

A Review on MVdc Collection Systems for High-Power Offshore Wind Farms

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Abstract— Recently, offshore renewable technologies have shown a rapid growth with the advancement in technology together with reduction of capital investment per unit size. This movement is further catalyzed by various government policy decisions and new set targets on renewable energy (RE) production. Due to higher wind speed, limited land availability and flexibility of transporting very large structures (with the increased size of a single wind turbine) offshore wind power plants provide commendable benefits over onshore wind plants. At present, only medium voltage ac is used in the offshore wind collection systems. However, the use of medium voltage direct current (MVdc) at the collection level is becoming more attractive due to advantages like lower systems losses, zero reactive power compensation and flexibility of power flow control compared to traditional ac collection systems. This paper intends to review opportunities and key challenges associated with the emerging MVdc technology for offshore wind collection systems. Attention is given to the DC wind turbine concept and selecting a suitable MVdc collection system topology with appropriate control modes.

Index Terms—Medium voltage dc (MVdc), offshore wind, wind power collection systems, dc wind turbine (dcWT), research challenges.

I. INTRODUCTION

The global trend towards power generation through renewable energy (RE) sources have been increasing over the last few decades due to significant advantages over coal- and fossil fuel- based power plants. The use of fossil fuels to meet the global energy demand has major drawbacks such as contribution to global warming and depletion of resources over time. According to [1], the use of coal for energy production in the global energy mix is set to decline by almost 80% from 2017 to 2040 under sustainable development scenario. In the context of Europe, by 2030 it is expected to produce at least 32% of total energy consumption from renewable energy and 40% cut in greenhouse gas emissions compared with 1990 [2].

The above issues have given rise to the promotion of RE solutions such as wind, solar PV, small hydro, biomass, geothermal, wave and tidal power. For example, by end of 2017, the regional wind power production capacity was distributed as follows: 177.5 GW Europe; 228.6 GW Asia; 105.3 GW North America; 17.8 GW Latin America; 4.5 GW Africa; and 5.1 GW Pacific regions [3]. The cumulative capacity of wind turbine

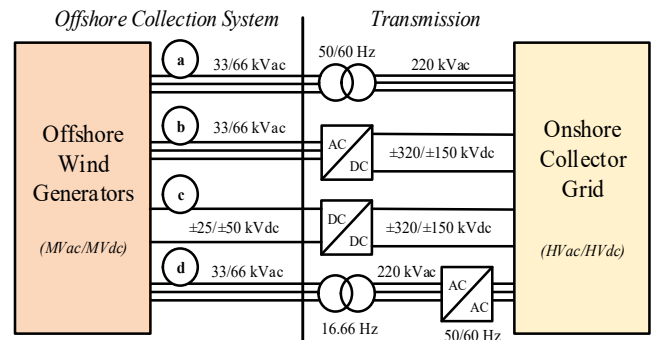


Fig. 1. Different OWPP Collection System Options: (a) MVac collection with HVac transmission; (b) MVac collection with HVdc transmission; (c) MVdc collection with HVdc transmission; (d) Low frequency MVac collection and HVac transmission.

(WT) installation was increased by 9.1% by the end of 2018 [4]. These figures are forecasted to be risen in the future with the advancement of wind power technology, incentives from governments and reduction in capital investment per MW. Offshore wind technology provides added benefits such as higher energy yield and lesser public disturbance over its counterpart onshore wind technology. At present, Europe is the leader in offshore wind power plant (OWPP) development. As at 2018, total globally installed offshore wind capacity is 22,045 MW and more than 80% is concentrated to Europe [5]. Within Europe, the UK has the largest amount of offshore wind capacity with 44% of all installations. Some major projects such as Walney Extension, London Array, Norfolk Vanguard and Norfolk Boreas are notable [6].

Different OWPP collection system options with transmission technologies are shown in Fig. 1. At present, all existing offshore wind parks feature an internal ac network with either ac or dc transmission to onshore power grids. The advantage of using the state-of-the-art ac technology from the onshore power grid is obvious in terms of know-how, experience, and, to a certain extent, cost [7]. However, as the OWPP distance to onshore grid increases (where wind conditions are superior) the ac cable transmission may become problematic due to high capacitive cable charging. Thanks to the development of voltage source converter (VSC), particularly the modular multilevel converters, the high voltage

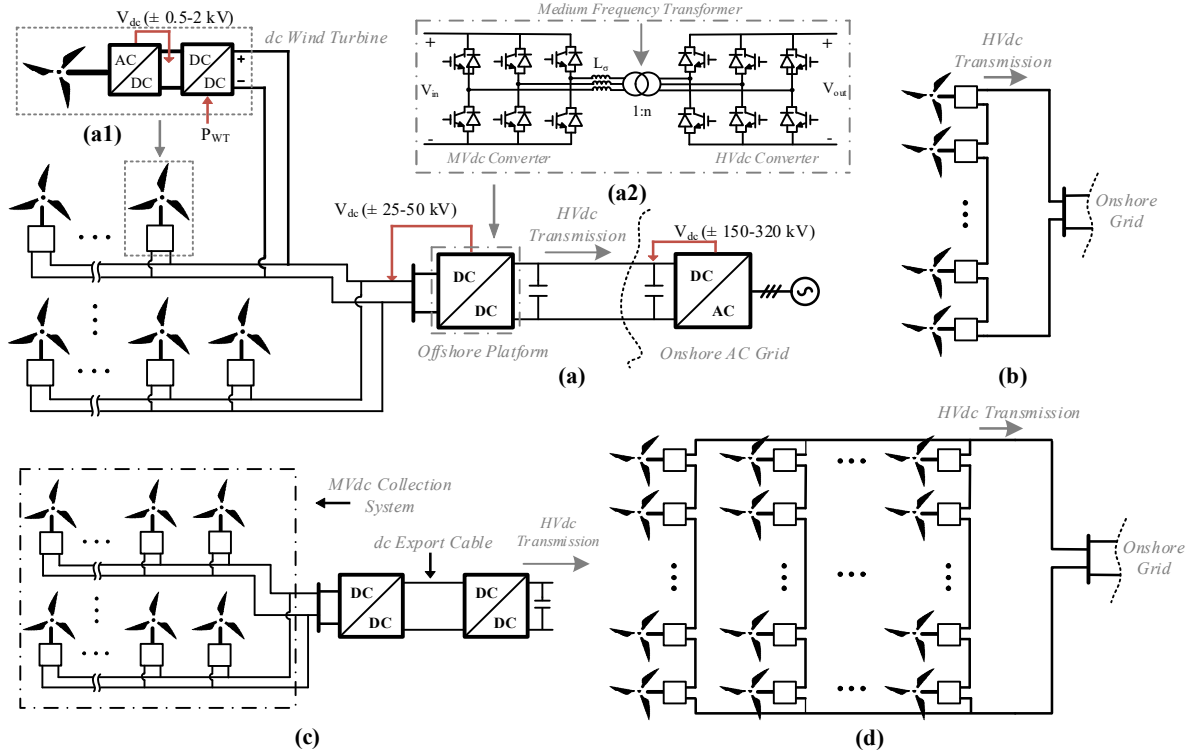


Fig. 2. Different MVdc collection systems: (a) Shunt topology -1; (b) Series topology; (c) Shunt topology -2; (d) Series-parallel topology.

TABLE I. OWPP COLLECTION SYSTEM OPTIONS: ADVANTAGES AND DISADVANTAGES

Option	Advantages	Disadvantages
MVac collection with HVac transmission.	-Maturity of the ac technology. -Market availability. -Comparatively low capital investment.	-Higher losses with increase distance to shore. -Large offshore platform. -High capacitive cable charging.
MVac collection with HVdc transmission.	-Suitable for longer distance power transmission. -Higher transmission efficiency.	-HVdc converter unavailability is very costly. -High capital investment
MVdc collection with HVdc transmission.	- Less power conversion stages. - Lower loss compared to ac solution. - High power density with increased size and capacity of single WT.	- Uncertainty in reliability and typical availability of dc wind turbines. -MVdc protection technology not fully developed. -Higher capital investment.
Low freq. MVac collection and HVac transmission.	-Increase of power capacity and transmission distance for a given submarine cable compared to ac solution. -Use of normal ac breakers for protection.	-Higher risk associated with low-frequency ac technology know-how. - Larger size of the LF ac transformer. -No specific standard available for LFac technology

direct current (HVdc) connection can be an alternative for long-distance offshore power integration [8]-[10]. Bard-1, 400 MW wind park 130 km off the coast of Germany, is the first offshore

wind park connected through a HVdc transmission link to the main grid [11]. Table I. summarizes the OWPP collection system options with their advantages and disadvantages. Due to additional benefits such as lower losses, zero reactive power compensation, elimination of 50/60 Hz bulky transformers, lightweight and reduction in the size of power electronic converters MVdc technology will be a promising option for future OWPP collection systems [12]-[14]. Thus, this paper attempts to review suitable MVdc collection systems and dcWT topologies for future large scale OWPPs.

The rest of the paper is organized as follows. Section II. discusses feasible MVdc collection system topologies with different control modes. The key component in an all-dc OWPP; the dc wind turbine (dcWT) is discussed in Section III. Section IV. highlights existing technical barriers of MVdc collection systems. Finally, Section V. summarizes the main conclusions from this paper with some important future research directives.

II. DIFFERENT DC COLLECTION SYSTEM TOPOLOGIES AND CONTROL

Irrespective of the technology used identifying a suitable offshore wind farm collection system is important. The main factors to be considered are power losses and capital investment. In [15]-[16], it has shown that the use of MVdc collection systems for energy harvesting from OWPPs are economically beneficial over existing MVac collection systems. However, other technical challenges such a) protection against dc faults; b) stability and control under wake effect and other system disturbances; c) availability under scheduled maintenances; d) reliability of the overall collection

system (with the use of a large number of power electronic devices) need to be addressed. Special attention should be given to reliability and maintainability upon wind turbine and collection system component failures under marine harsh weather environment [17].

The primary requirement of a high-power MVdc collection system is the development of a dcWT which is still at incubator research stage. The collection system comprises of several MVdc clusters (typical voltage range between ± 25 kV to ± 50 kV) which will be collected by one or several offshore collection system platforms (depending on the distance to shore) and export to the onshore grid via HVdc transmission. Different dc collection system configurations have been proposed in the literature. Primarily it can be categorized into shunt- and series- topology [7], [18] and others are variants of these two basic topologies as shown in Fig. 2.

A. Collection System Topologies

a) Shunt configurations

Depending on the distance to the intermediate offshore platform, there may be different shunt configurations as shown in Figs. 2(a) and (c). Shunt topology-1 can be used if the wind turbine clusters are located close to centralized collection platform and all the MVdc cables directly connect to the offshore HVdc converter platform. Shunt topology-2 is very similar to topology-1 except the additional dc/dc converter. This topology can be used if clusters are located far away from the onshore grid and power transmission requires an additional intermediate step to boost the voltage before HVdc transmissions. However, reliability of these two configurations at the cluster level can be increased by introducing additional dc/dc converters at the expense of capital investment. The inter-array cable network can be configured as single-sided radial feeder, bifurcated-radial feeder, single-sided or double-sided ring feeder as discussed in [12].

b) Series and series-parallel configurations

The main advantage of series and series-parallel (SP) topologies is the elimination of the offshore collector platform. Individual dc wind turbines are connected in series in such a way that the voltage is built up to transmission levels. Theoretically, the current in the series connected wind array needs to be the same. If all the WTs have the same rated output, to satisfy this condition they must produce the same output power. However, in a condition where WTs in the same array produce different power outputs, the WTs operating below the average wind speed must increase its terminal voltage (and vice versa for WTs operating above the average) to maintain the nominal transmission voltage.

If the permissible voltage limit exceeds, these WTs will be forced to shut down which may result in the total failure of the entire string. This is the major drawback of this topology. To address this issue in SP topology a novel configuration called ‘‘matrix topology’’ was introduced in [19] which uses intermediate switches between adjacent strings. However, with the increase of number of parallel branches a sophisticated control scheme is necessary to switch between adjacent wind arrays in SP topology.

B. Offshore Collection Platforms

In an all-dc OWPP, core of the offshore collection platform is the dc/dc converter which boost the MVdc voltage level to HVdc transmission voltage level. There are many variants of dc/dc converter topologies which are suitable for high-power DC grids [20]. The isolated dc/dc converter which uses a medium frequency transformer (operating at 1-10 kHz) is considered here. It operates on phase shift control mode [single active bridge (SAB) and dual active bridge (DAB)]. Fig. 2(a2). shows the configuration of a three-phase variant of the DAB proposed in [21]. As expressed in (1) and (2) (for single-phase and three-phase) the power flow can be varied by regulating the phase shift. In (1) and (2), V_{in} and V_{out} represent the input and output dc voltages, ϕ – the phase shift, n – transformer turns ratio, f_s – switching frequency and L_σ – leakage inductance.

$$P_{DAB(1\phi)} = \frac{V_{in}V_{out}}{n2\pi f_s L_\sigma} \phi \left(\frac{1-\phi}{\pi} \right) ; 0 \leq \phi < \frac{\pi}{2} \quad (1)$$

$$P_{DAB(3\phi)} = \frac{nV_{in}V_{out}}{2\pi f_s L_\sigma} \phi \left(\frac{2}{3} - \frac{\phi}{2\pi} \right) ; 0 \leq \phi < \frac{\pi}{3} \quad (2)$$

However, in the shunt topology-1 of Fig. 2(a), the control objective of the offshore collection platform is to maintain the collection system MVdc voltage. Once the HVdc voltage is fixed by the onshore VSC, collection system MVdc voltage can be regulated with closed-loop control as illustrated in [22].

C. Control of MVdc OWPP Collection Systems

In order to harmonize with the onshore grid requirements and harness maximum power from the offshore wind plant, the optimum controlling of entire OWPP cluster is important. Thus, in a pure dc-based wind farm, maintaining the specific dc voltages at different stages of the OWPP collection system is essential. However, no frequency and reactive power control is required unlike in MVac collection systems.

The control responsibilities of different converters starting from the dcWT level up to onshore converters are illustrated using Fig. 1(a). Respective arrow in the figure indicates the dc voltage control requirements from the specific converter. For instance, the MVdc voltage is regulated by offshore collection system dc/dc converter and HVdc voltage by onshore VSC. The power output from wind turbines (P_{WT}) is controlled by the wind turbine dc/dc converter which is discussed in the next section.

III. DC WIND TURBINES

Before discussing the dcWT concept, it is worth to consider the exiting ac wind turbine technology (acWT) currently deploying at OWPPs. At present, majority of offshore WTs are constructed with variable speed permanent magnet synchronous generators (PMSG) due to benefits such as compact in size, no requirement of external power supply for magnetic field excitation, robust construction and less maintenance compared to classical asynchronous wind generators.

A. PMSG based full-scale ac Wind Turbine

In a conventional variable speed full-scale offshore wind turbine, the generator output is connected through a back-to-back (ac/dc/ac) converter, with a constant frequency and voltage. At the collection level, the acWT output voltage increase up to 33kVac or 66kVac using a step-up transformer. The control schematic of a typical grid connected PMSG based full-scale acWT is shown in Fig. 3.

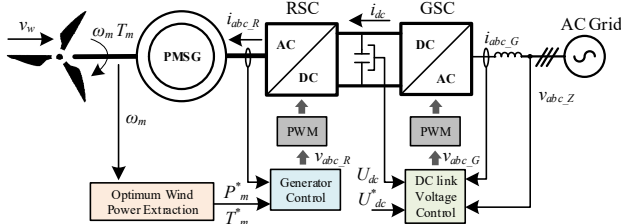


Fig. 3. Control scheme of a PMSG based full-scale acWT.

According to Fig. 3, there are three different control objectives of a full-scale wind turbine:

a) Optimum wind power extraction

It provides the necessary power (P_m^*) or torque reference (T_m^*) based on the operational points of maximum efficiency. The optimal reference value depends on the rotor speed, wind speed, and pitch angle.

b) DC link voltage control

The grid side converter (GSC) is responsible for maintaining a constant dc link voltage and it is able to provide reactive power. Typically, the control objective is achieved by the vector control which is based on dq components. This consists of an outer loop that regulates the dc voltage through a proportional integral (PI) controller and an inner loop that controls the current.

c) Generator control

The rotor side converter (RSC) controls the power extracted from the wind turbine or the mechanical torque. However, in [23] it has shown that it is possible to swap control objectives of GSC and RSC with enhanced fault ride-through and voltage support capabilities.

B. DC Wind Turbines

a) Proposed Configurations

There are several dcWT concepts discussed in the literature as illustrated in Fig. 4. They are classified according to the number of converter stages assuming state-of-the-art wind generators are employed [20].

Minimum number of components, simplicity and galvanic isolation are the important factors to be considered when selecting a suitable dcWT topology. The simplest design is the topology-(a) but the maximum output voltage is restricted by generator's nominal voltage level and it has no galvanic separation. The isolation issue in concept-(a) can be eliminated by adding a non-isolated dc/dc converter. The topology in Fig.4(c) uses a low-frequency transformer with a passive

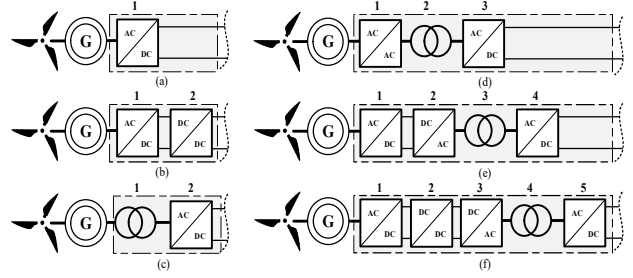


Fig. 4. Different dcWT configurations: (a) Active rectified based dcWT; (b) non-isolated dc/dc converter based dcWT; (c) ac transformer and passive rectifier based dcWT; (d) matrix converter, medium frequency transformer and passive rectifier based dcWT; (e) active rectifier and galvanic isolated dc/dc converter based dcWT; (f) boost converter between the active rectifier and galvanic isolated DC/DC converter based dcWT.

rectifier as proposed in [24]. However, fixed speed operation and transformer saturation are the main disadvantages.

Concept-(d) deploys a matrix converter (MC) at stage-1 which is proposed in [25] with galvanic isolation. However, MC requires advanced control strategies to coordinate with variability of wind power which could be an interesting research topic. Concept-(e) provides galvanic isolation and uses state-of-the-art WT and active rectifier which is similar to type-4 ac wind generators. In this topology, high-power dc/dc converter is the only component added to complete dcWTs. The topology-(f) proposed in [26] uses a boost converter between the active rectifier and the isolated dc/dc converter. It assumes that the boost converter actively controls the LV side dc link, while the dc/dc converter operates in an open loop. Among the topologies discussed, concept-(e) is the most suitable topology due to low technology risk.

b) Suitable dc/dc converter configurations

Dc/dc converters need to consider as a combination of power conversion stages 2,3 and 4 of Fig. 4(e). This dc/dc converter topology can be SAB or DAB which operates on phase-shift control principle. In wind power applications, the active power flow is always unidirectional i.e. from WT side to grid side. Therefore, SAB will primarily serve our requirement. However, the major limitation of SAB is phase shift between primary and secondary occurs due to the leakage inductance of the medium frequency transformer [15]. Thus, to transfer large amount of power transformer leakage inductance should made very low. This problem shall eliminate with the use of DAB.

Generally, DAB is used when bi-directional power transfer is required such as in dc microgrids. However, DAB shall support for OWPP black-start by enabling reverse power flow to charge the dc-link of the dcWT. If SAB is used, there should be a stand-by diesel generator ready at all times. With severer marine weather conditions, re-fueling of diesel generators could be problematic. Thus, the use of DAB as the dc/dc converter in topology-(e) is advantageous.

c) dcWT control

As shown in Fig. 5. the main control objectives of topology-(e) (refer together with Fig. 4(e)) are dc link voltage control and active power control. This is similar to the control of PMSG based full-scale acWT with interchange of control responsibilities as discussed in section-A. The dc link voltage is controlled by the VSC connected to wind generator and power is regulated by the DAB on phase-shift control mode.

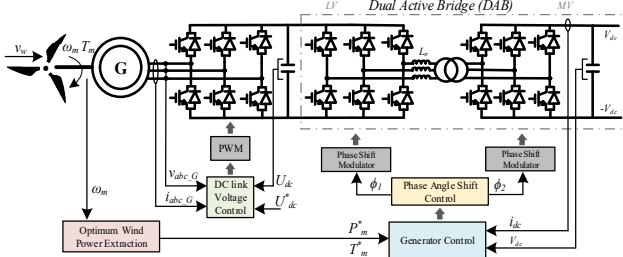


Fig. 5. Control scheme of dcWT topology-(e).

IV. EXISTING CHALLENGES AND PERSPECTIVES

Unlike for MVac offshore collection systems, there is no complete standard or design guideline (which specify voltage levels, design and operational requirements, recommended systems studies and analyses, etc.) for MVdc offshore collection systems yet. However, [27] provides a detailed specification for MVdc shipboard power systems which provides some common requirements of a dc power system. Further, CIGRÉ working group C6.31 was established in order to investigate the needs and feasibility of building MVdc grids. Key challenges of an MVdc OWPP are identified as:

- **DC Fault Protection:** Protection against dc faults is one of the main challenges that need to be dealt with in a pure dc grid. The key requirement of a high-power dc circuit breaker (DCCB) is acting quite fast to avoid extreme high currents [28]. Off-the-shelf DCCB for MVdc shipboard power systems and traction application are not suitable due to low fault current handling capabilities. In the family of DCCBs, solid-state circuit-breaker has the overall best performance with respect to technical and reliability parameters compared to different variants of mechanical and hybrid dc breakers [29]. However, ongoing efforts should be made to improve the DCCB technology for high-power MVdc grids.
- **Grid Code Compliances:** Irrespective of the collection system technology (MVac or MVdc) used at the offshore wind farm, it is necessary to fulfil the grid code requirements. Upon a system disturbance, dcWTs and offshore collection platform dc/dc converter must be able to control in a way that it will comply with the relevant grid code. Thus, new control strategies/methods are required to comply with stringent grid codes in an all-dc OWPP.
- **Reliability:** Reliability is another important factor to be considered in any engineering system. It can range from

component level to the system level. A system which comprises of a large number of power electronic devices may fail at any time [30]. Thus, reliability is a decision making factor when selecting a suitable dc collection system topology.

V. CONCLUSION

This paper reviewed different configurations of MVdc collection systems and dc wind turbine topologies for all-dc OWPPs. Due to advantages over classical MVac technology MVdc collection systems are suitable for future offshore wind power collection systems. Considering capital investment, controllability and reliability the variant of shunt topology is preferable for MVdc collection systems. Due to low technological risk active rectifier and galvanic isolated dc/dc converter based dcWT is suitable. Main challenges associated with the emerging MVdc technology for offshore wind collection systems are identify as dc fault protection, strict grid code compliances and reliability. In order to overcome these issues continuous research and development efforts are required.

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