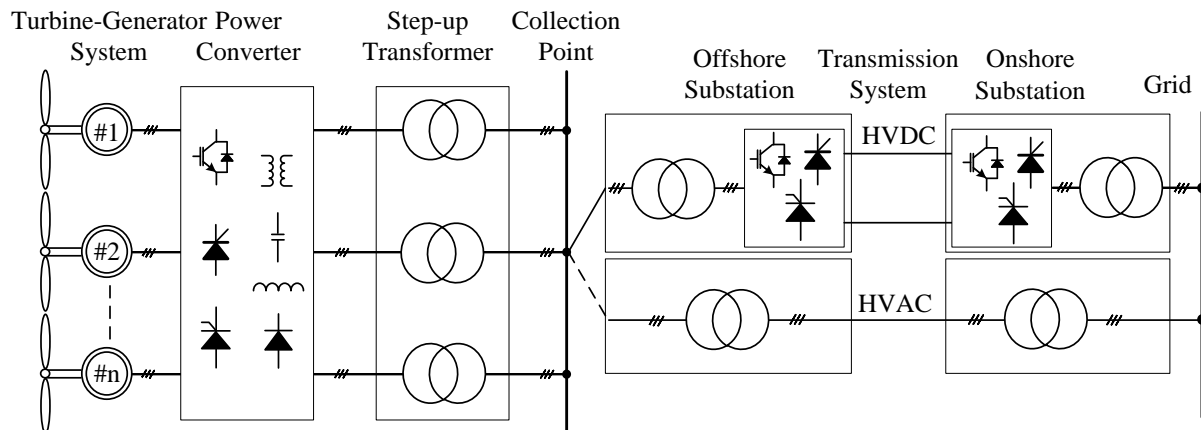


Figure 1. Basic structure of offshore wind farm.

2. Offshore wind farm configurations

The configurations of wind turbines directly affect the cost, efficiency, reliability and performance of an offshore wind farm. A couple of configurations have been proposed and reported and some of them have already been implemented in practice. In general, the offshore wind farm configurations proposed in literature and implemented practically can be classified into four types based on connection of wind turbines and the characteristics of the power to be delivered [4-7]: parallel AC connection with HVAC transmission system, parallel AC connection with HVDC transmission system, parallel DC connection with HVDC transmission system, and series DC connection with HVDC transmission system. In this section, these different types of configurations will be presented and analyzed thoroughly.

2.1. Configuration with parallel AC connection and HVAC transmission

Figure 2 illustrates the configuration with parallel ac connection and HVAC transmission system. The typical output voltage of wind turbines is 690 or 3000 (or 4000) V, which is converted to around 33 kV by the transformer. The outputs of the transformers are connected in parallel to form a medium voltage system, and then stepped up to an HVAC level by transformers housed on the offshore substation [8]. Between offshore and onshore converters is the HVAC transmission system.

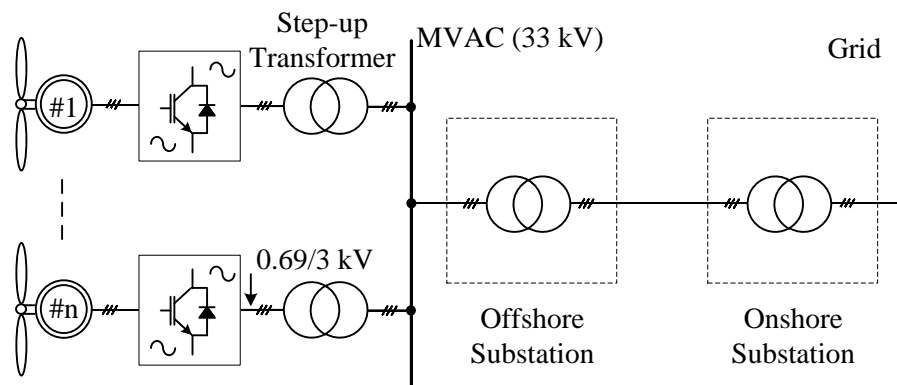


Figure 2. Parallel AC connection and HVAC transmission system.

This configuration is the simplest and most economic connection method when the distance between offshore and onshore connection points is less than 50 km. However, as the distance goes up, it has the following disadvantages [9]. First, the submarine ac cable produces large amount of reactive

current due to its high capacitance. As a result, the active current-carrying capacity of the cable is significantly reduced with increasing transmission distances and voltage levels. Thus, reactive power compensations are normally required at both ends. Second, HVAC is unable to directly connect two ac power networks of different frequencies. In addition, the faults on the HVAC cables negatively affect the system and vice versa.

2.2. Configuration with parallel AC connection and HVDC transmission

Figure 3 illustrates the configuration with parallel AC connection and HVDC transmission system. It is the most popular configuration for wind farms which are located far away from onshore and have large power capacity [6] in practice. A step-up transformer is used to convert the MVAC system to HVAC level and then an AC/DC converter is used to convert HVAC to HVDC. All the transformers, AC/DC converters, and other related components are housed in the offshore substation. A centralized DC/AC converter and a step-down transformer are used at the grid side and located at onshore station.

Both voltage source converter (VSC) and current source converter (CSC) can be used in such a configuration. The classical line-commutated converter (LCC)-based configuration where line-commutated CSCs with naturally commutated thyristor valves are used features low cost. However, a couple of disadvantages are associated with this configuration [10]: (1) a relatively strong synchronous voltage source is needed to assist the commutation of thyristor valves; (2) the conversion process demands reactive power which needs to be supplied from the large ac filter, shunt banks or series capacitor; and (3) the LCC-HVDC system cannot provide independent control of active and reactive powers. Although the reliability of the LCC-based HVDC is demonstrated by more than 50 years of service experience on-land, its large footprint due to the huge space requirements for the converter station and auxiliary makes it impractical for offshore application.

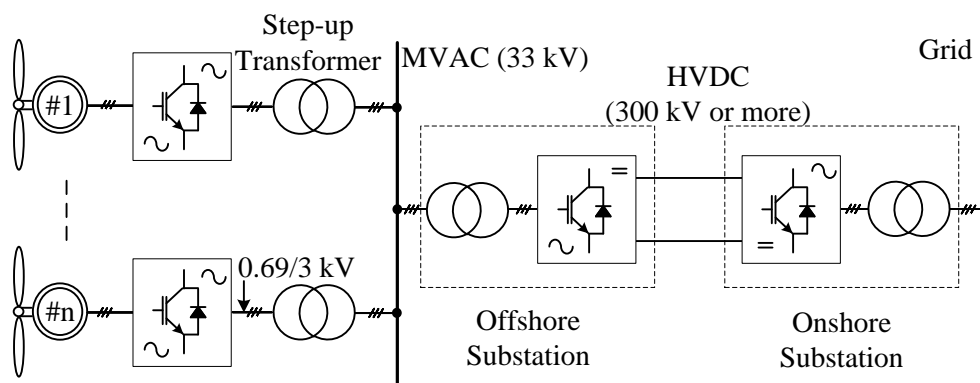


Figure 3. Parallel AC connection and HVDC transmission system.

VSC-based configuration featuring compact size, independent control of real and reactive power, and fast dynamic response [11], on the other hand, is now dominating the market of far located offshore wind farm applications. Two-level VSC with connected in series are mainly used in the traditional VSC-HVDC systems. The critical issue of such a configuration is the voltage balance control among series-connected switching devices. Modular multilevel converter (MMC)-based configuration has become a mainstream in HVDC-based offshore wind farm applications. MMC features modular structure, less derating of semiconductor switches, near sinusoidal output waveforms with low switching frequency, and high efficiency [12]. The main drawbacks for this configuration are significant initial and maintenance costs, especially for the very bulky and costly offshore substation required to house all the step-up transformers, power converters, batteries, and other related components.

2.3. Parallel DC connection and HVDC transmission

Figure 4 shows the configuration with parallel DC and HVDC system where an intermediate DC/AC/DC converter is used to step the low output voltage (1200/5000 V) of the AC/DC converter up to a MVDC level, that is ranging between 30 and 50 kV [13]. A MVDC collection system is formed by connecting the outputs of DC/DC converters in parallel. Then, the MVDC system is stepped up to an HVDC level with the help of a centralized DC/DC converter housed on an offshore substation. The DC/DC converters normally consist of three conversion stages, that are DC/AC, medium/high frequency transformer, and AC/DC. Compared with the parallel AC connection and HVDC system shown in figure 3, the size and weight of this configuration is smaller mainly thanks to the medium/high frequency transformer-based DC/DC converter. This configuration has not been implemented yet.

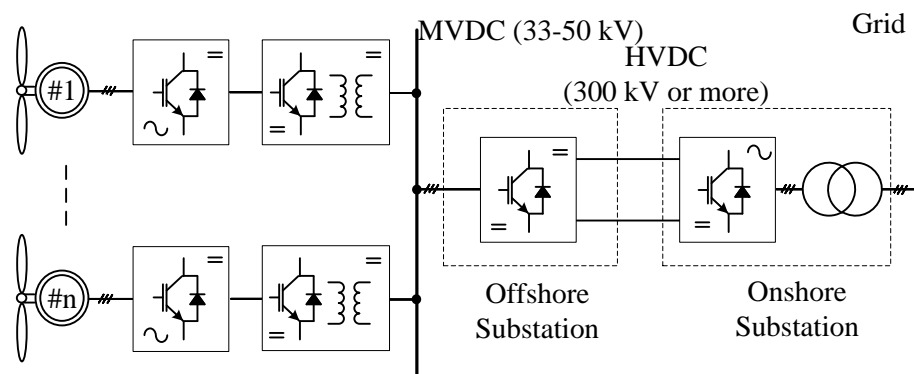


Figure 4. Parallel DC connection and HVDC transmission system.

2.4. Configuration with series DC connection and HVDC transmission

The configuration with series DC connection and HVDC transmission can eliminate the bulky and costly offshore substation, thus greatly lowering the cost of the whole offshore wind farm system. Both CSC- and VSC-based series-connected configurations have been developed for offshore wind farms in the literature. Figure 5 shows the LCC-based series-connected configuration [14]. Such a configuration is less suitable for the offshore wind farm as aforementioned, thus not repeated here.

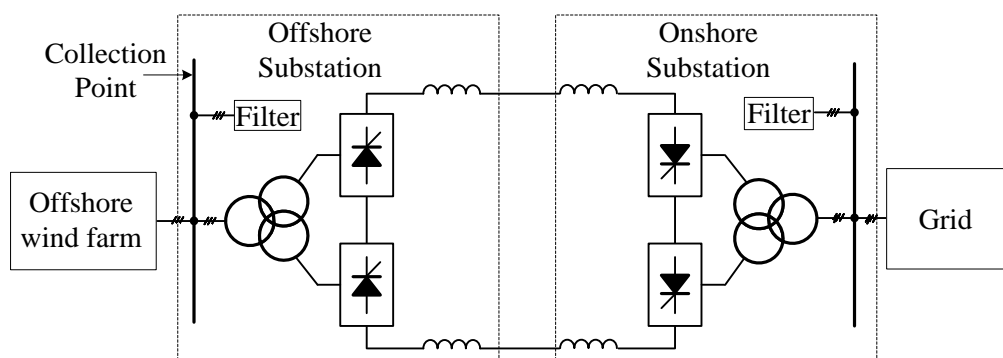


Figure 5. LCC-based series DC connection and HVDC transmission system.

Figure 6 shows the VSC-based series-connected configuration [15]. The DC outputs of turbine-generator AC/DC converters are connected directly in series to reach an HVDC level without any step-up transformers. Compared with the LCC-based configuration shown in figure 5, the VSC-based one features compact size, independent control of real and reactive power, and fast dynamic response.

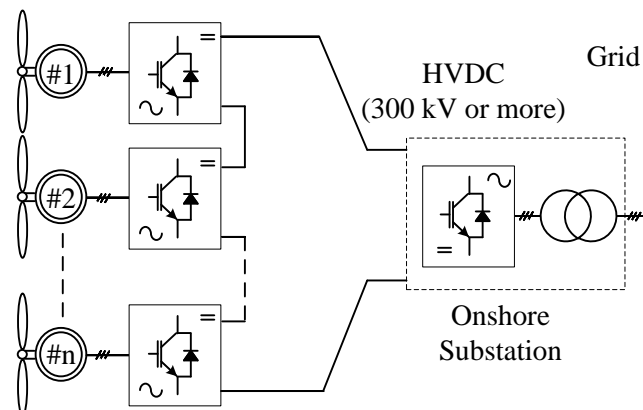


Figure 6. VSC-based series DC connection and HVDC transmission system.

Pulse width modulation (PWM) CSCs are well proven converters in applications of medium-voltage (MV) drives [11]. It features advantages like simple topology, grid-side friendly waveform, and reliable short-circuit protection. It is considered as highly promising converters for wind energy conversion systems. Figure 7 shows such a PWM CSC-based series-connected configuration developed for offshore wind farm [16]. A number of MV turbine-generator units are used offshore. The output DC voltage of each offshore CSC is connected directly in series to reach an HVDC level, then transferred to onshore by transmission cables. A same number of CSCs is connected directly in series to construct a DC/AC converter connected to the grid system through transformers.

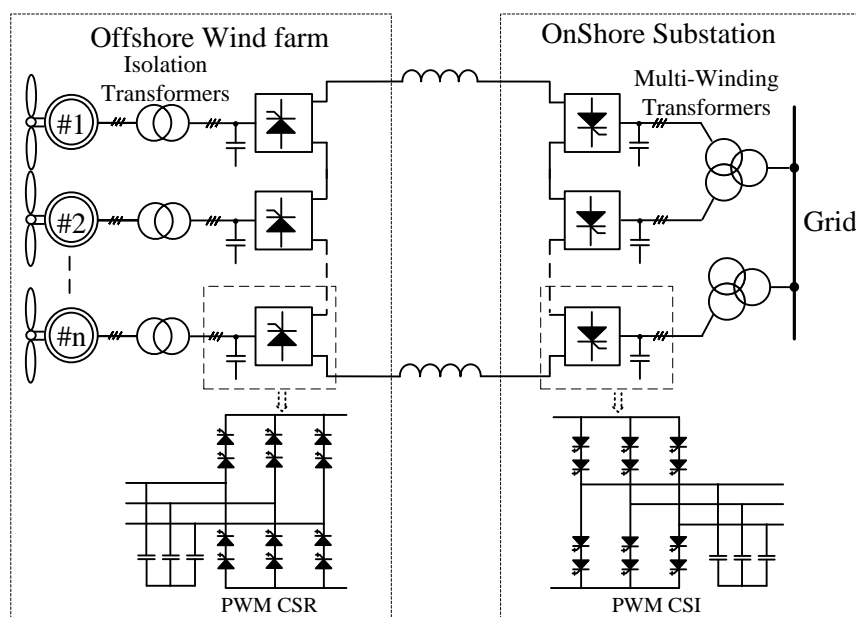


Figure 7. PWM CSC-based series DC connection and HVDC transmission system.

The most attracting feature for series-connected configuration is the elimination of the bulky and costly offshore substation used in existing offshore wind farms. However, the wind generators in this configuration need careful consideration when it comes to the system insulation. The wind generator furthest from the ground needs to withstand the transmission level. To tackle this issue, a couple of methods are developed [17].

- insulate the generator winding, and offshore converter for high potential (the full transmission voltage) to the ground, or

- insulate the wind turbine tower for high potential (the full transmission voltage) to the ground and keep the nacelle on high potential, or
- using transformers

where the transformer-based solution seems more practical. As shown in figure 7, a three-phase isolation transformer is employed between generator and the front-end CSC. Such a three-phase transformer, however, is a high-power low-frequency transformer which is bulky, especially for the offshore application where the space in the wind turbine is limited.

To lower the size and weight along with enhancing the reliability of the system, a medium-frequency transformer (MFT)-based configuration is proposed for CSC-based offshore wind farm as shown in figure 8 [18]. For each offshore turbine-generator unit, it consists of an MV permanent magnet synchronous generator, a diode rectifier, a MFT-based cascaded DC-DC converter. MV CSC is used at onshore as same as that in figure 7. The MFT-based modular DC-DC converter is composed of a number of H-bridge converters with series input and series output. The three-phase diode rectifier interfacing the generator shown in figure 8 displays the advantages of high reliability, low cost, and small size and weight. The side effect of this passive converter is that it generates a relatively high torque ripple in the generator. However, various methods have been proposed in literature to solve this problem [19]. Furthermore, the synchronous inductance of a permanent magnet synchronous generator is usually above 0.4 per unit (pu) for high-power, low-speed wind applications, which further helps mitigate the torque ripple.

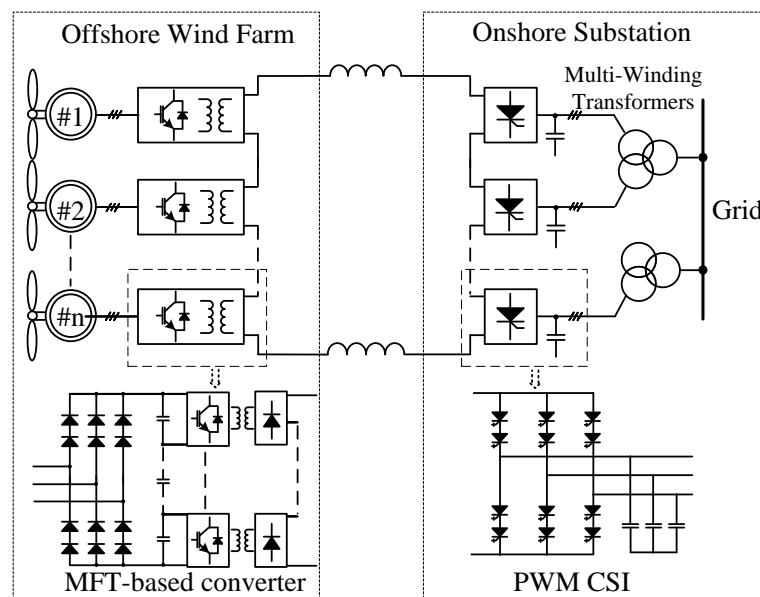


Figure 8. MFT-based series DC connection and HVDC transmission system.

The MFT-based modular DC-DC converter shown in figure 8 plays two roles [18]. First, it is for generator-side control. The primary objective for the generator-side control is to obtain the maximum power input from varying wind speeds. This can be achieved by regulating the modular MFT-based converter. Second, MFT is employed to solve the issue of generator insulation. For a series-connected wind farm, the farthest generator from the ground must withstand the full transmission level. In contrast to the low-frequency transformers shown in figure 7, MFT gives advantages of smaller size and weight. Furthermore, a modular design is implemented based on a number of cells that are connected in series at input and output. This helps reduce the burden of transformers implementation as one transformer only accounts for one part of a megawatt-level power. The modular design of the DC-DC converter also contributes to the choice of low-cost, low-voltage switching devices instead of high-voltage ones, and increasing the reliability and flexibility of the system.

3. Summary of different configurations

Apart from considering reliability and efficiency as the main requisites for all onshore conversion systems, the footprints and weights of the components are particularly important in offshore infrastructure [20]. In offshore wind farms, the offshore substation usually needs to accommodate step-up transformers, HVDC converters and compensator, depending on the type of wind farm configuration. These offshore substations are very bulky and very costly. Figure 9 shows one of the world's large offshore substations used for offshore wind farm "Dolwin2" commissioned by ABB [21]. The complete platform including substructure weighs around 23,000 tons and is around 100 meters long, 70 meters wide and 100 meters tall.



Figure 9. Offshore substation used in "Dolwin2" by ABB [21].

Compared with parallel-connected configurations shown in figures 2-4 where the offshore substation is required, the series-connected configuration shown in figures 5-8 is more attracting as the offshore substation can be eliminated which is more important for offshore applications.

Among the series-connected configurations, the thyristor-based one requires a relatively strong synchronous voltage source to assist the communication of thyristor valves, needs large ac filter, shunt banks or series capacitor for successful conversion process, and cannot provide independent control of active and reactive power. The PWM CSC- and VSC-based ones, on the other hand, are more promising due to their high dynamic performance and independent active and reactive power control.

However, both PWM CSC- and VSC-based series-connected configurations require low-frequency transformers to solve the issue of generator insulation. Such low-frequency transformers are high-power rated level, and are heavy and bulky, that adding burden to offshore infrastructure as the space in the wind turbine is limited.

Table 1. Summary of investigated offshore wind farm configurations.

Parallel AC connection with HVAC transmission	Parallel AC connection with HVDC transmission	Parallel DC connection with HVDC transmission	Parallel DC connection with HVDC transmission	
			Conventional configuration	MFT-based configuration
Offshore substation	Offshore substation	Offshore substation	No substation	No offshore substation
Transmission distance <50 km	Transmission distance >50 km	Transmission distance >50 km	Transmission distance >50 km	Transmission distance >50 km
			Bulky and heavy low-frequency transformer	MFTs with smaller size and weight

The recently proposed MFT-based configuration helps solve the above issues. By employing an MFT-based converter interfacing the generator, the issue of the generator insulation is solved and the size and weight of the MFT are greatly smaller compared with the low-frequency transformer. In addition, the modular structure contributes to the implementation of MFTs in practice as each MFT only accounts for one part of megawatt-level power. In summary, the investigated configurations are summarized in table 1.

4. Conclusions

In this work, existing offshore wind farm configurations are investigated. Apart from considering reliability and efficiency as the main requisites for all onshore conversion systems, the footprints and weights of the components are particularly important in offshore infrastructure. On this basis, the comparison among investigated configurations is carried out that the series-connected one is an attractive choice for future offshore wind farms as the offshore substation used in existing offshore wind farms is not needed.

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