Review of wind farm power collection schemes

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***Abstract*- The main development trend of wind power generation systems is large offshore wind farms (OWFs) with grid connection. However offshore wind farms have grown rapidly due to much better wind conditions. Hence, several large scale offshore wind farms are planned to be built and installed at distances greater than 100 km from the coast. Traditionally, an AC collector scheme collects energy from the wind farm and step up the voltages by power transformers and transmit power via AC submarine cables to the onshore substation. However, this is suitable for shorter distances about 50 km. When the distances are greater the AC transmission of bulk power from the wind farm to the onshore grid via undersea cables is not viable due the reactive power issues. Therefore HVDC transmission is now being considered for the grid connection of wind farms. However as wind farms constitute weak systems Line commutated converter (LCC) based HVDC is not viable and newer Modular Multilevel Converter (MMC) based Voltage Source Converters(VSC) are needed for AC-DC conversion. Opting for dc systems for both power collection and transmission pose a number of technical challenges in terms of developing HVDC breakers and DC –DC converters.**

Index Terms-- Offshore wind farm, onshore wind farm, HVAC, HVDC transmission and collection.

I. Introduction

WIND power has emerged as one of the most dominant renewable sources of energy with immense growth potential across the globe [1]. In fact the global wind energy capacity has increased rapidly and has become the fastest developing renewable energy technology [2]. With the rapid development of wind energy, the wind energy conversion systems have been developed by researchers and manufacturers [3]-[4].

Offshore wind farms have many advantages over onshore wind farms. Some of those are strong less turbulent wind, the availability of large sea areas and the reduced visual and noise impact from offshore structures. These advantages lead to an increase in energy production and also to a reduction of fatigue on the blades and the structural components of the wind turbines [5]. The target for installed capacity in Europe is 40 GW by the end of 2020 [6].

The offshore technology has a number of issues in terms of modest efficiency, high weight, and size of the offshore installation, cost of transportation, installation and maintenance [7]. Presently, there are two solutions to integrate offshore electrical power transmission: HVAC and HVDC VSC [8]. HVAC has the advantage of a simpler system structure and the lower cost. However, the transmission distances are getting longer, and the capacities of offshore wind farms are increasing, leading to the following problems [5]:

- The stability of the system decreases with the increase of transmission distance.
- Dynamic reactive power compensation must be provided, in particular under AC faults.
- Cost increases with the increase of transmission distance.

These problems can be overcome by using HVDC VSC which has the following advantages:

- Maximum capture of wind energy by frequency control
- Black-start capability.
- Independent control of real and reactive power.

The paper is divided into four sections. In Section I, a general introduction is given. In Section II, a summary of general wind power generation is given followed by explanations of, HVAC and HVDC transmission system topologies based on VSC- HVDC transmission systems. In section III different methods of wind power collection schemes are also explained. Finally, in Section IV, conclusions are drawn.

II. Wind Power Generation

Wind energy has the potential to be the cheapest power source in Europe [8]. EU targets will require a significant change in renewable energy development over a relatively short period of time [8]. According to the Commission's Renewable Energy Roadmap, 34% of all electricity consumption in 2020 is expected to be met by renewable sources, and around 12% could be generated by wind power alone [9]-[10].

The Global cumulative wind power capacity from 1999 to 2020 shows that the wind power has grown quickly to a capacity of 283 GW with 45 GW installed in 2012, and this number is expected to achieve 760 GW in 2020 based on a moderate growth scenario [10]. Wind energy grows more rapidly than any other renewable energy source and is becoming a major player in the modern energy mix. For example, Denmark has a high penetration of wind power and today more than 30% of the electrical energy is supplied by wind [10]. The ambition of Denmark is to achieve 100% non-fossil based power generation by 2050 [10]-[11]. In the United Kingdom renewable energy target is to achieve 20% of energy by 2020. However, it is expected that wind energy will form a large proportion of the renewable energy increase [11]-[12]. Wind farms can either be on shore or off shore.

A. Onshore Wind farms (OWF's)

Onshore wind already plays a leading role in the generation of renewable electricity in the UK [13]-[14]. In 2010, it generated around 7TWh which is more than a quarter of the electricity provided by British renewables at that time and onshore wind is expected to generate up to 30TWh.

The UK's first commercial wind farm was built in Delabole, Cornwall in 1991. Since then, onshore wind energy has

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established itself as a mature, clean and productive technology. It is now the UK's largest source of renewable energy. [14]. In the UK, there are numerous onshore wind projects, ranging from single turbines to larger, multi-turbine schemes. Projects are developed by an increasingly diverse range of people, from large energy companies and independent developers, to community groups or small businesses and farms [15]. Tallentire was also one of the very first operational wind farms to receive the RES' Local Electricity Discount Scheme. Tallentire onshore wind farm, which was completed in June 2013, is made up of six wind turbines located on Tallentire Hill near Cockermouth, Cumbria [16].

B. Offshore Wind farms (OWF's)

The concept of offshore wind power is the extension of onshore wind power, and the main differences between offshore wind farms and the traditional onshore wind farms are as follows:

- High wind speed, large available areas
- Less restriction. Due to the less noise limit, higher speed turbines can be used
- Difficulties of offshore wind power transmission and integration to the grid [9].
- High cost of construction and maintenance. Structures need to resist huge disturbance, such as slat-spray and sea-waves, the initial investment is higher than that on the shore [17].

Over the past 20 years, offshore wind farms developed rapidly, with the transmission distances ranging from 3 km to 56 km and the capacities increasing from 5 MW to 504 MW [8]. The worldwide capacity will reach 75 GW by the end of 2020 [18]. The offshore wind energy potential in the seas of the European Union with water depths of up to 50 m, and is several times larger than the total European electricity consumption [18]. Consequently, in addition to the current large number of onshore sites, many offshore sites are in the planning or implementation stages.

Offshore wind farm capacity in the North Sea and the Baltic Sea (off the northern coast of Europe) alone is expected to rise to 20–25 GW by 2030 [16]-[18]. Many offshore wind farms will be installed at distances greater than 100 km from the coast. It is a great technical challenge to integrate such a large amount of wind power through long distance transmission systems [18].

The UK has done more than any other country to support the development of a sustainable and ambitious offshore wind industry. During 2013, Government has been working in partnership with industry to develop the UK's offshore wind industry, provide the tools necessary to support large scale investment in the UK supply chain and raise awareness of the commercial opportunities in the UK and overseas, to deliver the innovation and competition needed to bring down costs the innovation and competition needed to bring down costs for consumers [16].

Furthermore, the world's largest offshore wind farm, London Array was opened in July 2013. London Array has a 630 MW capacity and produces enough electricity for nearly half a million homes which is equivalent to two thirds of the homes in Kent [19].

III. GRID CONNECTION SCHEMES

The Future offshore wind farms (OWF's) will be mostly located far away from the shore, and have to be connected to the grid point of common coupling (PCC) via undersea cables over long distances [20]. The wind farm electrical system consists of wind turbine clusters, undersea power collection and transmission cables, platform substation, transformers and onshore substation [21]. The key criteria that offshore wind farm connection design must consider are the trade-offs between the initial capital investment, power losses and availability due to scheduled maintenance or wind turbine failure and other system faults [22].

The availability and reliability issue is particularly important as the repairing process is very difficult in the marine environment [20]-[22]. The mature transmission technology is High Voltage Alternating Current (HVAC). However the problems arising from reactive power flow has led to the consideration of High Voltage Direct Current (HVDC) technology, particularly, for windfarms considerably away from the shore.

The electrical system of a wind farm can be considered as several distinct subsystems. As shown in Fig 1, the electrical system of OWF typically consists of five sub-systems.

- Wind farm (generation)
- Power collection
- Voltage step up
- Transmission system
- AC grid

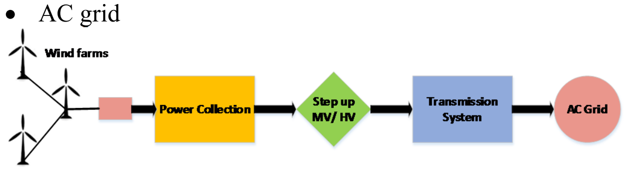

Fig. 1. The different components on OWF's electrical system

A. Alternating Current transmission (AC)

Most of the existing offshore wind farm transmission systems use HVAC for the transport of electrical power between mainland and stations located on (or under) the sea [23]. It is a well-established technology, and HVAC system contains the following main components:

1) AC collection system.
2) Offshore transforming substation with transformers and reactive power compensation.
3) Three-phase submarine cable
4) Onshore substation with transformers and reactive power compensation.

The electrical system depends on the distance and the windfarm capacity. For short distances if the connection voltage is at distribution level. High voltage transmission may not be necessary and hence the number of voltage transformations can be reduced. If the transmission distance is long, the number of cables and the losses are too high and a raise in the transmission voltage is necessary. Horns Rev Wind Farm in Denmark, with a power of 160 MW and a

transmission distance of 21 km, is first offshore wind farm using HVAC [23].
The distributed capacitance in submarine cables is much higher than the capacitance in overhead lines [23]. Therefore, due to economic and technical reasons the practical transmission length is short for marine applications. Reactive power increases with voltage and length of the cable and long-transmission distances require large reactive compensation equipment at both ends of the line [23]-[24]. Therefore for longer transmission lengths DC is the only option.

B. High Voltage Direct Current transmission (HVDC)

As offshore wind farms become larger and more distant from shore, the justification of using HVDC to transmit the power to the onshore network becomes easier, particularly at power levels of *500* MW or more, and at a distance of 60-80 km for offshore submarine transmission [25]. The costs of the converter stations, offshore and onshore, are significant in themselves, but when put in the context of the complete project cost, including the cables and the wind turbine generators, they feature less prominently.
Two types of converters are available, the Line-Commutated Converter (LCC) and the more recently introduced Voltage-Sourced Converter (VSC). For offshore wind power LCC converter is not suitable, because the LCC requires a strong network voltage to commutate, and wind farms usually have weaker grids that cannot supply such a strong voltage. In addition, the capability to energize the system from shore (black start) is a challenge [26]. These issues can be alleviated by combining the LCC-interface for an offshore wind farm with some auxiliary source of reactive power. The LCC produces considerable AC side current harmonics that require filter banks [25]-[26].
High power IGBT (Insulator Gate Bipolar Transistor) development allows the use of VSCs in HVDC systems with much lower harmonic distortion than HVDC LCC systems although with higher power losses [23]. The VSC is able to control active and reactive power independently and generates a voltage on the AC side. It is therefore able to operate in weak networks [26]. A VSC connected wind farm requires a tailored control system. The main drawback of the VSC is its lower current capability. Even for very short durations, over currents cause thermal stresses that degrade or cause permanent damage to the switching elements [23][26].

C. Wind farm power collection system

The wind farm collection system gathers the wind turbine's power production and brings it to a central collection point (CCP), which then ties in to the main grid through the transmission system (TS) [22]. This section presents the state of the art MVAC collector systems and MVDC collector systems.

1) MVAC collector systems

There are a number of possible turbine arrangements in wind farm MVAC collector systems but three of them are being currently considered: namely radial layout, star connection and double-sided ring collector systems [22].
A radial collect system (CS), also known as string, is that in which a number of OWTs are connected to a single cable feeder within a string. Such a system is used in Barrow, Lillgrund, Thorntonbank-1 and Belwind-1 [22].
The number of wind turbines on each string feeder is determined by the capacity of the generators and the maximum rating of the MVAC submarine cable within the string. Its advantages are the simplicity of its control and the smaller total cable length.
Its major drawback is its poor reliability, as cable or switchgear faults at the hub end of the string can prevent all downstream turbines from exporting power.
The main purpose of the star connection is to reduce cable ratings and to provide a high level of security for the entire wind farm. Voltage regulation along the cables between wind turbines is also likely to be better in this design [24]-[26]. However, there are additional expenses due to the longer diagonal cable runs and some short sections of higher-rated cabling; but these expenses are not likely to be significant.
The more complex switchgear requirement at the wind turbine is the major cost implication [26]-[27]. The main advantages of star topology are better voltage regulation and reliability.
Double-sided ring design is a way to lower losses through high voltage collection, and provide greater security; however this kind of connection requires much more expensive high voltage cables [16]. This layout has higher reliability compared to the radial layout. In case of fault, the radial connection (in normal operation) can be reconfigured and the energy produced is not lost [28]. Because of higher cable sections, higher cable length (connections between collector groups), more complex system (depending on location and number of reconfiguration switches), this solution implies higher investing costs [28]-[29].

2) MVDC collector systems

Conceptually, MVDC collector systems are those linking turbines with DC output and a HVDC transmission link to shore. In a general sense, the arrangement of these collector systems (CSs) can be one of those previously commented on for MVAC collector systems.
In general, the DC grid consists of several clusters, which are connected either in parallel or in series [12]-[30]. Since the difference between the output power of each turbine and the total power transferred to the shore is huge, several voltage steps are needed [30]. Consequently, a DC/DC converter system is needed for stepping up the voltage [12]-[30]. Three possible DC collection schemes for offshore wind farms as discussed below.

a) AC Collection – DC Transmission

As shown in Fig. 2, wind turbines are arranged in clusters and the wind generator produces variable frequency variable magnitude voltage AC voltage, which needs to be processed as the grid voltage is at fixed frequency and voltage [7].
This process is carried out by a DC link converter-comprising a generator side rectifier and a grid side inverter. Then this

voltage, which is 690V in UK, is stepped up to the level required by the medium voltage collection bus. This medium voltage is then stepped up to the transmission level and fed to a HVDC converter for dc transmission. At the onshore substation the DC power is converted back to AC for connecting to the grid. This arrangement requires a large number of conversion stages [8].

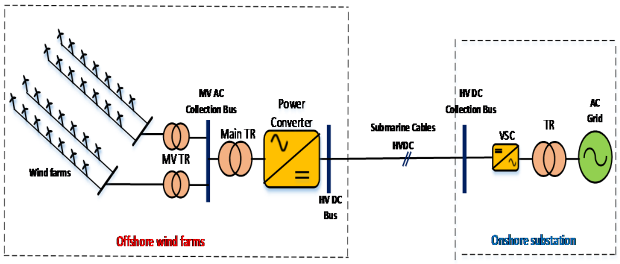

Fig. 2. AC collection - DC transmission

b) DC Collection – DC Transmission: one cluster step-up

The second solution is shown in Fig. 3 (a) where the power is collected first and then a DC-DC converter steps up the voltage to the transmission level. Since the number of converters is lower and the transformers are eliminated, this design is better [30]-[31]. However, only two voltage levels are used and consequently the distribution level strongly depends on the generator voltage. The advantage of this collection is that it leads to the lowest losses because of the short distances within the wind farm [30]-[32]. However the required voltage transformation may not be achievable with one stage of dc-dc conversion.

c) DC Collection – DC Transmission (two step-ups)

In this method as shown in Fig. 3 (b), two DC/DC converters are used; one steps up the voltage after each turbine up to the medium-voltage level. Afterward the power is collected and stepped up a second time to the transmission level.

The use of high power DC-DC converters may lead to significant reduction in the overall system size and weight as well as the construction and installation cost of the wind turbines and substation platform [12]-[31].

An advantage of this configuration is the direct step-up of the voltage after the turbine, which leads to reduced cable losses at the distribution level. Furthermore, the voltage can be controlled individually, but there is one drawback of this configuration method is the additional DC-DC converter, leading to extra losses, investment cost and low efficiency.

c) DC Collection – DC Transmission (turbine step-up)

The final HVDC collection, only use single DC/DC converters are connected directly to each turbine as shown in Fig. 3 (c). Hence, only two levels are used and the losses at the distribution level are reduced, because of the high voltage [30]. Nevertheless, the output rectifier of the DC-DC converter needs to be designed for the transmission voltage with quite a low power level e.g. 160 kV at 5 MW, which could reduce the efficiency of these converters [31]-[32].

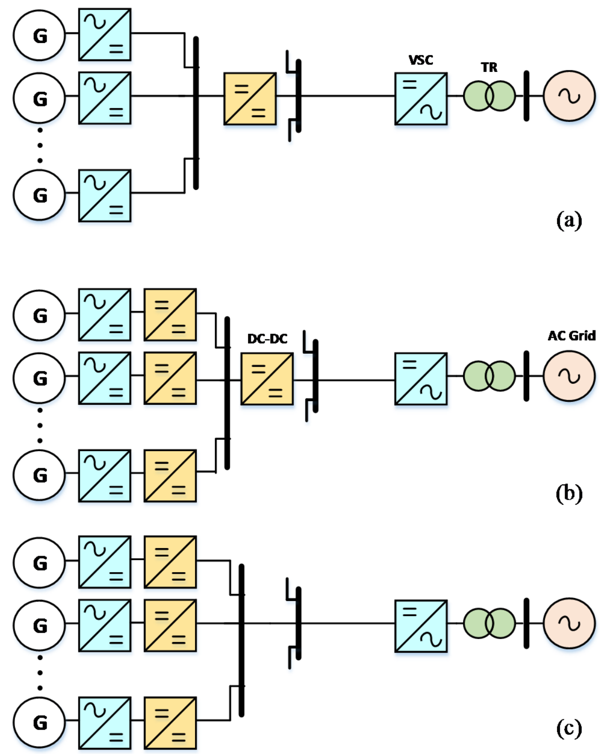

Fig. 3. Different configurations for the dc grid. (a) One cluster step-up. (b) Two step-ups. (c) Turbine step-up [30].

IV. CONCLUSIONS

Offshore wind farm technology has experienced a major transformation in terms of both the level of installed capacity and the technological maturity. All indications are that there is a further significant growth potential in the years ahead. This paper has highlighted the main features of HVDC systems. It has made a comparison with HVAC systems and shown that HVDC systems have good characteristics interms of electrical, economic and environmental considerations.

VSC-based HVDC system is a viable transmission connection for large offshore wind farms, especially when long distances are involved. HVDC and HVAC connection systems for offshore wind power plants have been proposed, which HVDC would offer lower cost, higher efficiency, and enhanced grid support in comparison with AC solutions.

By eliminating the offshore substation and having grid interface converters at the onshore substation, the overall system maintainability and availability would be greatly improved. This design concept may become attractive as wind farms move into deeper water and offshore platforms potentially become even more expensive.

There is no available high power MV DC-DC converter for offshore wind farm energy system at present, but a number of different topologies have been studied recently. The specification requirements of high power MV DC-DC converters, because the offshore wind farm with MVDC-grid collection does not exist today, but is a promising alternative, specification analysis of high power MV DC-DC converter is necessary.

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