Journal of
Marine Science and Engineering

MDPI

Article

Offshore Wind Power Integration into Future Power Systems: Overview and Trends

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Abstract: Nowadays, wind is considered as a remarkable renewable energy source to be implemented in power systems. Most wind power plant experiences have been based on onshore installations, as they are considered as a mature technological solution by the electricity sector. However, future power scenarios and roadmaps promote offshore power plants as an alternative and additional power generation source, especially in some regions such as the North and Baltic seas. According to this framework, the present paper discusses and reviews trends and perspectives of offshore wind power plants for massive offshore wind power integration into future power systems. Different offshore trends, including turbine capacity, wind power plant capacity as well as water depth and distance from the shore, are discussed. In addition, electrical transmission high voltage alternating current (HVAC) and high voltage direct current (HVDC) solutions are described by considering the advantages and technical limitations of these alternatives. Several future advancements focused on increasing the offshore wind energy capacity currently under analysis are also included in the paper.

Keywords: offshore wind energy; HVAC; HVDC; P2X; hydrogen storage; CAES

1. Introduction

Energy demand has been increasing non-stop during the last decades [1]. Nowadays, fossil fuel sources (i.e., coal, oil and natural gas) provide around 85% of the world energy demand, according to the BP Energy Outlook of 2019 [2]. However, with the Paris climate agreement established in December 2015, this energy scenario is about to change [3]. This climate agreement aims to restrict maximum increase in the global average temperature below 2 °C above pre-industrial levels [4]. To fulfill this goal, greenhouse gas (GHG) emission trends should drastically change [5]. Consequently, the use of fossil fuels should be reduced, as they are considered as the main source of GHG emissions [6]. Actually, global GHG emissions are dominated by the emissions of CO_2 due to the combustion of fossil fuels, which has been increasing continuously since 1990 [7]. The power sector should be decarbonized by 2050 to meet the Paris agreement target [8]. Furthermore, Liddle and Sadorsky estimated that increasing by 1% the share of non-fossil fuel electricity generation can reduce by up to 0.82% the CO_2 emissions [9]. This environmental worry is one of the reasons to promote the integration of renewable energy sources (RES) into power systems [10]. Moreover, RES can also mitigate the energy dependence on fossil fuels imported from other countries [11]. Apart from the economic costs of these fossil fuel imports, decreasing energy dependence increases electricity supply security [12]. The International Energy Agency defines electricity supply security as the uninterrupted availability of energy sources at an affordable price [13]. However, political stability, market liberalization and foreign affairs are nowadays linked to energy supply security [14]. As a consequence, it is important to be energy-independent to guarantee the energy security of a country [15].

While RES provide an acceptable solution for these two problems, they also face many challenges as their integration increases into the grids, mostly based on their intermittency, variability and uncertainty due to their dependency on weather conditions [16]. Actually, they are usually considered as 'non-dispatchable' sources [17]. This fact makes them hard to integrate into power systems [18], as transmission system operators (TSOs) have to deal with not only the uncontrollable demand but also uncontrollable generation [19,20]. RES include bioenergy, geothermal energy, hydropower, ocean energy (tide and wave), PV, thermal solar energy and wind energy (onshore and offshore) [21]. Some of them (such as wind and solar installations) are connected to the grid through power electronic converters, reducing the rotational inertia of the system as they replace conventional generation units [22,23]. This fact compromises the frequency stability and alters the transient response [24]. As a result, several frequency control strategies have been proposed in the specific literature [25-30]. Other alternatives to increase the RES share in power systems and avoid the aforementioned problems are to complement one source with another (for instance, wind with solar and/or hydropower) [31-33] or to use storage systems (such as flywheels, pumped hydroelectric storage, batteries, hydrogen, etc.) [34,35].

Among these renewable technologies, wind is one of the most economic, prominent and matured RES technologies [36,37]. In fact, since 2001, global cumulative installed wind capacity has shown an exponential growth, as can be seen in Figure 1a. Among the total wind capacity, 23 GW came from offshore installations in 2018, compared to 1 GW in 2007, refer to Figure 1b [38]. Despite offshore wind energy dating back to the 1990s, its popularity started around ten years ago [39]. This increase is due to the current interest of the wind energy industry in offshore wind power [40]. For instance, offshore wind energy investments surpassed onshore investments in Europe in 2016, as presented in [41]. Moreover, nearly 40% of the total wind capacity is expected to come from offshore wind energy in Europe in 2030 [42,43].

In addition, offshore wind energy presents many advantages compared to onshore wind power plants, especially related to wind energy potential [44,45]: (*i*) Offshore mean wind speeds are higher and wind power variability is also lower than onshore wind power; (*ii*) their visual and acoustic impact is usually lower than onshore; subsequently (*iii*) larger wind turbines (WTs) can be installed [46]. Actually, on the European coasts, the available offshore wind energy is about 350 GW [47]; the USA's shores present an offshore wind power potential of more than 2000 GW [48]; the offshore wind resource in China is about 500 GW in water depth under 50 m [49]; and the east and west Indian coasts have an offshore wind potential of 4.4 GW and 6.7 GW, respectively [50].

Furthermore, offshore wind speed usually increases with distance from the shore, thus increasing the power generated, as it depends on the cube of the wind speed [51]. However, higher installation and maintenance costs of offshore wind power plants (OWPP) far from the shore balance the benefits of higher energy production [52]. Indeed, OWPP are around 50% more expensive than onshore wind power plants [53], but their costs are expected to decline up to 35% by 2025 [54]. The global weighted average levelized cost of energy (LCOE) in 2018 was 20% lower than in 2010. These cost reductions can be a result of [55]:

- The evolution in wind turbine technology, installation and logistics
- The economies of scale in operations and maintenance
- The improved capacity factors due to higher hub heights, better wind resources and larger rotor diameters

This paper analyzes and reviews different aspects of offshore wind power plants, including several future alternatives to increase the offshore wind power capacity. The rest of the paper is organized as follows: Section 2 presents the current status of offshore wind power plants (WTs and OWPP sizes, water depth, distance from shore and electrical transmission to shore). Future advancements possible for larger offshore wind power plant integration are analyzed in Section 3. Finally, Section 4 gives the conclusions.

2. Current Status of Offshore Wind Power Plants

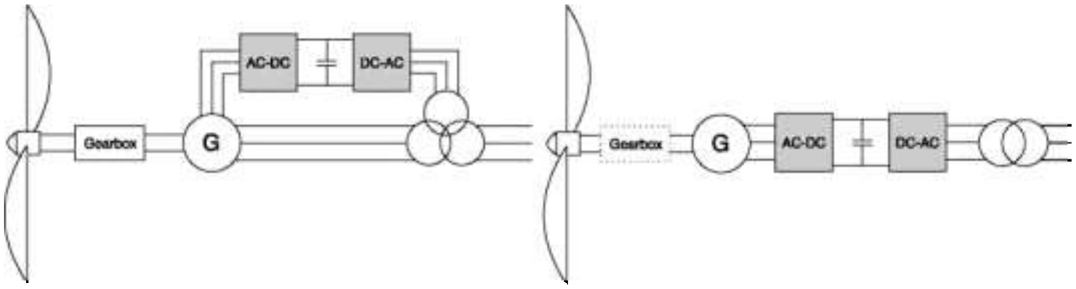
2.1. *Preliminaries: Classification of Wind Turbines*

WTs are usually classified as fixed speed wind turbines (FSWTs) and variable speed wind turbines (VSWTs) [56]. FSWTs work at the same rotational speed regardless of the wind speed [57]. VSWTs can operate around their optimum power point for each wind speed, using a partial or full additional power converter [58]. As a result, VSWTs are more efficient than FSWTs [59]. Moreover, WTs present different topologies depending on their generator [60]: type 1 includes a squirrel cage induction generator; type 2 includes a wound rotor induction generator; type 3 includes a doubly-fed induction generator (DFIG); and type 4 includes a full-converter synchronous generator [61]. Types 1 and 2 are FSWTs, whereas types 3 and 4 are VSWTs.

Nowadays, VSWTs are the most commonly installed WTs [62-65]. Among them, full converter generator WTs seem to be a better option than DFIG-based WTs for OWPP [66-72]. The main differences between DFIG and full-converter WTs are the following:

The DFIG configuration needs a gearbox, generator and partial-scale power converter (around 30%), as shown in Figure 2a. The gearbox couples the blades with the generator, increasing the rotational speed from the rotor hub to the induction machine [73-75]. The stator is directly connected to the grid, whereas the rotor is connected to the power converter [76]. As a result, the converter only covers the power produced by the rotor of the DFIG [77].

The synchronous generator of a full-converter WT is excited by an external DC source or by permanent magnets [78]. In this case, the hole generator is connected to the grid through a power converter [79]. Hence, all the generated power from a WT can be regulated accordingly [80]. They have low maintenance costs and negligible rotor losses [81]. Moreover, some type 4 WTs have no gearbox, as depicted with a dotted line in Figure 2b, using a direct driven multipole generator [82].



VSWTs	Variable speed wind turbines
WPP	Wind power plants
WTs	Wind turbines

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