A Review on DC Collection Grids for Offshore Wind Farms with HVDC Transmission System

Kabeya Musasa[1], Nnamdi I. Nwulu[1], Michael Njoroge Gitau[2], Ramesh C. Bansal[2]

[1] Department of Electrical and Electronic Engineering Science, University of Johannesburg, South Africa
[2]Department of Electrical, Electronics and Computer Engineering, University of Pretoria, South Africa
kabeyamusasa@gmail.com, nnwulu@uj.ac.za, njoroge.gitau@up.ac.za, rcbansal@ieee.org

Abstract: Traditionally, the internal network composition of offshore wind farms consists of alternating current (AC) collection grid; all outputs of wind energy conversion units (WECUs) on a wind farm are aggregated to an AC bus. Each WECU includes: a wind-turbine plus mechanical parts, a generator including electronic controller, and a huge 50-or 60-Hz power transformer. For a DC collection grid, all outputs of WECUs are aggregated to a DC bus; consequently, the transformer in each WECU is replaced by a power converter or rectifier. The converter is more compact and smaller in size compared to the transformer. Thus reducing the size and weight of the WECUs, and also simplifying the wind farm structure. Actually, the use of offshore AC collection grids instead of offshore DC collection grids is mainly motivated by the availability of control and protection devices. However, efficient solutions to control and protect DC grids including HVDC transmission systems have already been addressed. Presently, there are no operational wind farms with DC collection grids, only theoretical and small-scale prototypes are being investigated worldwide. Therefore, a suitable configuration of the DC collection grid, which has been practically verified, is not available yet. This paper discussed some of the main components required for a DC collection grid including: the wind-turbine-generator models, the control and protection methods, the offshore platform structure, and the DC-grid feeder configurations. The key component of a DC collection grid is the power converter; therefore, the paper also reviews some topologies of power converter suitable for DC grid applications.

Keywords: DC collection grid, active rectifier, offshore wind farm, HVDC system.

1 Introduction

Electricity production from fossil fuels has been widely adopted in the world because of diverse reasons, such as higher energy density in relative large quantity, cheaper cost and well-known technology. Coal-fired based power plants supply about 41% of global electricity [1] and in some countries, such as South Africa, it can be as high as 90% [2, 3]. However, it is estimated that if the energy from fossil fuels continue to be consumed at the present rate, it will not last long. Furthermore, electricity generation from coal is no longer a better choice due to several environmental concerns [4]. The global warming experienced due to the use of coal- and oil-fired based power plants has promoted the use of renewable energy solutions, such as photovoltaic (PV), small hydro and wind. Among various renewable generation technologies, the electric power generated by wind resources has become an increasingly important part of the world's energy production portfolio. For example, by the year 2015, the regional production of wind power capacity was distributed as follows: 175.573 GW Asia; 147.77 GW Europe; 88.74 GW North America; 12.22 GW Latin America; 3.3 GW Africa; and 4. 8 GW Pacific regions [5]. More details on the European statistics 2015 can be found in [6]. The global cumulative installed wind power capacity is expected to reach 760 GW in 2020 [7, 8].

Offshore wind technology is relatively new, and is expected to grow in the coming years as the technology evolves and the cost of installation decreases. It is the most promising choice, categorised as the key future power generation technology for renewable energy. The global installed offshore wind capacity by the year 2015 was 12.105 GW. The United Kingdom was leading with about 5 GW, followed by Germany 3.295 GW, the Republic of Denmark 1.27 GW, China 1.018 GW and Belgium about 0.712 GW [5]. The installations of offshore wind farm are less subjected to site restrictions. This is also of particular interest because of the strong and constant wind speed at sea, which enables production of high power output. The technical challenge with the offshore wind farm is that the structural stability needs to be strong and compact because of high wind speed out at sea.

However, most of the traditional offshore wind farms are constructed with aggregation of WECUs. Each WECU comprises of a wind-turbine with mechanical parts e.g. drive trains, a generator e.g. doubly fed induction generator (DFIG) or permanent magnet synchronous generator (PMSG) including power electronics circuits, and a huge 50- or- 60 Hz power transformer. The large quantity of magnetic components employed in the power transformer makes the WECUs to be less compact and not strong enough to withstand the high speed winds. The most commonly used layout of offshore wind farms consists of ring or series, radial or parallel, or both series-parallel, and star interconnections of WECUs; resulting to an offshore wind farm with internal AC collection grid [9-11].

The state-of-the-art technologies applied to the design of various traditional WECUs are presented in [7, 8, 12-16]. Pitchable blades are integrated in the wind-turbines, which facilitates the control of input power to the wind-turbine-generator. The active stall or pitch control method can be used to control the input power to the wind-generator. The use of asynchronous machines embedded with power electronic circuits in WECUs have led to the control concept named “variable speed wind turbine”. The electronic circuit provides the control of active and reactive power, speed or frequency, voltage, and torque. The use of variable speed concept is motivated by a number of reasons. These include the reduction of the mechanical stress of the drive trains (internal elements of the gearbox), enabling tracking of the maximum wind energy, and providing control of speed or frequency and voltage. The control of voltage and frequency is very important for satisfactory integration of offshore wind farms to the onshore grid [17-20]. The fixed speed wind turbine is another control concept which does not integrate power electronic circuits in the WECUs. The control of voltage and frequency is coordinated by a regulator e.g. STATCOM (static compensator) installed at the utility grid side. The principle of operating a fixed speed based WECU is such that, the speed of turbine-blade is boosted, via a gearbox, up to generator-rotor synchronous speed. The difference between the electrical angular frequency imposed by the utility grid and the generator-rotor mechanical speed produces a positive slip, thus enabling the power flow enhancement.

The total power produced by the WECUs on the wind farm is collected, via an AC collection grid, and transferred to onshore grid. Depending on the distance to the onshore grid and the power rating, either the HVAC or HVDC transmission system can be used for the power delivery. Actually, most of the offshore wind farms are planned to be installed far from the shore, e.g. at a distance more than 60 km. For tracking of maximum wind energy and for some others environmental issues such as to minimise the visual and audible impacts on nearby residences; the HVDC system is a preferable option than the HVAC system [21-23].

A typical configuration of an AC offshore wind farm with HVDC transmission system can be found in [22, 23]. The Power transformer station is installed offshore on a platform which steps up the voltage to 161 kV across the AC collector or AC bus. A short AC cable transfers power to the HVDC-rectifier platform, on which power converter is installed for HVAC to HVDC conversion. Once onshore, an HVDC-inverter platform is used for HVDC to HVAC conversion. A total of three platforms are required for an offshore wind farm integrating an AC collection grid with HVDC transmission line. The advantages of using HVDC transmission system is that, low quantity of DC cables is needed, no charging current and skin effect exist in the DC cables, power factor is always close to unity and there is less corona loss and radio interference [24].

The use of AC collection grids, instead of DC collection grids, on wind farms are mainly motivated by the availability of control and protection devices [25, 26]. Presently, efficient and cost-effective control and protection devices for the DC collection grids have already been addressed [27-33] and this may not be a problem anymore. For the design of a DC collection grid; the 50-or 60- Hz power transformers installed in the WECUs are replaced by the power converters or rectifiers [34, 35]. The power converters are significantly compact and smaller in size compared to the power transformers of similar power rating. This reduces the size and weight of WECUs, and hence the offshore wind farm. For an offshore wind farm with DC collection grid and HVDC transmission system, a total of two platforms (rectifier and inverter stations) is needed, this also reduces the cost of platform installation. Technically, the power converters in WECUs perform power rectification, power conditioning, power filtering, and power compensation. The power rectification enables the conversion of signals (voltage and current) from AC to DC. The power conditioning provides the control of frequency, voltage, power factor, and speed of rotating machines. The power filtering injects (or absorbs) specific signals components for power quality. And the power compensation enhances the voltage/angle stability.

Currently, there are no operational offshore wind farms with DC collection grids, only theoretical and small-scale prototypes are being investigated worldwide. Therefore, a suitable configuration for the wind farm with DC collection grid which has been practically verified is not available yet. This paper examines the key technologies associated with DC collection grids for offshore wind farms with HVDC transmission system; typical configurations of the DC collection grids, including control and protection methods are reviewed. The paper also provides an overall perspective of various types of power electronics converters or active rectifiers, possibly being employed in WECUs for DC grid applications.

2. Generalised concept for offshore wind farm development

Many factors contribute to the lower use of offshore wind resources. Among them are: access to data for determining resource levels and optimal locations as well as the cost of transmitting the wind-generated power to the utility grid. Several areas of research and development are currently available that can help to establish a roadmap to achieve greater levels of offshore wind power production. These research and development areas include [36, 37]:

(i) The offshore wind production profile development- This is an important aspect in the planning for future offshore wind power plant expansion to make sure that the installed capacity will be sufficient to provide adequate electricity when needed.

This group based research area determines the location for the offshore wind development based on geographic information. The model for this task provides a likely build-out scenario over time across various regions based on wind resource and wind variability. The task also determines the sites to be excluded for offshore wind development based on environmental, governmental, or technical constraints. A net capacity factor map for the offshore wind development can therefore be constructed. A typical illustration for this task can be found in [38], which reports the first international validation of wind-energy profiles analysis, testing NASA MERRA and MERRA-2 in 23 European countries. It is noted that the capacity factors are rising due to improving technology and locations.

Also, in [39] the wind-energy profiles for different European regions were analysed based on the developed computer-aided program which can be found online: see "https://beta.renewables.ninja/". Different factors of wind characteristics that can impact the reliability of electricity system have been evaluated. It was concluded that due to the effect of inter-annual variation of wind profile, reanalysis of the wind characteristics is important to accurately predict the wind power output capacity of a given region. Furthermore, the dispersed nature of wind profile provides a good reason for offshore wind farms to be installed at different locations. This is because diversity will provide added improvement on system reliability. However, wind developers always want to build their wind farms in locations that will offer a high wind power capacity; it would be better if the next wind farm is located in another region with a different wind profile, which will provide an added improvement to system reliability like observed by [39].

(ii) The technology assessments- This task assesses offshore wind farm collection and transmission technologies. The research areas that can originate from this task include: offshore platform size and weight reductions, cable developments, wind turbine configurations, wind farm collector system designs, and design of compact high-voltage power converters. The analyses that follow focused on the technology assessments for offshore wind development.

3. Technology assessments for offshore wind power plant

To enable use of the offshore resources, it is crucial to transport the wind-generated power to shore and feed that power into the utility network. In order to facilitate this process, three specific domains can be defined, as depicted by Fig. 1: namely, the generation or production, the collection, and the transmission. Each domain presents its own set of technical concepts. For example, based on Fig. 1, the topics that can be considered when designing the collection system include: wind-turbines and generators configurations, wind power plant layout, platform size, and cables and power electronics converters design. Actually, there are different methods that can be used to collect wind-generated power and deliver it to the utility power network.

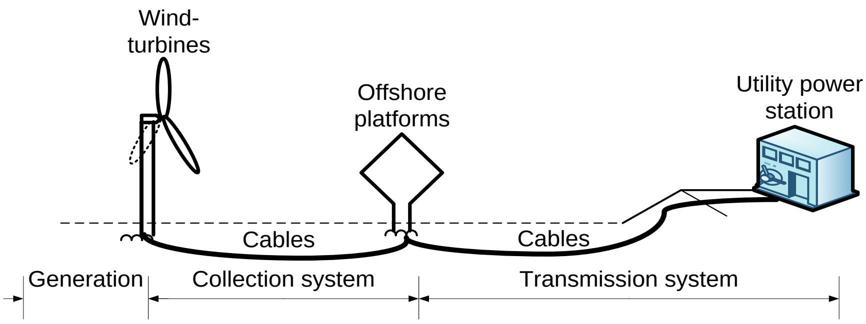

Fig. 1 Structure of an offshore wind power plant and transmission system

The technologies that utilise the AC concepts have distance limitations, because of the cable charging currents concern. This technology requires that the offshore wind farm be near utility power grid; or additional offshore platforms with voltage regulator (or reactive compensation) can be used, which increases the cost of the overall power distributed system. From the present verification, it has been demonstrated that the HVAC power delivery technology is the most economical option for distances shorter than 50 km [36].

The HVAC and HVDC power delivery systems are likely to be similar in terms of cost between 50 and 80 km. For distances longer than 80 km, the HVDC transmission option can be the least expensive. The HVDC transmission system does not experience the problem of distance limitation; cable charging is not a concern, but it requires use of large converter stations at offshore platforms. Uses of DC technologies for offshore wind farm collector systems with HVDC transmission line are generally expensive; however, these have always demonstrated the potential to bring important benefits that may help justify their higher costs. For example, by use of DC collection grids one can achieve flexible integration of wind farm into utility grid through an effective control of frequency, voltage, or active and reactive power. The use of DC collection grids in offshore wind farms also enables the use of compact components in WECU, making the offshore wind farm structure compact.

Furthermore, the DC technologies enable an easy and efficient integration of storage systems, which is attractive to overcome energy losses at low demands.

3.1 WECU concepts for wind power plants with DC collection grid

There are many factors that can influence the choice of WECUs for offshore wind farms with DC collection systems. Among them include: ability of speed control, type of power converter including control and protection methods. However, the most important requirement is that the WECUs must be robust and maintenance free; because it may be very expensive and difficult under some weather conditions to do offshore maintenance or repairs. Also, the selection of one type of WECU over another can only be made through appropriate analysis of the full operating cost, including losses. Furthermore, careful studies can be conducted to analyse the benefits that may accrue to the entire wind power plant for a given WECU option. Typical models of WECUs for offshore wind farm with DC collection grids are shown in Fig. 2 [14, 40]. These include:

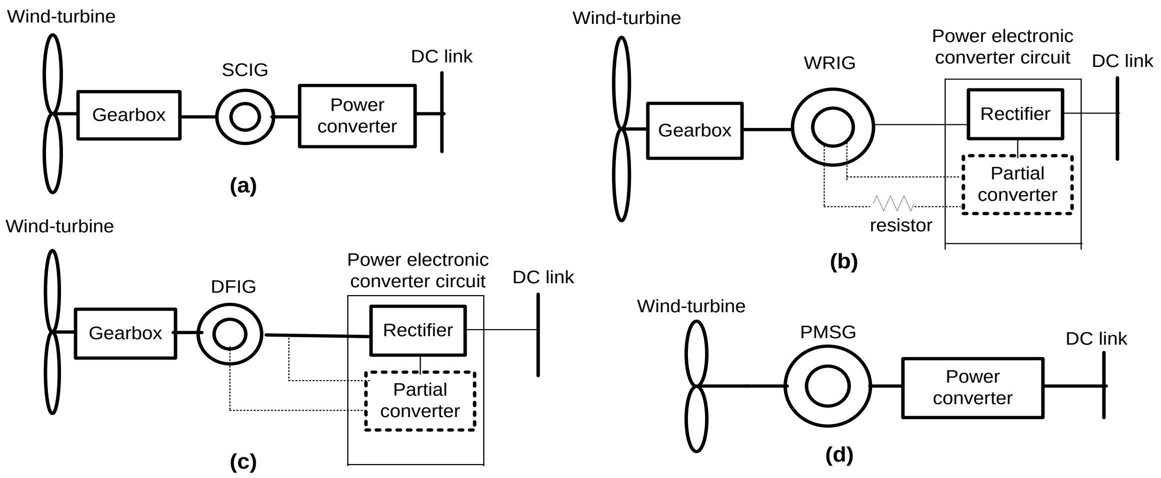

Fig. 2 Schemes of typical wind-turbine-generator models: (a) wind-turbine with multiple-stage geared and SCIG, (b) limited speed based wind-turbine concept with WRIG system, (c) variable speed based wind-turbine concept with DFIG system, (d) direct-drive based wind-turbine with EESG system, and (e) direct-drive based wind-turbine with PMSG system

(i) a variable speed wind-turbine with a multiple-stage gearbox and an asynchronous squirrel-cage induction generator (SCIG) with a full-scale power converter or active rectifier, i.e. Fig. 2a; the full-scale power converter on the generator stator side replaces the capacitor bank and soft-starter of “fixed speed based SCIG concept” or “Danish concept” [41]. The well-known advantages of this concept are: robustness, simplicity, flexible control, better performances of reactive power compensation and smooth grid connection. The drawbacks for this concept include high cost, high power losses, immensity of gearbox, does not support any speed control, it requires a stiff grid, and high mechanical stress caused by wind gusts. Currently, Siemens manufactures this type of wind-generator with a rated power of 3.6 MW and a generator speed range of about 595-1547 rpm [40].

(ii) A limited variable speed concept and a wound rotor induction generator (WRIG) system with a full-scale power converter, i.e. Fig. 2b; in this concept, the rotor winding of the generator is connected in series with a variable resistor and a power converter, as shown in Fig. 2b. It should be noted that for a wind farm with DC collection grid, all wind-turbine-generators on wind farm are connected to a DC link. Consequently, rectifiers are needed on the stator-side of the generators for the AC to DC signal conversion. In Fig. 2b, the control of speed or frequency is achieved by regulating the energy extracted from the rotor-winding; this energy is then dissipated in the external resistor in the form of heat. The full-scale power converter (or rectifier) on the stator side performs the power rectification and enables smooth grid connection. To reduce the electrical losses and frequency of maintenance, the use of slip rings with brushes can be avoided; the control signals between variable resistor and rotor winding can be transmitted using an optical coupling. Actually, the Danish manufacturer “Vestas Wind Systems” builds this type of generator with an optical coupling [40, 41]. The drawbacks of this concept include: high cost and losses due to large number of converters employed in the WECU circuits.

(iii) A variable speed wind turbine with a WRIG and a partial-scale converter on the rotor circuit, i.e. the doubly fed induction generator (DFIG) concept, with a full-scale power converter, i.e. Fig. 2c [42]. This is the improved version of the WRIG with a variable resistor. In this concept, the generator-rotor energy, instead of being dissipated as for the WRIG with variable resistor, it is fed into the grid through a partial-scale power electronic converter, as shown in Fig. 2c. The partial-scale converter installed on the generator-rotor side controls the rotor speed or frequency, whereas the full-scale converter installed on the generator-stator side performs power rectification and also enables smooth grid connection. A multi-stage gearbox is generally needed for this concept; however, the use of gearbox has some drawbacks, such as heat dissipation from friction and regular maintenance.

Other shortcomings of this concept include: use of slip ring to transfer the generator rotor energy to the grid, which results into regular maintenance and electrical losses. Also, under grid fault conditions large currents can be transferred to the rotor winding, thus the partial-scale converter on the rotor side needs to be protected; the corresponding protection strategies may be very complicated. The brushless DFIG (BDFIG) concept proposed by [40] does not require the use of slip ring. However, it requires double stator windings, with different number of poles in both stator layers. This second stator winding is connected through a partial-scale converter. The shortcoming of the BDFIG concept is its assembly which is relatively very complex.

(iv) A variable speed direct-drive concept with a full-scale power converter. There are two groups of direct-drive based wind-turbine-generator concept that can be found in the markets: namely, the electrically excited synchronous generator (EESG), and the permanent magnet synchronous generator (PMSG), depicted by Fig. 2d. In these concepts, the generator-rotor is connected directly on the hub of the wind-turbine rotor, resulting to a low speed and high torque operations. Presently, the direct-drive based wind-turbines with PMSGs are becoming more attractive than before; the performance is improving and the cost is decreasing. However, due to the low speed operation, further improvement was needed. The single-stage geared wind-turbine concept with PMSG was discussed in [40, 41]; the single-stage planetary drive train increases the speed of the PMSG by a factor of about 10. This concept has gained more attention because it has the advantages of a higher speed than the direct-drive concept and a lower mechanical component than the multiple-stage gearbox concept.

Table 1 contains the list of the top ten wind-turbine-generators manufacturers in the world, including the control method and performance characteristic of each scheme [41]. It can be observed that the market interest in the variable speed wind turbine concept with DFIG has become the most dominant option. This can be justified by the fact that most of the wind power plants are actually built based on AC collection systems. The use of DC collection grids in wind farms are not implemented yet. Theoretically, WECUs integrating the single- and the direct-stage geared wind-turbine with PMSG is mostly considered for DC offshore collection grid applications because of its compactness and robustness.

Table 1 List of top ten wind-turbine-generator suppliers in the world [41]

Manufacturers	**Control features**	**Wind-turbine-generator characteristics**
BONUS (Denmark)	Active stall fixed speed concept	2 MW and 2.3 MW wind-turbines with SCIG: Gen. voltage 690 V, gen. speed range 1000-1500 rpm, WT rotor speed range:11-17 rpm
NORDEX (Germany)	DFIG based variable speed concept with pitch control	2.5 MW wind-turbine with WRIG: Gen. voltage 690 V, gen. speed range 700-1300 rpm, WT rotor speed range:10.9-19.1 rpm
	DFIG based variable speed concept with pitch control	1.5 MW wind-turbine with WRIG: Gen. voltage 690 V, gen. speed range 1000-1800 rpm, WT rotor speed range:9.9-17.3 rpm
MADE (Spain)	Pitch full variable speed concept	2 MW wind-turbine with WRSG: Gen voltage 1000 V, Gen. speed range 747-1495 rpm, WT rotor speed range:7.4-14.8 rpm
	Stall fixed speed concept	2.32 MW wind-turbine with SCIG: Gen voltage 690 V, Gen. speed range 1010-1519 rpm, WT rotor speed range:12.5-18.8 rpm
REPOWER (Germany)	DFIG based variable speed concept with pitch control	2 MW wind-turbine with WRIG: Gen voltage 690 V, Gen. speed range 900-1800 rpm, WT rotor speed range:10-20 rpm
	DFIG based variable speed concept with pitch control	1.5 MW wind-turbine with WRIG: Gen voltage 690 V, Gen. speed range 1000-1800 rpm, WT rotor speed range:9.7-17.3 rpm

ECOTECNIA (Spain)	DFIG based variable speed concept with pitch control	1.67 MW wind-turbine with WRIG: Gen voltage 690 V, Gen. speed range 1000-1950 rpm, WT rotor speed range:10-19 rpm
	Stall fixed speed concept	1.25 MW wind-turbine with SCIG: Gen voltage 690 V, Gen. speed range 1012-1518 rpm, WT rotor speed range:12.4-18.6 rpm
VESTA (Denmark)	DFIG based variable speed concept with pitch control	2 MW wind-turbine with WRIG: Gen voltage 690 V, Gen. speed range 905-1915 rpm, WT rotor speed range:9-19 rpm
	OptiSlip based variable speed concept with pitch control	1.8 MW wind-turbine with WRIG: Gen voltage 690 V, Gen. speed range 1800-1980 rpm, WT rotor speed range:15.3-16.8 rpm
ENERCON (Germany)	Full variable speed concept with pitch control	4.5 MW multipole (gearless) wind-turbine with WRSG: Gen voltage 440 V, Generator/WT rotor speed range:8-13 rpm
	Full variable speed concept with pitch control	2 MW multipole (gearless) wind-turbine with WRSG: Gen voltage 440 V, Generator/WT rotor speed range:10-22 rpm
NEG MICON (Denmark)	DFIG based variable speed concept with pitch control	2.75 MW wind-turbine with WRIG: Gen voltage 960/690 V, Gen. speed range 756-1103 rpm, WT rotor speed range:12-17.5 rpm
	Active stall fixed speed concept	2 MW wind-turbine with SCIG: Gen voltage 960 V, Gen. speed range 1002.4-1503.6 rpm, WT rotor speed range:12-18 rpm
GAMESA (Spain)	DFIG based variable speed concept with pitch control	2 MW wind-turbine with WRIG: Gen voltage 960/690 V, Gen. speed range 900-1900 rpm, WT rotor speed range:9-19 rpm
	OptiSlip based variable speed concept with pitch control	1.8 MW wind-turbine with WRIG: Gen voltage 960/690 V, Gen. speed range 1818-1944 rpm, WT rotor speed range:15.1-16.1 rpm
GE WIND (USA)	DFIG based variable speed concept with pitch control	3.2 MW wind-turbine with WRIG: Gen voltage 3.3 kV/690 V, Gen. speed range 1000-1800 rpm, WT rotor speed range:7.5-13.5 rpm
	DFIG based variable speed concept with pitch control	1.5 MW wind-turbine with WRIG: Gen voltage 960/690 V, Gen. speed range 1000-2000 rpm, WT rotor speed range:10.1-20.4 rpm

3.2 Typical topology of power converter for WECUs

The DC collection grid for offshore wind farm begins with power converters at each wind turbine, usually in the base of the tower, which steps up the voltage output of the generator, typically 690 V, to a medium voltage of typically 25–40 kV. A medium-voltage submarine DC cable is used to connect the WECUs to a DC platform. Furthermore, the power converter performs the following functions: power rectification to convert signals (voltage and current) from AC to DC; power conditioning to provide the control of voltage and speed of rotating machines; and power filtering to inject (or absorb) specific signals components for power quality.

In fact, there are two types of power converter topology for WECUs, namely: those integrating a high frequency transformer and those with no high frequency transformers. For the one with no high frequency transformers, the suggested WECU topologies consists of wind-turbine-generator (e.g. PMSG) interfaced: by a three-phase diode bridge-rectifier cascaded with a single-switch DC-DC converter [43-47], by a three-phase diode bridge-rectifier cascaded with an interleaved single-switch DC-DC converter [48], by a conventional three-phase full-bridge voltage source converter [28, 49, 50], by a three-phase neutral point clamped (NPC) converter [51], by a half-bridge voltage source converter [52], by a thyristors-converter [53], and by a current source converter (CSC) with self-commutated switches [54].

Even though numerous power converter topologies have been introduced in the literature for DC WECUs, only a few can be considered realistic for high voltage applications. The thyristors-converters for example have been widely used for a long time in high-voltage applications. However, they require a large size of harmonic filter, which will result in a large footprint of the offshore wind farms. On the other hand, the VSC technology has distinctive advantages such as smaller size harmonic filters and independent control of active and reactive power. Actually, the conventional three-phase full-bridge VSC and the three-phase neutral point clamped (NPC) VSC topologies are the most promising technical solutions for high- voltage applications. Major advances in VSC-HVDC technology have also been achieved by the introduction of the modular multilevel VSC topology, e.g. in [40].

However, the drawback of not having high/or medium frequency transformers in the WECUs is that there is no galvanic isolation between the generators and the DC link. In fact, for WECU concepts integrating a medium frequency transformer [55-57]; the suggested topologies consist of a wind-turbine, an induction generator, and a VSC connected to a single active bridge (SAB) DC-DC converter. The SAB DC-DC converter consists of a high- frequency inverter, a high-frequency transformer, and a high-frequency diode-rectifier. With this WECU concept, the excitation of the induction generator can become a problem as it cannot be achieved from DC grid or shore due to the diode bridge-rectifier. Alternatively, the induction generator has been replaced by a PMSG which is self-excited making the use of a passive diode bridge-rectifier unproblematic. Otherwise, the SAB DC-DC converter can be replaced by a dual active bridge (DAB) DC-DC converter; in which the diode bridge-rectifier is replaced by an active bridge-rectifier.

3.3 Offshore wind power plant configurations

Another feature of the DC collection grid that must be considered is the configuration of the offshore wind power plant itself. Typical configurations of the wind farm with DC collection systems are presented in Fig. 3 [36]. The WECUs are connected into multiple strings or several branches circuits that feed into an offshore platform. These configurations are radial connection (Fig. 3a), bifurcated-radial or star patterns connection (Fig. 3b) where the cables of multiple strings come to a central node from which the energy of the entire group is shipped to the DC offshore platform, single-sided rings connection (Fig. 3c) with a secondary cable connected between the last WECU in a string and the DC offshore platform, and double-sided rings connection (Fig. 3d) which connects the far ends of two strings together.

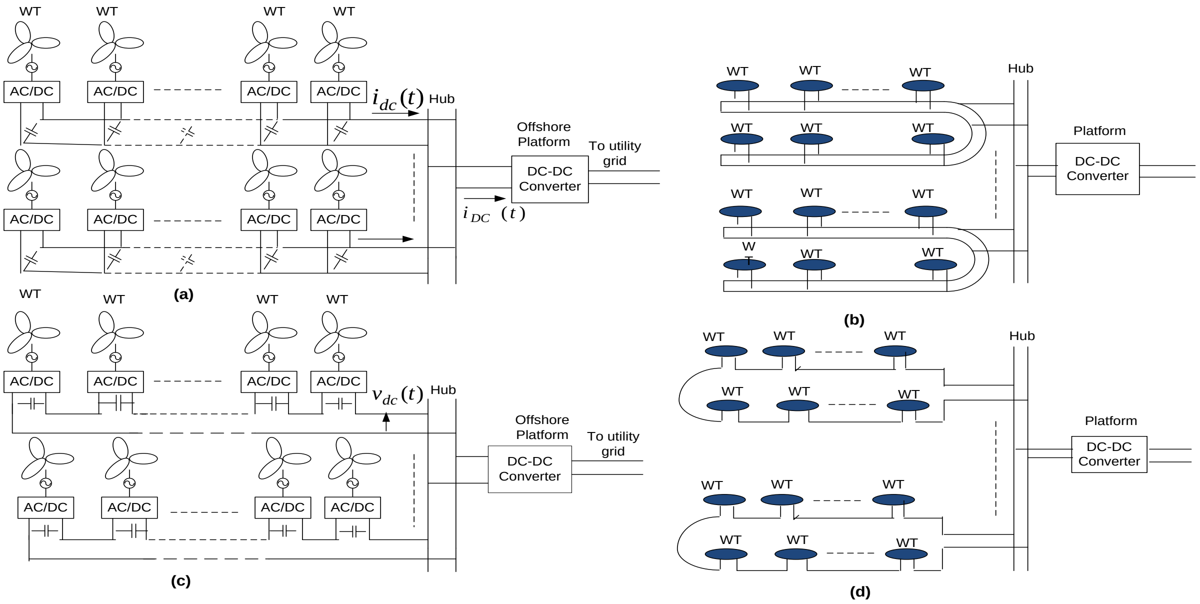

Fig. 3 Offshore wind farm collector system configurations, (a) single-sided radial feeder, (b) bifurcated radial feeder (or star pattern connection), (c) single-sided ring feeder, and (d) double-sided ring feeder

Most of wind farms today use the radial feeder configurations; because of low cable costs and simple control scheme. However, the drawback of the radial feeder configuration is poor reliability, since a cable fault at the hub end of the radial cluster may prevent the operation of the entire offshore power plant. The ring feeder configurations can provide higher reliability index than the radial feeder configurations [36, 58]. The drawback with the ring feeder configuration is that the series-connected converters must have the ability to operate towards a very high voltage. This is due to the fact that if one WECU fails and therefore its terminal DC voltage collapses leading to loss of output power, the other WECUs must compensate for this by increasing their output voltage.

Based on Fig 3a and Fig. 3b, the DC collector system begins with power converters located on each string. These power converters should step up the generated AC voltage, typically 690 V, to a medium DC voltage, typically 25–40 kV. The parallel-connected WECUs on each string are exposed to same terminal voltage, which is the medium DC voltage. Each string can generate a total current $i_{dc}(t)$, given by equation (1); where, $i_{do}(t)$ is the total current output of each WECU; and k represents the total number of WECUs on each string. A medium-voltage submarine DC cable is then used to connect the WECUs to an offshore platform. By considering n as the total number of strings on the wind farm; thus the total current collected from the wind farm output can be obtained using equation (2).

$$i_{dc}(t) = \sum_{k=1}^{k} i_{do(k)}(t) \tag{1}$$

$$i_{DC}(t) = \sum_{n=1}^{n} i_{dc(n)}(t) \tag{2}$$

From the radial feeder's analysis or Fig. 3a and Fig. 3b, it can be observed that the use of HVDC-offshore platform is compulsory in order to step up the medium DC voltage to HVDC for transmission. The parallel-connected WECUs in each string increases (or builds up) the current magnitude according to equation (1), but the WECUs operate at identical terminal voltage magnitude. Consequently, an offshore platform is needed to step up the voltage to HVDC for transmission. Due to the fact that the output terminal of each WECU in the radial feeders is connected to a medium voltage link, i.e. 25 kV-40 kV, and also the voltage boost ratio is high, i.e. from 690 V to a medium voltage level; all WECUs on a wind farm with radial feeder topology must integrate power converters with high boost ratio and that can support a medium voltage level. Actually, most of WECUs employed in the DC collection grids with radial feeders integrate "the three-phase VSC cascaded with an isolated boost DC-DC converter which consists of a single active bridge – or a dual active bridge DC-DC boost converter including a medium/or high frequency transformer", e.g. in [55]; these power converter topologies have generally a high voltage boost ratio, and also they are suitable for medium voltage applications.
For the ring feeder topology or Fig. 3c and Fig. 3d, the series-connected WECUs in each string build up a voltage $v_{dc}(t)$ across the DC collector as given by equation (3); where, $v_{do}(t)$ is the output voltage of each WECU; and k represents the total number of WECUs in the series-connected circuit.

$$v_{dc} = \sum_{k=1}^{k} v_{do(k)}(t) \tag{3}$$

For this topology, the use of HVDC-platform can be avoided; a voltage high enough for the HVDC transmission system can be achieved by increasing k, according to equation (3). The ring feeder configuration is the most simplified and cost-effective layout of offshore wind farm with DC collector systems; low-voltage based converter topologies can be integrated in the WECUs, e.g. in [43-45].

Others configuration options for offshore wind power plants consist of multi-terminal HVDC systems connecting several wind farms. Among these configuration methods one can find [32, 36]:
(i) the radial connection where a group of interconnected wind farms is connected to a single HVDC-platform; with this option, losing one pole in a bipolar HVDC transmission system may cause wind generation curtailment.
(ii) The split connection, where a single offshore wind farm is connected to a separate HVDC-platform.
(iii) The backbone connection, and/or the grid connection; with m groups of wind farm where each group has a separate HVDC-platform.

3.4. Offshore platform configuration

Generally, the offshore platform incorporates a DC-DC boost converter which is often connected to the HVDC link. The voltage level of platforms depends on the amount of power generated. For example, for a large offshore wind farm at hundreds of MW capacity with radial feeder configurations, high-voltage platform systems of above 100 kV (typically 130 kV-150 kV) are normally used [36]. Presently, there are no operational high-voltage DC-DC converters yet (e.g. above 100 kV) [59], but research is still ongoing to develop such a converter topology.

Traditionally platforms considered for wind-farms have incorporated the line-commutated converter (LCC) systems. These types of converter based platforms require connections to strong grids; consequently they may not be suitable for offshore wind power plants because of the strong wind perturbations that occur regularly at sea. Presently, voltage source converters (VSCs) are being designed for high voltage/and power applications (e.g., 115 kV to 345 kV) by a number of manufacturers [36]. A platform incorporated with VSC system does not require connection to strong grid; therefore, the VSC system can be appropriate for the design of offshore platforms.

Typical topologies of DC-DC converters that can be suitable for the offshore platforms include: the soft-switched high-power-density DC-DC converter developed in [60, 61]; the modular multilevel structure based DC-DC converter circuits or the series connection of multiple modular DC-DC converters [62-65]. Although, the series-connected modular DC-DC converter systems satisfies the high-voltage requirements for the offshore platform; some shortcoming of these topologies have been noted, such as: unequal off-state voltage distribution, unacceptable form factor, and simultaneous-gating requirements. Consequently, the number of series-connected sub-modules in the DC-DC converter system needs to be limited. The use of HVDC platforms in wind farms may be a very challenging option at the present; the alternative option consists of using the ring feeder configurations, where the HVDC link can be achieved through the series connection of WECUs.

3.5. DC collection grid protection and control

The reason why DC collection grids are not yet implemented in offshore wind farms is because of lack of realisable protection systems, standards and guidelines. The main requirement for integrating a wind farm with DC collection system to the utility AC grid is to maintain the DC link voltage within a limited variation band. An abnormal variation of the DC voltage within the DC collection grid can disrupt the normal operation or even cause the whole DC collection system to breakdown. The use of state-of-the-art programmable solid-state protection devices [66, 67], energy storage system [68, 69], and power electronics converters in offshore wind farm can offer greater flexibility in enabling effective protection and control of the DC collection system.

Considering only one string feeder of Fig. 3(c) and omitting the DC platform; this results in a typical structure of a wind farm with DC collector system shown in Fig. 4(a), including protection and control devices. In this structure, the utility grid connects to the DC collection system through a protective device (PD). Also, the wind-turbine-generators are integrated to the DC collection system through power electronics converters or active rectifiers which enable a smooth grid connection. Further, the energy storage system (ESS) is connected to the DC collection grid through a controlled bi-directional DC-DC converter; this is needed to provide necessary DC link voltage regulation during abnormal conditions.

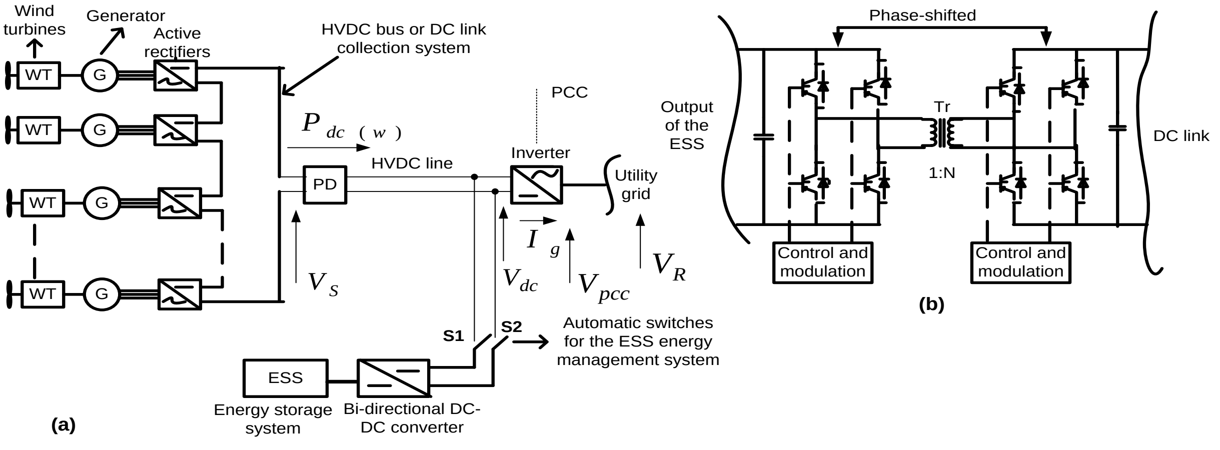

Fig. 4: (a) Distributed power grid integrating controlled and protective devices, (b) scheme of the bidirectional DC-DC converter: dual active full-bridge converter [65]

It should be noted that the series connection topology of Fig. 4 (a) is selected with the only aim to illustrate the function of protection and control devices (i.e. ESS, PD and bidirectional DC-DC converter). There exist diversities of wind farm DC collection grid arrangement; for example, Fig. 3 and section 3.3 described typical arrangement of wind farm DC collection grids, namely: radial feeder; bifurcated radial feeder; single-sided ring feeder; and double-sided ring feeder.

(i) Protective device (PD)-the key design criteria for a PD include [67, 70]: reliability - the predictability of the PD response to faults, speed- or fast removal of fault and rapid restoration of the normal condition, economics- low cost, and simplicity- less complexity. Because of the absence of natural zero crossings of DC fault current, the PD must be very fast in order to interrupt fault current on the rising slope within 2-5 ms before it reaches full fault level. Based on the state-of-the-art technologies on protective devices, fuses are not a good option to use for the DC collection system protection due to reliability and speed issues [67]. The use of DC circuit breakers (CBs) may be economical for DC collection systems with DC link voltage less than 600V [71]. There are three types of DC CBs that can be found in the market, namely: the conventional hybrid CB, the solid-state CB and the mechanical CB with snubber circuit [58]. The mechanical DC CBs have speed delay problems when responding to faults; the fault clearance time is within 50-100 ms [72]. The hybrid DC CBs can interrupt high DC currents within a few milliseconds but their cost is very high. The solid state CBs have the advantage of being able to stop current in the order of micro-second [67]; however, the size, power losses, weight and cost are significant. More details on the DC circuit breakers for high-power DC applications can be found in [73].

(ii) Energy storage system, - a chemical battery or a super capacitor can be used as typical model of ESS [74]. The aim of ESS is to maintain a constant DC link voltage by regulating the power exchange between the utility grid and wind farm. Fig. 4a illustrates an offshore wind power generation system, connected to an AC utility grid with equivalent short circuit impedance, Z_g. The utility AC grid voltage at the infinite busbar and the voltage at the point of common coupling (PCC) between the wind farm and utility grid are V_R and $V_{pcc} = f(V_{dc}, D)$, respectively, shown in Fig. 4a; V_{pcc} can be expressed in term of V_{dc} and D, where V_{dc} is the DC grid voltage and D is the converter duty ratio. The total real power and reactive power at the PCC are $P_{pcc(w)}$ and $Q_{pcc(w)}$, respectively; $P_{pcc(w)} = P_{dc(w)} - R_{dc}I_{dc}^2$, with $P_{dc(w)}$ being the total real power output of the wind farm; R_{dc} is the resistance of the DC transmission line; and I_{dc} is the DC transmission line current. The voltage difference between the utility grid and the wind farm power collection point or PCC is given by equation (4):

$$V_{pcc} - V_R = \Delta V_{RS} = Z_g \times \left(\frac{P_{dc(w)} - jQ_{pcc(w)}}{V_{pcc}} \right) \tag{4}$$

The voltage difference ΔV_{RS} is related to the short circuit impedance of the utility grid and the real power output of the wind farm. It can be noted from equation (4) that the variations of power at the output of wind farm will result in the variations of the voltage at the output of wind farm or PCC. If the impedance Z_g is small then ΔV_{RS} will be small (the grid is strong). On the other hand, if Z_g is large, then ΔV_{RS} will be large (the grid is weak).

For example, if $P_{dc(w)} = \sum_k P_{d(k)}$ is the real power output of a wind farm, with P_d being the real power output of each WECU; and if $P_{dc(g)}$ is the total real power required by the loads at the utility grid side, then the voltage across the DC collector (or output of wind farm) will tend to either increase/ or decrease if $P_{dc(g)}$ or $P_{dc(w)}$ varies regularly. In order to preserve the stability of the collection system, one must ensure at every instant that $P_{dc(w)} = P_{dc(g)}$ (neglecting the transmission power loss). Under normal operating conditions or if $P_{dc(w)} \approx P_{dc(g)}$, the ESS can simply remain at standby mode. However, during abnormal conditions, the ESS will operate at charge/or discharge mode to provide necessary DC link voltage regulation. The charge/or discharge current order is given by the automatic switches S_1 and S_2 as shown in Fig. 4a.

Under conditions of low wind or small $P_{dc(w)}$ and high demands or large $P_{dc(g)}$; to maintain the system stability, the ESS must switch its control from standby mode to discharging mode by providing the necessary power balancing. On the other hand, during conditions of high wind or large $P_{dc(w)}$ and light loads or small $P_{dc(g)}$, the ESS must switch its control from standby mode to charging mode. The required ESS/charging to accommodate the surplus power could also exceed its rating. This condition can be solved by reducing $P_{dc(w)}$ or P_d using the active stall or pitch control method.

(iii) Bidirectional DC-DC converter, the bidirectional DC-DC converter allows bidirectional power flow interchanges between the ESS and DC collection grid. The ESS absorbs the power fluctuations and improves the DC collection system dynamic properties. A typical circuit model of a bidirectional DC-DC converter for high power application is shown in Fig. 4b [74, 75], i.e., the dual active full-bridge (DAB) DC-DC converter. The DAB consists of two active bridges which are interfaced through a high or medium frequency transformer and are phase shifted from each other to regulate the amount of power flow from one

DC voltage source to the other. The DAB DC-DC converter works in boost mode to power the high voltage side; otherwise, it works in buck mode to recharge the batteries.

3.6. Control mechanism provided by active rectifiers in WECUs

Referring to Fig. 3, the active rectifiers in the WECUs are represented by AC/DC converters. The control strategy provided by each active rectifier can be schematically described by means of Fig. 5, where P_t is the fundamental expression that describes the total power that a wind-turbine can generate [67, 68]; ρ is the air density [kg/m^3]; $A=\pi r^2$ is the blade impact area [m^2], r is the blade radius [m]; V_w is the wind velocity [$m^2/\sec$]; $C_p(\lambda,\beta)$ is the power or performance coefficient; λ is the tip-speed ratio; and β is the blade pitch angle. The term ρAV_w^3 cannot be controlled, it changes unexpectedly and only the term $C_p(\lambda,\beta)$ which can be controlled through the regulation of λ and β. The adjustments of λ is done via the controls of the generator rotor speed ω_r by the active rectifier.

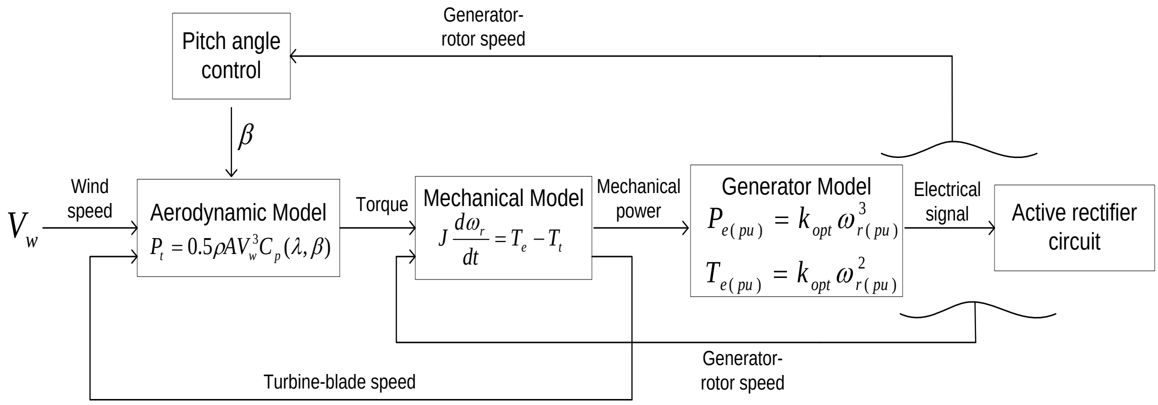

Fig. 5 Diagram describing the control technique provided by each active rectifier in WECU

The performance coefficient can be approximated by means of a nonlinear function given by equation (5) [76].

$$C_p(\lambda,\beta)=\frac{1}{2}\left(\frac{1}{\lambda}-0.022\beta^2-5.6\right)e^{-\frac{0.17}{\lambda}} \tag{5}$$

In order to maximise the wind-power penetration, the term $C_p(\lambda,\beta)$ has to be regulated at it maximum value; such that, if $C_p(\lambda,\beta)$ is max, P_t is also max. For the stall control (or passive control) strategy, the wind-turbine blades are bolted onto the hub at a fixed angle; usually β is left out in equation (5) and C_p is a function of only λ. But for the pitch control or active control strategy, the wind-turbine blades are turned away from or into the wind as the power output become too high or too low, respectively; β is actively controlled to limit P_t. Usually, β is set to zero degree for maximum wind energy tracking; or to about 90° for stopping the wind power generation.

3.7 Technical concept of active rectifier for WECUs

Another feature of the DC collection grids for offshore wind farms is the topology of power converters or active rectifiers in WECUs. The choice of power converter topology for WECU is mainly motivated by its ability to maintain the frequency, voltage magnitude, power factor, voltage/current harmonic distortion and velocity of the rotating machines within specified limits. These imply effective control of voltage, torque, and frequency or active and reactive power as well as proper mitigation of voltage/current harmonic distortion or ripple. The capacitors and inductors are also included in the power converter circuits to reduce harmonic or ripple in the current/voltage signals and to enhance the power quality.

(i) Active rectifier concept based on current source converter (CSC) system

Conventionally, the CSC- based converter system can integrate either the line-commutated switch or self-commutated switch. The conventional three-phase six-pulse thyristors-bridge, frequently used in HVDC transmission systems, is an example of a line-commutated converter (LCC) [77]. Also, the WECUs topologies in [59] and [53] integrate the LCC-converters, shown in

Fig. 6a. The commutation of the LCC-or thyristors-converters depend on the AC signals (voltage, current) output of the wind-turbine-generator. Due to strong perturbations of wind signals, the AC signals can be probably weak and consequently, the control of voltage, frequency, and active and reactive power may be badly affected at most instants. To ensure strong links, the short-circuit ratio (SCR) in the AC/DC junction has to be maintained higher; at about the value of 3 for a high SCR or 2 for a critical SCR [78, 79]. This requires the installation of reactive power compensators on the AC side of each active rectifier, thus contributing to the complexity of offshore wind farm structures. Furthermore, the LCC-converter operates with a low switching frequency; thus generating high harmonic distortion, but low power loss [80].

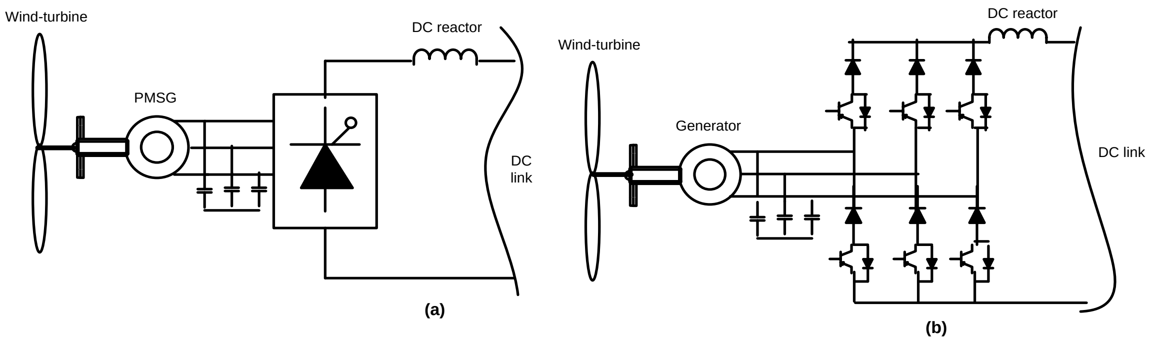

Fig. 6 (a) Scheme of a PMSG based WECU integrated with a line-commutated converter system [71], (b) scheme of a WECU integrated with CSC with forced commutated switches [75]

On the other hand, the topology of WECU in [54] integrates a CSC with self- or forced-commutated switches, depicted by Fig. 6b. Also the concept of WECU in [81] integrates a back-to-back CSC system with forced-commutated switches. Actually, the CSC systems with forced-commutated switches have not been widely employed for power system applications. The reason is that the CSC systems require switches that can withstand a relatively large reverse voltage; e.g. the bipolar electronic switches. Presently the power electronic industry has not yet established a widespread trade supply of bipolar switches [82]. Although fully controllable bipolar versions of the gate-turn-off thyristors (GTO) are commercially available, they are limited in terms of switching speed.

(ii) Active rectifier concept based on VSC system

Unlike the WECU model with LCC scheme, the VSC systems operate at high switching frequency, and thus, generate low harmonic distortion. However, the power loss is high due to switches operating at a higher switching frequency. Currently, most of the WECUs employed in DC collection grids integrate the VSC systems-with pulse width modulation (PWM) control scheme, e.g. in [28, 49, 56, 83]. Usually, the VSC-PWM use the insulated gate bipolar transistor (IGBT) or the insulated gate commutated transistor (IGCT) switches. The commutations of these switches do not depend on the output signal of the wind-turbine-generator. Consequently the control of voltage, frequency, torque, and active and reactive power cannot be affected by the wind signal perturbations. No reactive power compensator is needed in the WECUs, thus simplifying the WECU, and hence, the offshore wind farm.

The conventional three-phase full-bridge VSC technology, depicted in Fig. 7a, is the most promising technical solution for DC collections grids in which each of the "valve" consist of series connected IGBT cells. However, to use this technology, there is still a need to develop converter systems that can support the high-voltage DC link. Also, the converter system must provide a high voltage-boost capability. For example, in the radial feeder configurations, i.e. Fig. 3a, the output terminals of all WECUs are directly connected to a medium voltage level DC link i.e., 25 kV-40 kV. Therefore, all WECU in Fig. 3a must integrate active rectifier systems or AC/DC converters which are capable of stepping up the 690 volt output of the generators to 25 kV-40 kV. The converter system must also be able to support the high-voltage DC link (e.g. 24 kV). From the technology point of view, the first effort towards improved topology of VSC-HVDC system has been performed by developing the active neutral point clamped (NPC) VSC, shown in Fig. 7b [51]. However, the major breakthrough in VSC-HVDC technology has been provided by the introduction of the modular multilevel VSC [84].

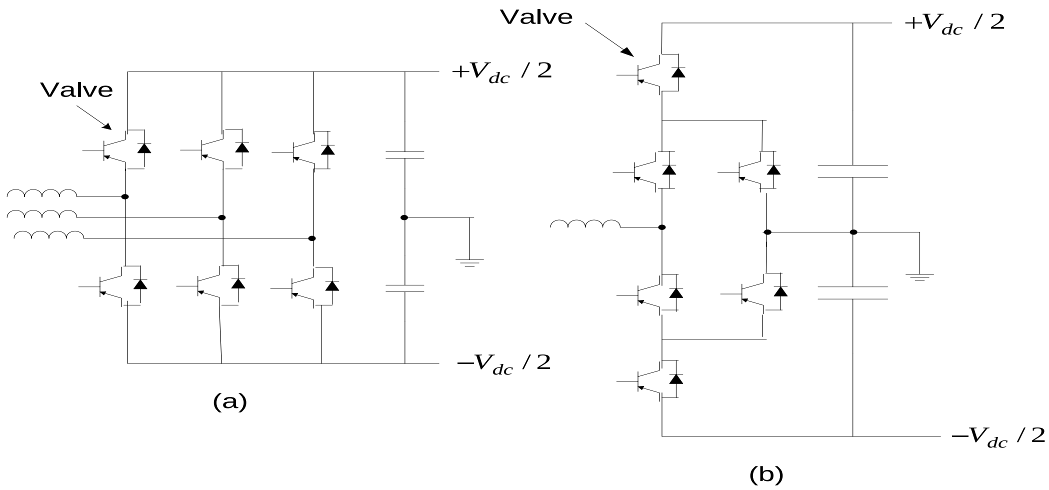

Fig. 7 (a) Three-phase full-bridge VSC, (b) phase leg of an active neutral point clamped VSC.

Alternatively, quite a lot of published works on the design of DC collection grids for wind farm have employed the "conventional three-phase VSC cascaded with an isolated DC-DC boost converter" as the power converter topology into the WECUs, shown in Fig. 8 [13, 55-57]. The isolated DC-DC boost converter includes either a single-phase single active bridge (SAB) DC-DC converter shown in Fig. 8a or a single-phase dual active bridge (DAB) DC-DC converter shown in Fig. 8b. The high or medium frequency transformer is needed to step up the voltage output of the VSC to the collection level voltage. In Fig. 8a, an induction generator is interfaced with the three-phase VSC connected to a single-phase active bridge-inverter, a high frequency transformer and a single-phase diode bridge-rectifier. With this topology, the excitation of the induction generator can become an issue as it cannot be achieved from the DC grid side; because of the diode bridge-rectifier which enables only one-directional power flow. The alternative is to replace the induction generator of Fig. 8a with a PMSG which is self-excited, making the use of a diode bridge-rectifier unproblematic. A further option is to replace the passive diode bridge-rectifier with an active rectifier, as shown in Fig. 8b; which results to a WECU integrating a "VSC cascaded with a dual active bridge (DAB) converter". The drawbacks of this concept include cost, complex control structure and high power losses.

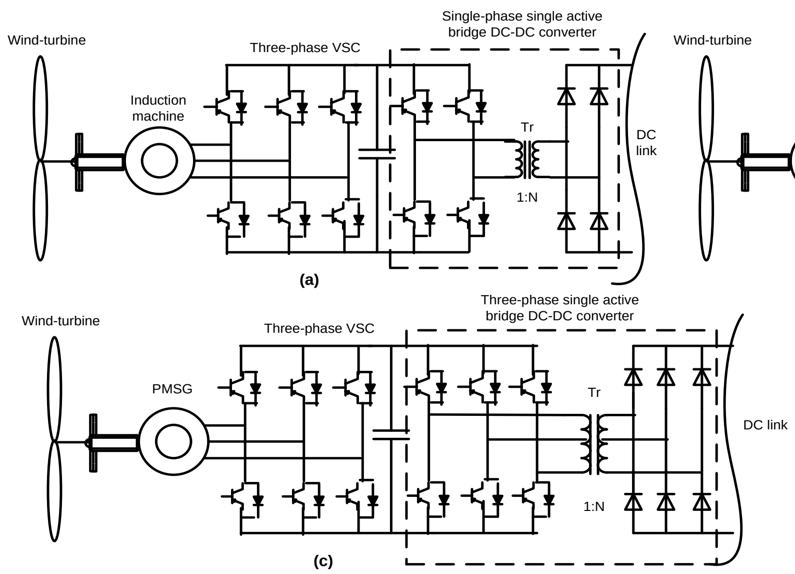

Fig. 8 Circuit diagram of WECUs employed in DC grids with medium voltage link: (a) WECU integrated with a single-phase SAB converter which enables only one directional power flow, (a) WECU integrated with a single phase DAB converter with bidirectional power flow, and (c) PMSG based WECU integrated with a three-phase SAB converter for high-power applications.

The WECUs concepts of Fig. 8a and 8b both include a single-phase scheme. Presently, most WECUs are built with a 2 MW rating [85]. However, there is clear trend toward increasing the ratings of WECUs. A 7.5 MW WECU is already being marketed [86]. The WECU topology proposed in [56] includes a three-phase scheme. This consists of a PMSG based WECU realised with a three-phase VSC connected to a three-phase SAB DC-DC converter, shown in Fig. 8c; the single-phase frequency transformer is replaced by a three phase scheme. The topology of WECU proposed in [57] consists of a PMSG based WECU realised with a three-level neutral-point-clamped (NPC) converter combined with an isolated full-bridge three-level DC-DC converter including chopper resistors for overvoltage protection.

The study conducted in [56], employs the WECU (Fig. 8) from which it is observed that a DC series wind farm of 10-MW rating has 10% more losses than the corresponding AC radial park. It was also noticed that the power converters were major contributors of power losses. Losses are high due to the high switching frequency of the valves. An alternative topology of the WECU integrating a high-frequency transformer is shown in Fig. 9, in which the VSC system has reduced number of valves. This topology offers less total harmonic distortion and reduced losses but at the cost of high mechanical complexity, increased converter size, and challenges in balancing the DC bus capacitors.

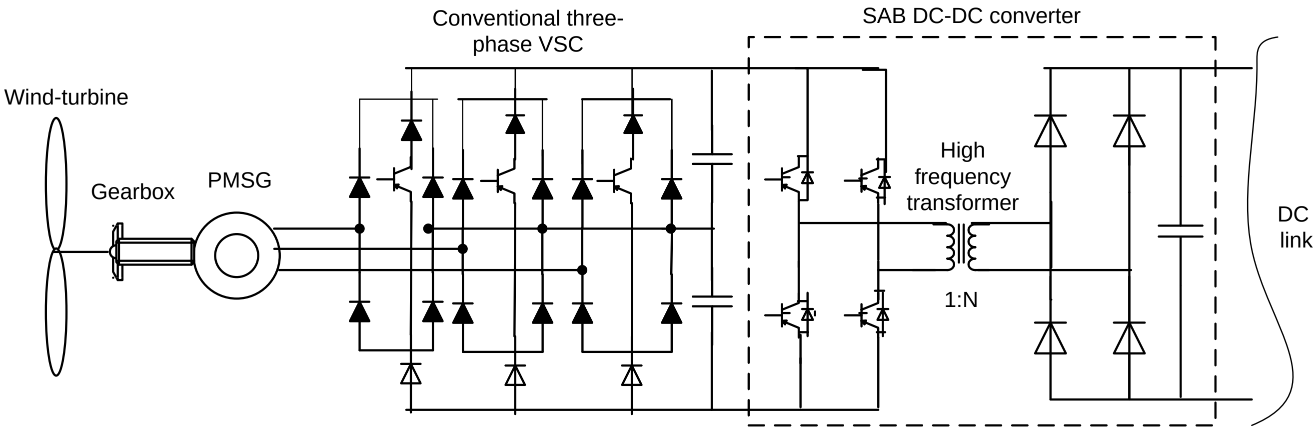

Fig. 9 Alternative topology of a WECU integrating the high-frequency transformer and VSC with reduced number of valve

Other possible topologies of WECUs for DC collection grids include: the PMSG based WECU comprising of a direct matrix converter, and the PMSG based WECU comprising of the indirect matrix converter [56]. Additional topologies of WECU for low-voltage applications include: WECU realised with the conventional three-phase full-bridge active rectifiers or VSC [28, 49, 50, 67]. In [52], a half-bridge VSC-PWM was adopted as power converter topology in WECUs. A cascade connection of a diode bridge-rectifier and a single-switch DC-DC buck converter was proposed in [43] as a potential converter topology in WECUs for low voltage application. From recent studies [44-47], a three-phase diode bridge-rectifier cascaded with a single-switch DC-DC boost converter was investigated. Another option was to use the interleaved single-switch DC-DC boost converter instead of the single-switch DC-DC boost converter in the WECUs [48]; which reduces switch stresses and the volume of magnetic components in the DC-DC boost converter.

4. General observation

The key factors that need to be considered when planning to develop DC collection grid technologies for offshore wind farms include: low maintenance frequency, compact offshore structure, and low energy losses and cost of energy delivered to shore grid. Moreover, power system operators have grid codes which describes the requirements for the quality and the form in which the power must be delivered to the utility grids [17]; therefore, DC offshore collection grids are required to possess grid fault ride-through (FRT) capability: they have to stay connected and contribute to the power system stability in case of any disturbances. Further requirements for DC offshore collection grids include: reliability, availability, maintainability, and protection against the aggressive humid and salty offshore environment. The WECUs on offshore wind farms are required to have a variable speed mechanism to allow an optimal match between the generator system and the aerodynamic of the wind-turbine rotor.

It should also be noted that there is no convergence yet toward a single optimal DC collection grid configuration for offshore wind farm, but instead the trend toward improved topologies of power converter for WECU including control and protection methods are increasing. The selection of one specific power electronic converter or active rectifier topology for WECU over another can only be made through appropriate analysis of the full operating cost, including losses. Moreover, thorough studies can be undertaken to analyse the benefits that may accrue to the entire DC offshore collection grid for a given WECU concept, control and protection methods.
The technical challenge with DC circuit breakers is the absence of natural zero crossings of DC fault current. Consequently, a DC circuit breaker must interrupt DC fault current on the rising slope within 2-5 ms before the DC current signal reaches full fault level. Presently, it is challenging to have such DC circuit breakers, but research is still being ongoing to develop such protective devices. An alternative approach to limit DC fault current is to develop a fault-tolerant VSC [72]. If all AC/DC links

can limit DC fault currents infeed from AC or DC sources, then fault levels will be low in the internal DC collection grid. For the high-voltage offshore platform; in power electronics, there is a trend toward reliable modular multilevel DC-DC converter topologies.

5. Conclusion

Offshore wind farms with DC collection grids can be developed only if several key components currently nonexistent are made available; these include protection and control devices. This study has reviewed some configurations of DC collection grids for offshore wind farms including the wind-turbine-generator systems, the power electronics converter topologies, and the control and protection methods. Several topologies of power converters being used into the WECUs are described. The power converters with VSC-PWM control circuits are better options for WECU applications. Simplified topologies of power converter for WECUs are also described. Due to the lack of effective protective device e.g. DC circuit breaker, the control and protection of DC collection system can be coordinated by the ESS, active rectifiers in WECUs, and power inverter. The ESS sustains the deficit or excess of power within the DC collection grid via a bidirectional DC-DC converter; the active rectifiers perform the power conditioning by enabling optimal wind energy tracking.

6. References

[1] Coal and electricity, Coal Industry, World Coal and Association, 2016. [Online]. Available: http://www.worldcoal.org/coal/user-coal/coal-electricity/.

[2] I. Pretorius, S. Piketh, R. Burger, H. Neomagus, "A perspective on South African coal fired power station emissions", J. Energy South Afr., vol. 26, no. 3, Aug. 2015.

[3] Coal resources, South Africa, Department of Energy, 2016. [Online]. Available: http://www.energy.gov.za/files/coal_frame.html/.

[4] F. Matthias, S. Julian, V. R. Dennis, "Analysis of the globally installed coal-fired power plant fleet", International Energy Agency-IEA, www.iea.org, 2012.

[5] L. Fried. (2015, Feb.) Global wind statistics 2015. Global Wind Energy Council (GWEC). [Online]. Available: http://www.gwec.net/wp-content/uploads/vip/.

[6] European Wind Energy, European wind energy statistics, European Wind Energy and Association (EWEA), 2015. [Online]. Available: http://www.ewea.org/.

[7] F. Blaabjerg, K. Ma, "Future on power electronics for wind turbine systems," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 1, no. 3, pp. 139–152, 2013.

[8] V. Yaramasu, B. Wu, P. C. Sen, S. Kouro, M. Narimani, "High-power wind energy conversion systems: state-of-the-art and emerging technologies", *IEEE Proceeding*, vol. 103, no. 5, pp. 740-788, 2015.

[9] D. Berenguel, M. Prada, O. G. Bellmunt, M. Martins, "Electrical interconnection options analysis for offshore wind farms," in *Europe's Premier Wind Energy Event (EWEA),* Vienna, Austria, 2013.

[10] G. Quinonez-varela, G. W. Ault, O. Anaya-Lara, J. R. McDonald, "Electrical collector system options for large offshore wind farms", *IET Renew. Power Gener*., vol. 1, no. 2, pp. 107-114, 2007.

[11] M. De Prada Gil, J.L. Dominguez-Garcia, F. Diaz-Gonzalez, M. Aragues-Penalba, O. Gomis-Bellmunt, "Feasibility analysis of offshore wind power plants with DC collection grid", *Renewable Energy,* vol. 78, pp. 467-477, 2015.

[12] L. Hansen, F. Blaabjerg, H. Christensen, U. Lindhard, K. Eskildsen, P. Madsen, "Generators and power electronics technology for wind turbines," in *27th Annual Conference of the IEEE Industrial Electronics Society (IECON),* 2001.

[13] Z. Chen, J. M. Guerrero, F. Blaabjerg, "A review of the state of the art of power electronics for wind turbines", *IEEE Trans. Power Electron.*, vol. 24, no. 8, pp. 1859–1875, 2009.

[14] H. Li, Z. Chen, "Overview of different wind generator systems and their comparisons" *IET Renewable Power Generation*, vol. 2, no. 21, pp 123-138, 2008.

[15] L. H. Hansen, L. Helle, F. Blaabjerg, E. Ritchie, S. Munk-Nielsen, H. Bindner, P. Sorensen, B. Bak-Jensen, "Conceptual survey of generators and power electronics for wind turbines", *Riso National Laboratory, Roskilde, Denmark*, ISBN 87-550-2743-1, Dec. 2001.

[16] B. Wu, Y. Lang, N. Zargari, S. Kouro, "Power conversion and control of wind energy systems", *IEEE Press Power Engineering,* John Wiley & Sons, Inc., 2011.

[17] V. Akhmatov, M. Callavik, C. M. Franck, S. E. Rye, T. Ahndorf, M. K. Bucher, H. Muller, F. Schettler, R. Wiget, 'Technical guidelines and prestandardization work for first HVDC grids', *IEEE Trans. Power Deliv*., vol. 29, no.1, pp. 327–334, 2014.

[18] O. A. Giddani, G. P. Adam, O. Anaya-Lara, G. Burt, K. L. Lo, "Control strategies of VSC-HVDC transmission system for wind power integration to meet GB grid code requirements", *International Symposium on Power Electronics Electrical Drives, Automation and Motion (SPEEDAM),* pp. 385-390, 2010.

[19] I. Erlich, H. Brakelmann, "Integration of wind power into the German high voltage transmission grid", *Power Engineering Society General Meeting*, pp. 1-8, 2007.

[20] I. Erlich, W. Winter, A. Dittrich, “Advanced grid requirements for the integration of wind turbines into the German transmission system”, *Power Engineering Society General Meeting*, pp. 1-7, 2006.
[21] C. Meyer, M. Hoing, A. Peterson, R. W. D. Donckeri, “Control and design of DC grids for offshore wind farms,” *IEEE Trans. Ind. Appl.*, vol. 6, no. 43, pp. 1475–1481, 2007.
[22] L. P. Lazaridis, “Economic comparison of HVAC and HVDC solutions for large offshore wind farms under special consideration of reliability”, *Royal Institute of Technology Department of Electrical Engineering Stockholm*, Master’s Thesis, 2005.
[23] C. J. Chou, Y. K. Wu, G. Y. Han, C. Y. Lee, “Comparative evaluation of the HVDC and HVAC links integrated in a large offshore wind farm – an actual case study in Taiwan”, *IEEE Trans. Ind. Appl*., vol. 48, no.5, pp. 1639–1648, 2012.
[24] K. Meah, S. Ula, “Comparative evaluation of HVDC and HVAC transmission systems”, *Power Engineering Society General Meeting*, 2007.
[25] X. Jin, C. Dai, P. Ji, S. Wu, P. Jing, “Research of fault current limiter for 500 kV power grid”, *International Conference on Power System Technology (POWERCON)*, 24-28 Oct. 2010.
[26] M. K. Zadeh, A. S. Akmal, E. M. Siavashi, A. Parvizi, “Impacts of TCSC on switching transients of HV transmission lines due to fault clearing”, *2nd International Conference on Power Electronics and Intelligent Transportation System*, pp. 231-237, 2009.
[27] K. D. Kerf, K. Srivastava, M. Reza, D. Bekaert, D. V. Hertem, R. Belmans, “Wavelet-based protection strategy for DC faults in multi-terminal VSC HVDC systems”, *IET Gener. Transm. Distrib.*, vol. 5, no. 4, pp. 496–503, 2011.
[28] L. Tang, B. T. Ooi, “Locating and isolating DC faults in multi terminal DC systems”, *IEEE Trans. Power. Del.*, vol. 22, no. 3, pp. 1877–1884, 2007.
[29] F. Deng, Z. Chen, “Operation and control of a DC-grid offshore wind farm under DC transmission system faults,” *IEEE Trans. Power. Del.*, vol. 28, no. 3, pp. 1356–1363, 2013.
[30] B. Silva, C. L. Moreira, H. Leite, J. A. P. Lopes, “Control strategies for AC fault ride through in multiterminal HVDC grids,” *IEEE Trans. Power. Del.*, vol. 29, no. 1, pp. 395–405, 2014.
[31] W. Xiang, Y. Hua, J. Wen, M. Yao, N. Li, “Research on fast solid state DC breaker based on a natural current zero-crossing point,” *Journal of Modern Power Systems and Clean Energy*, vol. 2, no. 1, pp. 30-38, March 2014.
[32] S. Gang, C. Zhe, C. Xu, “Overview of multi-terminal VSC HVDC transmission for large offshore wind farms”, *International Conference on Advanced Power System Automation and Protection (APAP)*, pp. 1324-1329), 2011.
[33] J. Yang, J.E. Fletcher, J. O'Reilly, G.P. Adam, S. Fan, “Protection scheme design for meshed VSC-HVDC transmission systems of large-scale wind farms”, *9th IET International Conference on AC and DC Power Transmission*, 19-21 Oct., 2010.
[34] M. P. Gil, J. L. Dominguez-Garcia, F. Diaz-Gonzalez, M. Aragues-Penalba, O. Gomis-Bellmunt, “Feasibility analysis of offshore wind power plants with DC collection grid”, *Renewable Energy*, vol. 78, pp. 467-477, 2015.
[35] P. Lakshmanan, J. Liang, N. Jenkins, “Assessment of collection systems for HVDC connected offshore wind farms”, *Electric Power Systems Research*, vol. 129, pp. 75-82, 2015.
[36] J. P. Daniel, S. Liu, E. Ibanez, K. Pennock, G. R. S. Hanes, “National Offshore Wind Energy Grid Interconnection Study Executive Summary”, ABB rapport DOE Award No. EE- 0005365, (2014).
[37] M. M Hand, S. Baldwin, E. DeMeo, J. M. Reilly, T. Mai, D. Arent, G. Porro, M. Meshek, D. Sandor, “Renewable Electricity Futures Study: Entire Report”, NREL/TP-6A20-52409, Golden, CO: 2012.
[38] I. Staffell, S. Pfenninger, “Using bias-corrected reanalysis to simulate current and future wind power output”, *Energy*, 114, pp. 1224-1239, 2016.
[39] H. Y. Phoon, “Generation system reliability evaluations with intermittent renewable”, *MSc dissertation, Energy Systems and Environment*, University of Strathclyde, Sept. 2006.
[40] H. Polinder, J. A. Ferreira, B. B. Jensen, A. B. Abrahamsen, K. Atallah, R. A. McMaho, “Trends in wind turbine generator systems”, *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 1, no. 3, pp. 174-185, Sept. 2013.
[41] A. D. Hansen, L. Florin, B. Frede, H. H. Lars, “Review of contemporary wind-turbine concepts and their market penetration”, *Wind Engineering*, vol. 28, no. 3, pp. 247-263, 2004.
[42] P. D. Chung, “DC voltage collection for DFIG-based offshore wind farms using HVDC compliance with the power system operator’s power control requirement”, *International Electrical Engineering Journal (IEEJ)*, vol. 4, no. 1, pp. 869-879, ISSN 2078-2365, 2013.
[43] E. Veilleux, P. W. Lehn, “Interconnection of direct-drive wind turbines using a series-connected DC grid”, *IEEE Trans. Sustain. Energ.*, vol. 5, no. 1, pp. 139–147, 2014.
[44] K. Musasa, M. N. Gitau, R. C. Bansal, “Performance analysis of power converter based active rectifier for an offshore wind park,” *Electric Power Components and Systems*, vol. 43, no. 8-10, pp. 1089–1099, 2015.
[45] K. Musasa, M. N. Gitau, R.C. Bansal, “Dynamic analysis of DC-DC converter internal to an offshore wind farm”, *IET Renew. Power Gener*., vol. 9, no. 6, pp. 542-548, 2015.

[46] K. Musasa, M. N. Gitau, R.C. Bansal, "Comparative analyses of DC collection grid based power converter topologies for offshore wind farm", *4th IET Renewable Power Generation International Conference on Renewable Power Generation*, China, 17 – 18 October, 2015.
[47] K. Musasa, M. N. Gitau, R.C. Bansal, "Dynamic analysis of DC-DC converter internal to an offshore wind farm", *3rd Renewable Power Generation Conference (RPG)*, 24 – 25 September 2014, Ramada Naples, Via Galileo Ferraris, Naples, Italy.
[48] K. Musasa, M. N. Gitau, R. C. Bansal, "Analysis of a DC collector- based power converter topology for an offshore wind farm", *Electric Power Components and Systems*, vol. 43, no. 10, pp. 1113-1121, 2015.
[49] W. Lu, B. T. Ooi, "Optimal acquisition and aggregation of offshore wind power by multiterminal voltage-source HVDC", *IEEE Trans. Power Del.*, vol. 18, no. 1, pp. 201–206, 2003.
[50] C. Guo, C. Zhao, "Supply of an entirely passive AC network through a double-infeed HVDC system," *IEEE Trans. Power Electron.*, vol. 24, no. 11, pp. 2835–2841, 2010.
[51] L. Zeni, T. Haileselassie, G. Stamatiou, A. G. Eriksen, J. Holboll, O. Carlsson, K. Uhlen, P. Sorensen, N. A. Cutululis, " DC grids for integration of large scale wind power", Nordic Energy Research, concluding report from the Offshore DC project, 2011.
[52] M. Guan, Z. Xu, "A novel concept of offshore wind-power collection and transmission system based on cascaded converter topology," *International Transactions on Electrical Energy System*, Oct. (2014).
[53] S. Nishikata, F. Tatsuta, "A new interconnecting method for wind turbine/generators in a wind farm and basic performances of the integrated system," *IEEE Trans. Ind. Electron.*, vol. 57, no. 2, pp. 468–475, Feb. 2010.
[54] H. J. Lee, S. Seung-Ki, "Wind power collection and transmission with series connected current source converters", *European Conference on Power Electronics and Applications* (EPE), (2011).
[55] L. Max, "Design and control of a DC collection grid for a wind farm," *Ph.D. dissertation*, *Chalmers Univ. of Technology*, Sweden, 2009.
[56] N. Holtsmark, H. J. Bahirat, M. Molinas, B. A. Mork, H. K. Hoidalen, "An all-DC offshore wind farm with series-connected turbines: an alternative to the classical parallel AC model?", *IEEE Trans. Ind. Electr.*, vol. 60, no. 6, pp. 2420–2428, 2013.
[57] F. Deng, Z. Chen, "An offshore wind farm with DC grid connection and its performance under power system transients," in *IEEE Power and Energy Conference, San Diego, USA*, 2011.
[58] S. J. Shao, V. G. Agelidis, "Review of DC system technologies for large scale integration of wind energy systems with electricity grids", *Energies*, *3*, 1303-1319, 2010.
[59] J. Robinson, D. Jovcic, G. Joos, "Analysis and design of an offshore wind farm using a MV DC grid," IEEE Trans. Power Del., vol. 25, no. 4, pp. 2164–2173, 2010.
[60] R. W. A. A. Doncker, D. M. Divan, M. H. Kheraluwala, "Three-phase soft-switched high-power-density DC/DC converter for high-power application," *IEEE Trans. Ind. Appl*., vol. 27, no. 1, pp. 63–73, 1991.
[61] R. L. Steigerwald, R. W. D. Doncker, M. H. Kheraluwala, "A comparison of high-power DC-DC soft-switched converter topologies," *IEEE Trans. Ind. Appl*., vol. 32, no. 5, pp. 1139–1145, 1996.
[62] I. A. Gowaid, G. P. Adam, A. M. Massoud, S. Ahmed, D. Holliday, B. W. Williams, "Modular multilevel structure of a high power dual active bridge dc transformer with stepped two level output," *presented at the 16th European Conference on Power Electronics and Applications* (EPE'14-ECCE), Europe, 2014.
[63] L. Yiqing, P. A. Grain, H. Derrick, J. F. Stephen, "Medium-voltage DC/DC converter for offshore wind collection grid," *IET Renew. Power Gener*., vol. 10, no. 5, pp. 651–660, 2016.
[64] K. Filsoof, P. W. Lehn, "A bidirectional multiple-input multiple-output modular multilevel DC-DC converter and its control design," *IEEE Trans. Power Electron*., vol. 31, no. 4, pp. 2767–2779, 2016.
[65] Z. Xing, X. Ruan, H. You, X. Yang, D. Yao, C. Yuan, "Soft-switching operation of isolated modular DC/DC converters for application in HVDC grids," *IEEE Trans. Power Electron*., vol. 31, no. 4, pp. 2753–2766, 2016.
[66] X. Yuhong, N. Jia, H. Yanquan, J. Junbo, J. Zhihui, "A review of DC-micro grid protection", *Springer-Verlag*, Berlin Heidelberg, pp. 338-347, 2013.
[67] M. R. Cuzner, G. Venkataramanan, "The status of DC micro-grid protection", *IEEE-Industry Applications Society Annual Meeting*, Edmonton, Alta, 5-9 oct., 2008.
[68] R. Puran, J. N. Patrick, D. A. F. Steven, J. G. Stuart, M. B. Graeme, "Evaluation of the impact of high-bandwidth energy-storage systems on DC protection", *IEEE Trans. Power Deliv*., vol. 31, no. 2, pp. 586-594, 2016.
[69] X. Lie, C. Dong, "Control and operation of a DC microgrid with variable generation and energy storage", *IEEE Trans. power deliv*., vol. 26, no. 4, pp. 2513-2522, 2011.
[70] G. Stamatiou, K. Srivastava, M. Reza, P. Zanchetta, "Economics of DC wind collection grid as affected by cost of key components", *World Renewable Energy Congress*, Linkoping, Sweden, 8-13 May, 2011).
[71] D. Salomonson, A. Sannino, "Low-Voltage DC Distribution System for Commercial Power Systems With Sensitive Electronic Loads", *IEEE Trans. Power Deliv.*, vol. 22, no. 3, pp. 1620-1627, Jul. 2007.
[72] M. Hajian, L. Zhang, D. Jovcic, "DC transmission grid with low-speed protection using mechanical DC circuit breakers", *IEEE Trans. Power Deliv* , vol. 30, no. 3, pp. 1383-1391, 2015.

[73] C. Meyer, M. Kowal, R. W. De Doncker, “Circuit breaker concepts for future high-power DC-applications” *IEEE-IAS Conference Record*, vol. 2, pp. 860 – 866, 2-6 Oct, 2005.
[74] S. Jalbrzykowski, T. Citko, “A bidirectional DC-DC converter for renewable energy systems”, *Bulletin of the Polish Academy of Sciences, Technical Sciences*, vol. 57, no. 4, 2009.
[75] M. H. Kheraluwala, R.W. Gascoigne, D.M. Divan, E.D. Baumann, “Performance characterization of high power dual active bridge dc-to-dc converter”, *IEEE Trans. Ind. Appl*., vol. 28, no.6, pp. 1294 - 1301, 1992.
[76] J. G. Slootweg, H. Polinder, W. L. Kling, “Representing wind turbine electrical generating systems in fundamental frequency simulations”, *IEEE Trans. Energ. Conv*., vol. 18, no. 4, pp. 516–524, 2003.
[77] N. Mohan, T. M. Undeland, W. P. Robbins, ‘Power electronics: converters, applications, and design’, John Wiley & Sons, Inc., 3rd edn, 2003.
[78] A. Gavrilovic, “AC/DC system strength as indicated by short circuit ratios”, *International Conference on Transmission and Distribution System*, London, UK, 17–20 September 1991).
[79] O. B. Nayak, A. M. Gole, D. G. Chapman, J. B. Davies, “Dynamic performance of static and synchronous compensators at an HVDC inverter bus in a very weak AC system”, *IEEE Trans. Power Syst*., vol. 9, no. 3, pp. 1350–1358, 1994.
[80] N. Flourentzou, V. G. Agelidis, G. D. Demetriades, “VSC-based HVDC power transmission systems: an overview,” *IEEE Trans. Power. Electron.*, vol. 24, no. 3, pp. 592–602, 2009.
[81] I. Abdelsalam, G. P. Adam, D. Holliday, B. W. Williams, “Modified back-to-back current source converter and its application to wind energy conversion systems”, *IET Power Electron*., vol. 8, no. 1, pp. 103–111, 2015.
[82] A. Yazdani, R. Iravani, ‘Voltage-sourced converters in power systems: modelling, control, and applications’, *IEEE Press*, John Wiley & Sons, Inc. Book, 2010.
[83] W. Lu, B.-T. Ooi, “Premium quality Power Park based on multi-terminal HVDC”, *IEEE Trans. Power. Del.*, vol. 20, no. 2, pp. 978–983, 2005.
[84] T. H. Nguyen, D. C. Lee, and C. K. Kim, “A series-connected topology of a diode rectifier and a voltage-source converter for an HVDC transmission system”, IEEE Trans. Power Electron., vol. 29, no. 4, pp. 1579-1584, April 2014.

[85] “Horns Rev 1 offshore wind farm,” [Online]. Available: www.vattenfall.dk, 2010, Tech. Rep.
[86] “Enercon wind energy converters product overview,” Enercon, Aurich, Germany, 2010, Tech. Rep.