Comparison of Standard Power Converters for HVDC Transmission in Type 3 and Type 4 Offshore Wind Generators

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Abstract As offshore wind generation matures, wind farms are constructed at increasing ocean depth and distance from shore. To prevent significant power loss and decrease length of cables used, high-voltage direct current (HVDC) transmission lines are often preferred for the link to an onshore point of interconnection. Since HVDC transmission requires power conversion from AC to DC and back to AC, choice of power convertor topology can greatly influence performance, specifically: (1) compliance with power grid standards — particularly voltage and frequency control, reactive power capabilities, and total harmonic distortion; (2) efficiency of the system, and (3) relevant capital and maintenance costs — influenced by cost and number of semiconductor devices, weight and volume of converter, and reliability of components. This paper offers a comparison of standard power converter topologies for variable speed Type 3 and Type 4 wind generators with regards to the above-mentioned performance criteria. A partial two-level back-to-back voltage source converter (2L BTB VSC) is identified as the industry standard for Type 3 doubly fed induction generators (DFIG), with advantages of low-complexity and low price and offering satisfactory efficiency and control. The three-level back-to-back neutral point clamped voltage source converter (3L BTB NPC VSC) is identified as a higher-complexity option which offers larger control, low maintenance, and decreased necessity for output LCL filters which leave space in nacelle for further efficiency-increasing step-up transformers. While cost-inefficient in low-power systems, 3L BTB NPC VSC is especially suitable for higher-power Type 4 synchronous generators (SG).

***Index Terms*— 2L BTB voltage source converter, 3L BTB neutral point clamped voltage source converter, HVDC transmission, Type 3 wind generator, Type 4 wind generator, variable speed wind generator.**

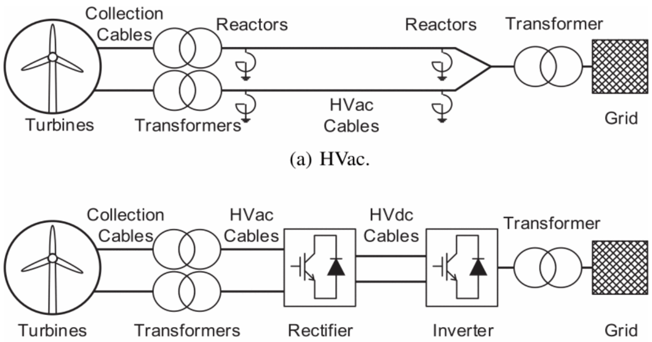
I. Introduction

Wind power generation has been experiencing a steady decrease in levelized cost of electricity (LCOE), with onshore wind generation achieving 39 USD/MW in 2020 [1], which represents the current lowest value among all available generation resources. However, offshore wind generation has remained significantly more costly, only achieving 84 USD/MW in 2020 [1]. Nevertheless, offshore wind power generation has been receiving increased attention because of its potential for expansive power plants with individual turbines achieving higher power capacities due to increased blade length. In the USA, an interest in offshore wind has been marked by President Biden's commitment to 30 GW of operating wind generation in the ocean by 2030 [2]. Therefore, there is significant industry effort to bring LCOE of offshore wind down and enable successful integration of such large intermittent resource into the power grid.

Unlike onshore wind power plants which can be directly connected to the grid, wind power produced offshore must be transmitted under water, sometimes tens of kilometers to reach the closest onshore grid connection. Standard high-voltage alternating current (HVAC) transmission represents a significant source of power loss and capital costs due to large cable length, which motivates the use of high-voltage direct current (HVDC) transmission instead.

For the vast majority of current applications, HVDC transmission is more expensive than HVAC due to the need for voluminous and heavy power conversion substations in the ocean. However, for applications above 100 MW and further than 90 km offshore [3], the benefits of HVDC — namely lower power loss, lack of resonance between cables and AC equipment, fast control of active and reactive power, and decreased total cable length — become significant, making HVDC a cost-effective technology.

Unlike in HVAC application, in HVDC applications, power converters form a crucial component of the system, as illustrated on Figure 1, and affect performance of the entire system, both in terms of overall efficiency, cost, and compliance to grid codes. The choice of converter topology for specific wind generator types is therefore a critical design decision.



(a) HVac.

(b) HVdc.

Fig. 1. High level illustration of (a) HVAC and (b) HVDC transmission systems, showing the additional requirement for AC-DC and DC-AC power conversion in the latter case. [4]

This paper will commence by a brief overview of four basic wind generator types and will isolate the ones used for HVDC transmission as the sole focus of the following parts. Design considerations for power converters across grid code requirements and technical specifications will be outlined. Finally, an industry standard power converter will be examined for each generator type and will be evaluated with respect to those design considerations.

II. Wind Generator Types [5]

A. *Constant speed wind generator*

There is only one widely used constant speed generator: the Type 1 generator, or the squirrel-cage induction generator (SCIG). Constant speed wind generators limit the operation of the rotor to one rotational frequency. The rotor is then connected to the generator shaft by a fixed-ratio gearbox in the nacelle, so that the generated power is aligned with the grid. This design is the most simple but suffers from fluctuating reactive power (which can only be controlled by additional hardware) and low efficiency due to the low utilization of the wind energy. No power conversion system is needed for this generator because the generated AC power corresponds in phase and frequency to that of the grid.

B. *Variable speed wind generators*

Variable speed generators operate at the optimal aerodynamic frequency and require an AC-DC and DC-AC conversion to step up the output voltage and adjust the frequency and phase of the signal to match that of the grid. There are three types of variable speed wind generators.

Type 2, the wound-rotor induction generator (WRIG), is a partial variable speed turbine which can compensate for power fluctuations during gusting conditions with a variable resistor which controls the rotor current. The generator can accommodate for +/-10% fluctuations in rotational frequency while maintaining output frequency which matches the grid, again avoiding any need for power conversion.

Type 3, the doubly-fed induction generator (DFIG), is a partial variable speed turbine which can compensate for fluctuations in wind speed with a partially rated voltage source converter. The rotor-side voltage rectifier which can adjust current’s magnitude and phase nearly instantaneously is connected back-to-back with a grid side inverter [6]. The DFIG is the most commonly used wind power generator, representing about 50% [7] of the current capacity, due to its higher efficiency, control over voltage parameters, and relative simplicity. A disadvantage of the generator is the high need for maintenance of the rotor, which is caused by the short lifetime of slip rings and brushes (about 6-12 months) which connect the power converter to the rotor [7].

Type 4, the synchronous generator, is implemented either as a permanent magnet synchronous generator (PMSG) or a wound-rotor synchronous generator (WRSG). The generator uses a full-scale power converter, achieving full decoupling from the grid, full control over frequency and voltage, and the ability to operate at the optimal aerodynamic frequency. The system is low maintenance, does not require a gearbox, and is capable of best compliance with grid codes, but it requires a bulkier power converter due to its full power rating [8].

Since Type 3 and Type 4 implement partial or full power conversion, they are ideal for use in HVDC transmission systems. In the rest of the paper, only Type 3 and Type 4 will be evaluated.

III. Design Considerations

A. *Grid code* [8]

Several requirements relating to the quality of the power injected into the grid are specified by the authority managing the local grid (in the US, standards are imposed both by the Federal Energy Regulatory Commission (FERC) and by the relevant regional transmission operator (RTO) or independent system operator (ISO)) [9]. The most important considerations are listed here, though the list also includes other constraints such as ramp rate control or ride-through during grid fault conditions:

(1) Voltage and frequency control — Control of the output frequency/voltage to match grid frequency/voltage or provide frequency/voltage support is required and is easily achieved by the grid-side power inverters through a controllable switching sequence.

(2) Reactive power control — Requirement for reactive power capabilities is specified at the point of interconnect. Typical specifications require 0.95 lag to lead at the machine terminals for variable generators. This means the wind generator must be capable of injecting or absorbing reactive power equivalent to roughly one third of its rated active power. Reactive power control can be achieved fully by the grid-side inverter, however, to avoid increase in converter size, external hardware such as static var compensators (SVC) or static compensators (STATCOMS) can be used instead [9].

(3) Total harmonic distortion — A stringent 5% THD requirement [7] can be met by implementing switching sequences to achieve harmonic elimination, and/or by adding an LCL filter between the converter and the grid connection.

B. *Performance and costs*

Grid requirements must be met while maintaining high performance, low initial cost of system and low maintenance costs. High efficiency is usually linked to decreasing amount of switching losses in the system, e.g. by decreasing the switching frequency or choosing efficient switching devices.

Low initial cost is usually linked to simplicity of design, and the overall volume and weight of the power conversion system, which affects the size and weight of the nacelle or an offshore substation, which adds substantially to the overall cost of the power plant.

To achieve low maintenance costs, robust design can be implemented by using a low number of active components and symmetry between stresses in the system to avoid accelerated wear out of certain components, causing unnecessary frequent downtime of the entire wind generator.

IV. Type 3 Power Conversion

A. *Type 3 power conversion system* [4]

In a type 3 wind generator, the stator is connected directly to the grid while the rotor is fed into a partial voltage converter, as illustrated on Figure 3. The converter controls the speed of the rotor across its rated power range. A 1/3 partial-scale power converter can therefore enable a +/- 1/3 variation in rotor speed around synchronous speed. The role of the converter is to enable the generator to act as a dynamic power source for the grid, while controlling active and reactive power, DC-link voltage, and grid power factor. Use of partial scale converters as opposed to full-scale converters decreases the size of the system in the nacelle, which enables placement of additional step-up transformers that help lower transmission losses.

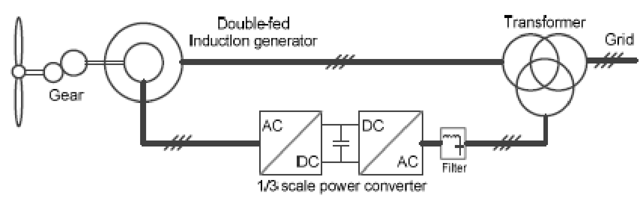


Fig. 2. Type 3 wind generator power conversion system [4]

B. *Partial 2L BTB voltage source converter* [7], [4], [11]

A standard implementation of such a converter for type 3 generators is a two-line back-to-back voltage source converter (2L BTB VSC) illustrated on Figure 3. This three-phase system is composed of a two-level voltage source rectifier and a two-level voltage source inverter, each with six active switches and 6 antiparallel diodes, connected by a DC link. Due to the high voltage rating of each switch, they can be implemented as integrated gate bipolar transistors (IGBTs) or integrated-gate commutated thyristors (IGCTs). At the grid-connection side of the converter, an LCL filter is added to decrease total harmonic distortion according to the applicable grid code. Additionally, the switches are controlled by a pulse width modulated signal so that some harmonics are avoided altogether. A switching pattern is implemented such that the switching frequency of each active switch equals six-times the fundamental frequency of the AC signal on the respective side of the converter, which leads to a uniform power loss and stress on the six switches within each converter.

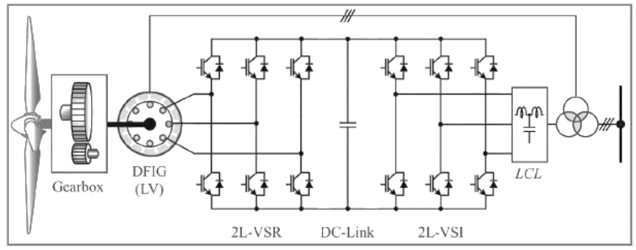


Fig. 3. Type 3 wind generator power conversion system [7]

Due to the power converter's relatively low complexity and number of components, the topology has been proven as a reliable one, with a typical efficiency of the system exceeds 98% [10]. A disadvantage of the 2L BTB Converter is a high rate of change of voltage (dv/dt) because of the presence of only two output voltage levels. This causes excess stress and harmonic distortion in the generator and the transformer, which can only be offset by very bulky output filters, challenging the volume and mass constraints in the nacelle. The presence of a partial voltage converter decreases the volume and size of the converter but causes incomplete control over the output waveform and reactive power, which means that the system cannot operate and inject power into the grid under extreme aerodynamic conditions.

V. Type 4 Power Conversion

A. *Type 4 power conversion system* [4]

In a type 4 wind generator, the generated is completely decoupled from the grid by a fully rated power converter, as illustrated on Figure 4. This allows for full control over output waveform characteristics as well as reactive power over a large variety of wind speeds.

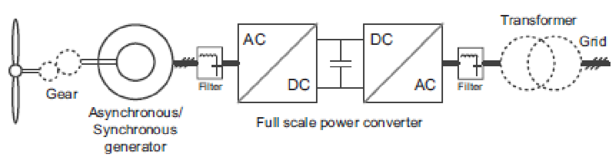


Fig. 4. Type 4 wind generator power conversion system [4]

B. *3L BTB NPC voltage source converter* [7], [4], [11]

Similarly to Type 3, the 2L BTB converter topology can be used for Type 4 wind generators. However, since Type 4 is often used for high power capacity applications (especially relevant to offshore wind farms where wind speeds are higher and rotor diameter can be larger), the 2L BTB converter faces significant challenges. Its switching losses increase, efficiency decreases, and switching devices must be paralleled or connected in series, increasing complexity of the converter and posing higher risks to reliability. Instead, the more complex multi-level converters are considered the state-of-art solution for Type 4 generators with power capacities between 3MW and 7MW, a level at which the converters become cost-effective.

Specifically, the industry standard is the three-level back-to-back neutral-point clamped voltage source converter (3L BTB NPC VSC) illustrated in Figure 5. Again, the total power conversion system is composed of a rectifier and an inverter, each with twelve active switches and six clamping diodes, connected by a DC link and followed by an LCL filter. Just like in the two-level converter, due to the need of high-voltage power rating of the switches, either IGCTs or IGBTs are used in industry. To minimize switching losses and enable proper heat dissipation, switching frequency is kept at a few hundred Hertz. The switches are again controlled by pulse width modulation or schemes specifically designed to eliminate certain harmonics. At full-load operating condition, the efficiency is about 98% [3].

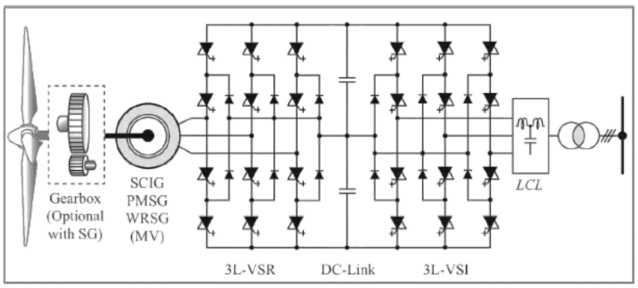


Fig. 5. 3L BTB NPC voltage source converter [7]

At first sight, this converter looks much more complicated. However, this is not the case when compared with the standard 2L BTB converter for example in a 6 MW wind turbine. In such a high-power generator, eight 2L BTB converters must be combined, which leads to a total of 96 active switches instead of 24 active switches (plus 12 clamping diodes) in the 3L BTB NPC converter [7]. Apart from lower complexity and lower risk of failure in high-power applications, the converter enables the use of smaller LCL filters because of the lower dv/dt [4]. This means that the power density of the converter is larger, leaving space in the nacelle for additional hardware such as step-up transformers which can further decrease the transmission losses.

Apart from advantages in complexity, the converter produces higher quality waveform, because the output voltage of the inverter has three voltage levels as opposed to two, which is responsible for the lower dv/dt stress and lower THD compared to the two-level converter.

The topology suffers from two main challenges. Firstly, the DC bus capacitor is split in two, creating a neutral point in the middle of the system, which must experience charge balance so that there is no voltage drift across the capacitors (normally holding voltage equal to $V_{out}/2$). Such a drift would asymmetrize the converter and lead to larger power losses and stress in some switches. The problem can be solved by controlling redundant switch status [4]. Secondly, there is an uneven switching pattern between the inner and the outer switches, which causes uneven power loss, and a slight derating of the converter [7].

VI. Conclusion

A standard 2L BTB VSC for Type 3 generators was compared with the 3L BTB NPC VSC for Type 4 generators. Analysis of the two converter topologies with respect to different technical, economic, and grid compliance criteria is summarized in Table 1.

TABLE I
COMPARISON OF PERFORMANCE CRITERIA

Criterion	2L BTB VSC for Type 3 generator	3L BTB NPC VSC for Type 4 generator
Voltage and frequency control	High	Excellent
Reactive power control	High	Excellent
Total harmonic distortion	Medium (only 2 output voltage levels)	Low (3 output voltage levels)
Efficiency	>98%	98%
Volume and weight	Low (partial power rating related to partial size)	High
Power density	Low	High
Complexity	Low for low power applications; high for high power applications	Medium
Risk failure	Low (stacking increases component number but also allows for greater modularity)	Medium

Neither of the converters is overwhelmingly a better choice. The 2L BTB VSC is found suitable for lower-power applications, where stacking of converters is unnecessary and the converter can therefore offer advantages in lower complexity and size, which leads to savings both in initial costs and in costs related to risk failure. However, these advantages disappear when multiple converters are stacked to accommodate a medium or high-power application, leading to a high number of switches and large switching losses. In the latter scenario, a 3L BTB NPC VSC is a better choice, allowing for higher power density, lower overall number of switches, and better grid code compliance.

The advantages and disadvantages of the converters are combined with those of the respective generators. Namely, the Type 3 generator is a highly mature, simple technology, however one suffering from high maintenance costs due to low brush lifetime. Type 4 generators, on the other hand, is a less mature technology, but offer benefits of lower maintenance and better efficiency due to a full capability of accommodating variable speeds.

This comparative study has demonstrated different technical, regulatory, and financial tradeoffs of converter topologies for HVDC transmission from offshore wind Type 3 and Type 4 power generators above 90 km away from point of connection. The list of converter topologies in the industry is long and steadily increasing, so this paper does not come close to identifying best converter topologies for the Type 3 and Type 4 generators. Nevertheless, the paper illustrates the complexity of factors that must be taken into account when choosing an optimal power conversion system for such applications.

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