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A Review on Topology, Operating and Control Methods of HVDC Transmission System for Offshore Wind Farms

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Abstract. High-voltage direct current (HVDC) transmission systems are a promising solution for long distances power transmission offshore wind farms. In order to satisfy the reliability requirements of receiving-end grid and system, the topology, operation and control of HVDC transmission systems for offshore wind farms should be paid more attention. Thus, the aim of this manuscript is to offer a comprehensive summary of existing topology, operation and control methods applied to HVDC transmission system for offshore wind farms. Special attention is provided to the ac grid fault through control methods, droop control methods, power sharing rules and specific requirements of HVDC system planning, model, design and investment. The results are important for understanding the operation of VSC-HVDC in offshore wind farms.

1 Introduction

Recently, the energy problem has given rise to significant impacts on the life and production. Offshore winds have their advantages compared to onshore wind, which produce larger power. Due to the higher power and long distance transmission, DC transmission topology is currently the preferred for far offshore wind applications.

HVAC and HVDC transmission systems have been compared in many papers for offshore wind farms projects. Based on the fault recovery ability, reference [1] showed the advantage of HVDC compared to HVAC. Although HVAC has an advantage for small power plants (less than 300MW), HVDC is more economical for a long distance transmission system[2]. Based on system loss, [3] studied that HVAC system is 12% more than HVDC for a long distance and large power plant system. Thus, the higher cost and device losses in maintenance are critical problems for traditional HVAC transmission for a long distance and large power wind farms. Reference [4] provided a novel transmission structure with ac cable and onshore converter. It is limited by the dc grid scale and ability of the receiving-end grid.

Due to large-scale development in short distance offshore wind resource, long distance and power wind plants are paid more and more attention to. Thus, HVDC transmission system is a pivotal element for offshore wind farms. VSC and LCC are two typical converters. Due to LCC cannot operate in island for an offshore converter, and LCC will bring frequent commutation failure for an onshore converter. LCC-HVDC is inadaptable compared to VSC-HVDC in actual offshore wind farms projects. Extensive literatures introduce the operation and control methods of VSC-HVDC applied in actual projects. However, few literatures presents the VSC-HVDC for offshore windfarms. Thus, this paper will provide a comprehensive review for different VSC-HVDC topologies, operation strategies, and fault through methods.

2 DC transmission topology and DC converter topology

2.1. DC transmission topology

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Fig. 1 shows simplified single line representations of DC transmission topologies. Five topologies existing in engineering or literatures are discussed in Table I. Point-to-point shown in Fig. 1(a) is a traditional transmission structure. Every wind farm has its offshore converter and dc line. It is easy to implement the protection configuration. Radial shown in Fig. 1(b) is also applied in actual project. Different wind farms are connected to a same offshore converter by ac cables. Radial+ shown in Fig. 1(c) is a novel structure which wind farms are connected to the offshore converter by dc cables. However the dc breaker has not been utilized in offshore wind farms, the cost and occupation is the key problem in the actual project. The ring structures shown in Fig. 1(d) and (e) achieve transmission flexibility, however the complicated protection

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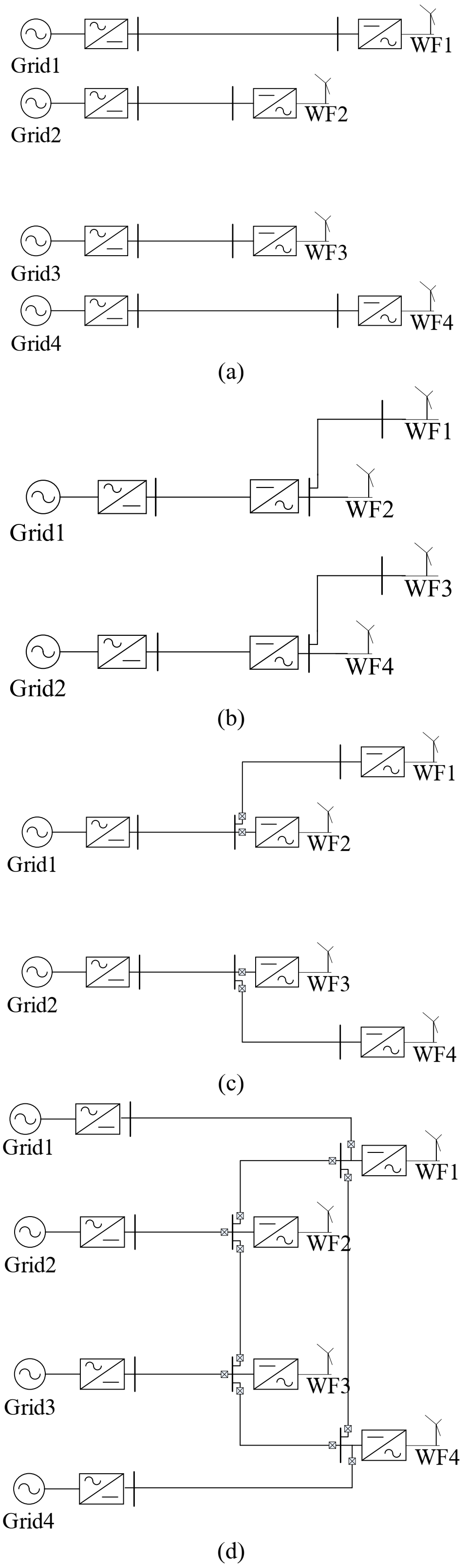
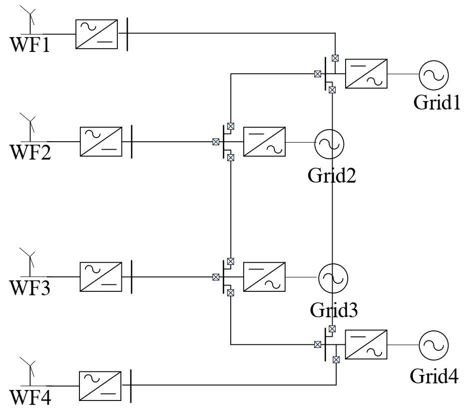
configuration and high cost will limit the application in offshore wind farms.





(e)

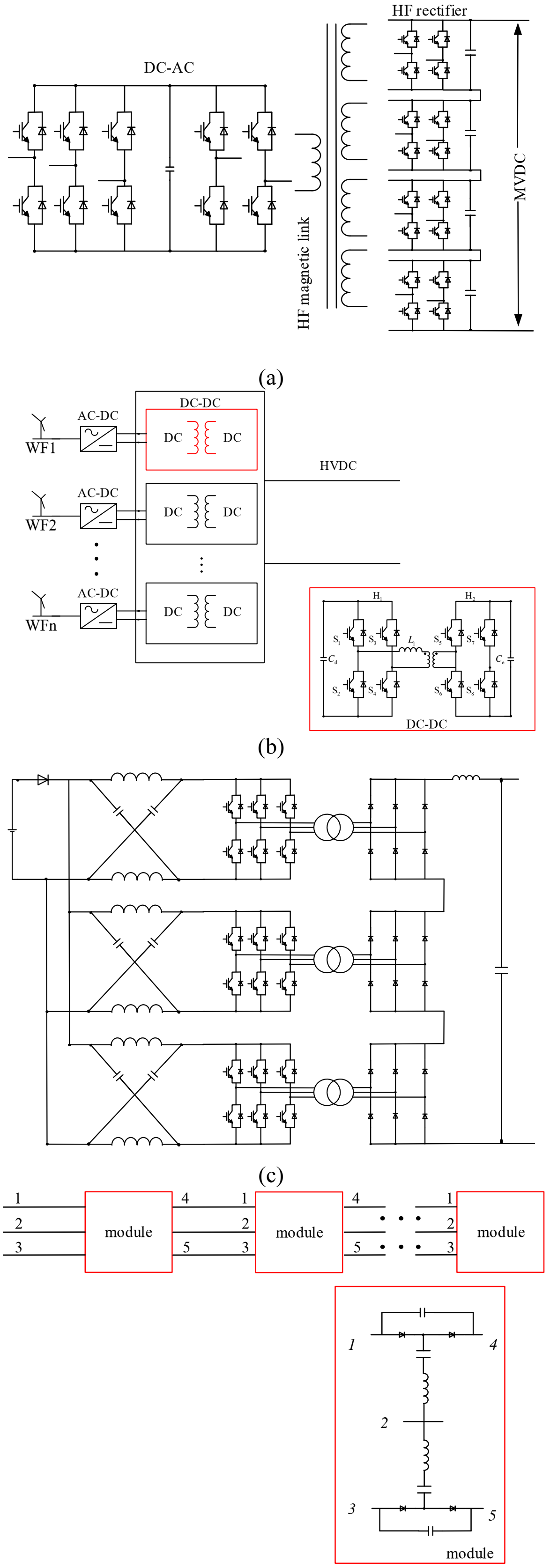
Figure 1: DC transmission topologies: a) point-to-point, b) radial, c) radial+, d) wind farm ring, e) substation ring

Table 1. Comparison of different DC transmission topologies

Topology	***advantages***	***disadvantages***
Point-to-point [5]	1.Simplified protection configuration; 2.engineering application.	1.More dc cables and sea area.
Radial [3]	1.save resource of dc cables and sea area; 2.engineering application.	1.large occupation area and high cost of offshore converter ; 2.interacts with each WF.
Radial+[5]	1. save resource of dc cables and sea area.	1.DC breaker configuration.
Wind farm ring [6]	1. offshore transmission flexibility.	1.dc breaker configuration 2.complicated protection configuration; 3. large occupation area and high cost of offshore converter.
Substation ring [6]	1. receiving-end grid flexibility.	1.dc breaker configuration; 2.complicated protection configuration.

2.2 DC converter topology

In actual projects and existing literatures, MMC is the most conventional structure for offshore converter[5][7]. It has been applied in offshore wind farms engineering. Similar to MMC, other high voltage and large power AC-DC converters, AAC[5] and LCC[8], are also proposed. But offshore LCC cannot operate in islanded, the wind farms cannot be charged by it. AAC has better dc fault blocking ability compared to MMC with half bridge submodule. But the control strategy is relatively complex. A DC-AC topology with series capacitor-clamped module shown in Fig. 2(d) is proposed for offshore wind farms[9]. It achieves the minimal switching loss and maximum efficiency. However, the unused module topology brings the challenge for its application. Three DC-DC topologies are shown in Fig. 2 (a)-(c). Medium-voltage dc system shown in Fig. 2 (a) can eliminate the low-frequency heavy and large step-up transformers[10]. The topology shown in Fig. 2(b) achieves high system efficiency[10-13]. The modular impedance source shown in Fig. 2(c) has better fault-tolerant ability.



(a)

(b)

(c)

(d)

Figure 2: DC-DC converter topologies

Table 2. Comparison of different DC transmission topologies

Topology	advantages	disadvantages
MMC + half bridge SM [5]	1. engineering application	1. dc fault-tolerant ability
AAC [5]	1.dc fault blocking ability	1. high system loss 2, complex control strategies
LCC [8]	1.lower investment	1. cannot operate in isolated mode
Media-voltage DAB converter [9]	1.eliminate low-frequency and step-up transformer 2.supress voltage conversion stages	1. more construction cost 2.complex control strategies
DC-DC converter [10-13]	1. high system efficiency	1. more construction cost 2.complex control strategies
modular impedance source DC-DC converter [14]	1.fault-tolerant ability 2. lower cable costs	1. more construction cost 2.complex control strategies 3.power quality
capacitor-clamped module DC-DC converter [15]	1.better output voltage 2.high voltage gain	1. more construction cost 2.complex control strategies 3.higher investment

3 Control methods

3.1. Fault ride through strategy

DC bus fault and AC grid fault are common faults that converters should deal with for VSC-HVDC transmission offshore wind farms. Based on DC bus fault, [16] analyzed the influence of the wind power plant control methods on the MMC-HVDC system based on the detailed cable model. DC bus fault is a critical failure, thus, the additional equipment or control method is necessary for DC fault ride through. In addition to the dc bus fault blocking converter structure (for example AAC[5]), chopper resistor is a common way to handle the dc fault for traditional offshore converter. Instead of the chopper resistor, a flywheel energy storage system is designed in[17]. Fast wind power plant control method can also reduce the influence of dc bus fault[18].

For the AC grid fault, [19] introduced the fault ride through implementation, while analyzing the AC grid characteristics and fault power recovery rate. A nine switch converter is designed for ac grid fault ride through[20]. A new configuration of U-VSC-HVDC onshore converter structure is proposed in [21]. In addition to the new configurations, reactive current prioritizing method is also discussed to improve the transient stability and response during ac grid fault[22]. Meanwhile, a frequency droop control strategy is introduced for ac grid fault ride through by power reallocation[23]. A fault current injection method is also introduced to enhance the overcurrent protection[3]. The advantage and disadvantages of these methods are shown in Table III.

3.2. Droop control and power sharing for multi-terminal HVDC

In section 2.1, a series of DC transmission topologies are introduced. For solving the control issue of multi-terminal ends in offshore windfarms, [24] forcused on the stability of MTDC and provided more interconnections for power grids and other forms of energy. Based on the stability of VSC-HVDC in windfarms, [25] investigated the stability consequences of offshore wind power into the existing Northwest European transmission system. In [26], a flexible DC transmission control method for offshore windfarms is introduced. It utilized DC voltage droop control for inverters and kept the dc voltage statble under some failure conditions. About droop control in VSC-HVDC for offshore windfarms, [27] also provided a droop control method to guarantee a safe operation while keeping the optimal operation of the DC grid. Compared to the droop control method proposed in [26] [27], [28] proposed a droop control strategy in terms of losses and reduced the system investments.

For the multiterminal-HVDC network in offshore windfarms, power sharing is also a key probelm. Reference [29] proposed a supervisory control method for multiterminal-HVDC offshore windfarms systems. It designed the sharing of the active power generated from offshore windfarms among onshore AC grids under normal operation conditions. Reference [30] designed a mixed-integer linear program for day-ahead scheduling problem with linearised AC optimal power flow and multiterminal-HVDC system models. For solving the power sahring based on fault conditions, [31] provides a power redistribution strategy to achieve a better frequency performance of the onshore AC grids.

3.2. Special issues

To analyze the offshore windfarms system more accurate, the mathematical model is a key problem. A simplified model of HVDC transmission system connecting offshore windfarms to AC grid is proposed in [32]. Based on a multiterminal-HVDC system, [33] uses small-signal analysis model to investigate the influence of control parameters and DC breakers.

For improving the HVDC system control performance, [34] introduces a system frequence regulation strategy based on a ancillary frequence controller in onshore converter without additional investments. Reference [35] utilizes the arm energy control strategy to achieve a better performance.

4 Conclusions and future work

The features of the offshore wind farms have made it an attractive research point for energy production and transmission. The demand to conform established rules has led to the development of VSC-HVDC topologies and control methods. This work presents a comprehensive review of the dc transmission topology, dc converter topology and fault ride through strategies for offshore wind farms. This review is important for understanding the operation of VSC-HVDC in offshore wind farms. In the future work, some operation performance and implementational methods in actual projects will be introduced and discussed.

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