Electrical Collection Systems for Offshore Wind Farms: A Review

Padmavathi Lakshmanan, Ruijuan Sun, and Jun Liang, *Senior Member, IEEE*

***Abstract*—A review of the electrical collection systems in offshore wind farms (OWFs) is presented in this paper. The review is based on a categorization of offshore wind power electrical collection systems. The classification encompasses three categories of electrical collection systems, medium voltage AC collection, medium voltage DC collection systems and low frequency AC collection systems (LFAC). This paper summarizes the related research on different collection systems and explores their operational characteristics and challenges. As the initial cost of an OWF is very much influenced, to a great extent, by the configuration of electrical collection and transmission systems, it is necessary to understand the key components and challenges in each collection system configuration.**

***Index Terms*—DC collection systems, LFAC, offshore wind farms.**

I. INTRODUCTION

OFFSHORE wind farms have received increasing interests due to their being more stable, more efficient and providing higher energy capture. More OWFs are developing a significant transmission distance from the shore and encompassing power ratings from several MW to GW [1]. OWFs are likely to move further from the shore for the purpose of reducing visual impacts and allowing an increase in their size. High Voltage DC (HVDC) transmission has proved to be feasible for long distance bulk power transmission [1], [2]. The known challenges of the OWFs are weight and size of the offshore installations, which leads to high transportation, installation and maintenance costs [2].

In an OWF, electrical system concerns represent all the electrical components that connect the wind turbine output to the onshore power grid. This includes the generating units, power electronic converters, transformers, inter turbine cables, transmission cables and switch gears [3]. There are two sections of electrical systems for OWF power transfer networks [3]. One is the interconnection of the wind turbines within the wind farm, known as the collection system and the other one is the connection from the OWF to the onshore grid, which is called the transmission system, usually operating at a high voltage. The design of an OWF is a technically complex process and consideration must be given to the components of collection and transmission systems [4].

The collection systems interconnect all generators of the wind farm and aggregate the generated power, operating at a medium voltage. The offshore collection system collects the generated electrical power from all the wind turbines and transmits it to the onshore grid by transmission systems.

The unique location of the OWF projects demands significant interconnection facilities in terms of collection and transmission system requirements. The interconnection requsirements are also sometimes project specific. This has the implication in terms of electrical collection and transmission systems of the OWF [3].

HVDC transmission essentially decouples a wind farm from the onshore grid, and this removes the requirement of the inter wind farm collection network to comply with the grid code. This provides an opportunity to explore different technologies that may be more reliable and provide an efficient way for collecting the generated power from the individual wind turbines [5].

As the ratings of the wind turbines increase and the size of the wind farms grow, the quantity of power that has to be transferred through the collection network is pushing up the cost of the present technology. This is another driving consideration for innovations in electrical collector configuration studies [5]. Finally, the performance cost and reliability of the wind farms depend on the configuration of collection and transmission systems. These factors explain the motivation behind the collection configuration studies.

The size of the wind farms and the required reliability levels are the key factors in deciding upon the configuration of individual collection systems. The OWF networks are usually complex. In order to reduce the complexities of offshore installations and to improve the feasibility of offshore wind power integration, research studies of novel collection system configurations, such as the DC collection systems [6]–[14], and Low Frequency AC (LFAC) [15], [16] are being undertaken. These novel collection systems are aimed at achieving reduced footprint and size for OWFs.

While most of the commissioned offshore projects use AC collection and transmission systems, they represent the matured technology with respect to components and protection requirements. However, the novel collection topologies such as DC and LFAC are in initial stages of research, so an un-

---

Manuscript received September 19, 2020; revised February 2, 2021; accepted March 18, 2021. Date of online publication July 9, 2021; date of current version July 15, 2021.

P. Lakshmanan (corresponding author, e-mail: cl.padmavathi@gmail.com; ORCID: https://orcid.org/0000-0002-4525-2741) is with CSIR-Central Electronics Engineering Research Institute (CEERI), Pilani Rajasthan, India.

R. J. Sun is with School of Elctrical Engineering, Zhengzhou University, Zhengzhou 450066, China.

J. Liang is with School of Engineering, Cardiff University, UK.

DOI: 10.17775/CSEEJPES.2020.05050

derstanding of their key components and technical challenges are essential in order to build cost-effective OWFs. This paper will present a comprehensive review of research conducted on OWF collection topologies, which is of significant interest in the present scenario.

A. Components of Electrical Collection and Transmission Systems

The components of electrical collection and transmission systems are shown in Fig. 1. The collection system usually begins with a transformer at the basement of the tower of each wind turbine stepping up the voltage from 690 V typically to [5] 25–40 kV. The collection system primarily uses the 33–36 kV AC inter-array cables to collect the energy from the wind turbines. This voltage range is preferred considering the cross section of the towers. An array of medium voltage submarine cables connects the wind turbine output to the offshore substation.

The power output of each of the wind turbines is collected by an offshore substation. Transformers at the offshore substation step up the collection system voltage to 132–150 kV for transmission purposes and enable the onshore grid interconnection. Offshore transformer platform stations are complex and include a large support structure leading to higher costs. The electrical collection system interconnects with the wind turbines in the wind farm and connects them to a single point. For larger wind farms, the collection point can be part of an offshore substation or multiple collection points can be used.

II. OVERVIEW OF OWF COLLECTION SYSTEMS

A. AC Collection Systems

In a typical AC collection system, as shown in in Fig. 1, the power conversion routine includes the wind turbine generators, back-to-back converters (AC–DC–AC), 0.69 kV/36 kV transformers, Medium Voltage (MV) AC cables, and 36 kV/150 kV transformers.

The majority of the commissioned wind farms around the world employ AC collection systems.

1) AC Radial Collection Systems

In this collection system [3] as shown in Fig. 2(a), the wind turbines are connected to a common cable depending on the current carrying capacity. The total power from the wind farm is collected by these radials and connected to a substation.

The Hornes Rev OWF in Denmark, BARD 1 (Germany), and Walney 1 (UK), are some of the wind farms using radial design.

2) AC Radial Loop Collection Systems

Generally, looped systems are preferred for reliability improvement in comparison with the radial systems. It is possible to reconfigure a radial system from looped systems during the fault conditions, without losing the energy production. A radial loop connection is classified into single sided ring design and double-sided ring design and is shown in Fig. 2(b) and Fig. 2(c), respectively. The ringed layouts can provide more secured supply compared to the radial design at the expense of additional cables. These cables provide a path for redundant power flow within a string [3]. In the double ended ring design (Fig. 2(c)), the last two wind turbines of each string are interconnected.

London Array (UK), En Baltic 2 (Germany), Butendiek (Germany), Amrumbank West (Germany), and Alpha-Ventus (Germany) are some of the OWFs using AC loop collection systems.

3) AC Star Collection Systems

In this collection system, individual turbines are connected to a star/cluster point with its own cable. A main cable is connected to the medium voltage collector hub. Several such clusters are connected to the hub and transmit power to the shore. This is illustrated in Fig. 2(d).

Borkum Riffgrund1 (Germany), Gwynt-Y-Mor (UK), and Walney 2 (UK) are some of the OWFs using star collection systems.

B. AC Collection Systems with Higher Inter-array Cable Voltage

The inter-array collection cables used in the OWFs are usually rated at 33–36 kV. A collection bus voltage of 33–36 kV is usually preferred because of the ready availability of protection and switch gear equipment. As the size of the wind farm grows and the ratings of the wind turbines increase, the benefits of transmitting at a higher voltage are being considered for electrical design optimization and cost minimization.

In this aspect, some standard voltages, including 48 kV, 56 kV, 66 kV and 72 kV are being analyzed [17]–[19]. The number of inter-array cables and offshore substations can be reduced by considering a collection bus voltage in the range of 66–72 kV. With higher inter-array cable voltages, the number

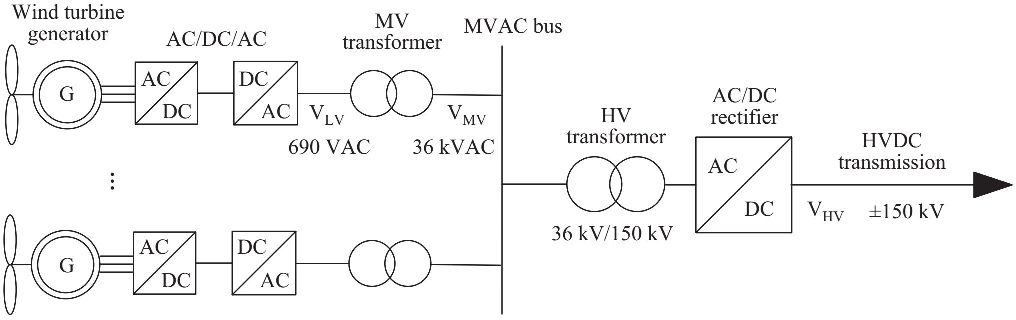


Fig. 1. General representation of components in electrical collection and transmission systems.

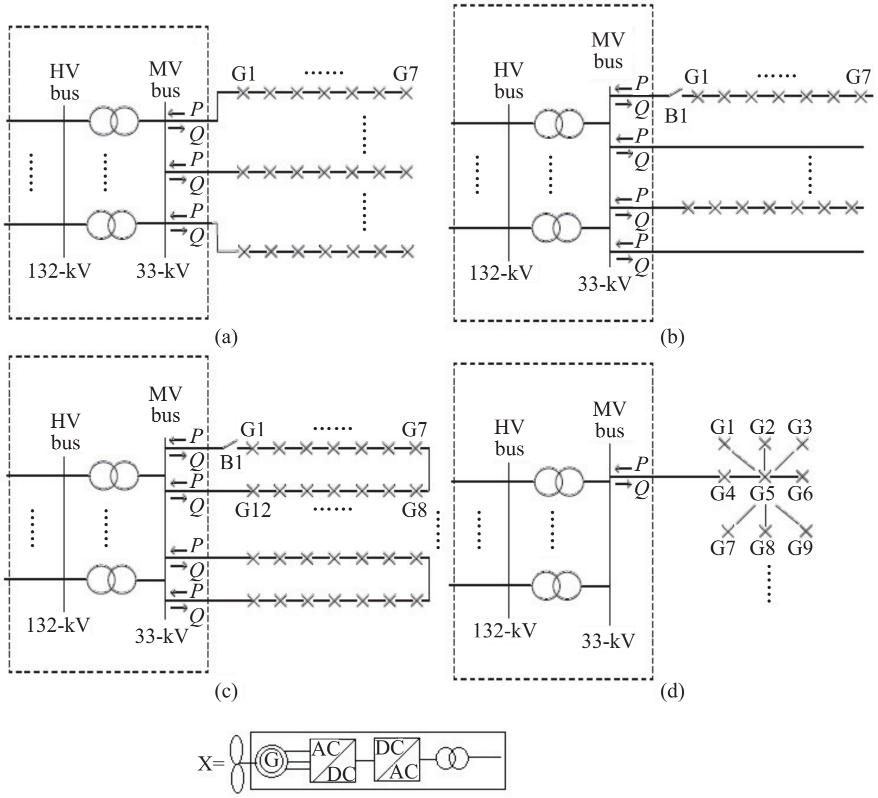


Fig. 2. AC collection systems (a) AC radial. (b) AC Single sided ring. (c) AC double sided ring. (d) AC star [3].

of wind turbines connected in a single string can be increased. The overall cable length is reduced and consequently, reduction in the collection cable losses and increases in the system availability occur. A higher inter-array cable voltage provides definite advantages in terms of transportation, installation and maintenance requirements, compared to the nominal voltage inter-array cable systems.

Reference [17] compared the 33 kV, 48 kV and 66 kV inter-array cables for a radial topology of an OWF rated at 1 GW, demonstrated that it is more beneficial to move to 66 kV than 48 kV taking into account of the equipment vendors for 66 kV inter-array voltage levels. The focus of the industry is on 66 kV inter-array cable voltage and this has been commercialized as well.

The requirements in implementing a higher inter-array cable voltage are the wind turbine structure, which need to house the high voltage transformers and switchgears inside the wind turbine towers. In collection systems, with higher inter-array cable voltages, the transformers and the switchgears also need to be rated at higher values and their costs and dimensions need to be evaluated. The high voltage transformer's size is expected to increase for a 66 kV system compared to 33 kV systems. The required switchgears and the transformers compatible with 66 kV ratings are currently available in the market [20].

The reactive power compensation equipment with 66 kV inter-array cabling is considered to be another significant issue. Increase in the inter-array cable voltage causes increases in reactive power losses in the array cables. Reactive power compensation equipment needs to be provided in the offshore substations. The size of the reactive power compensation units increases for 66 kV inter-array cables compared to the nominal rated 33 kV cables.

The viability and cost benefits with higher collection bus voltages are analyzed in [17]–[19]. A potential cost reduction is possible with higher inter-array cable voltages for large scale OWFs. The design options of 33 kV and 66 kV inter-array cables for a wind farm rated at 1400 MW are compared in [21], which shows the significant benefit in terms of the length of the cables required and consequent potential cost savings.

The transformers were identified to be in a reasonable cost comparison to the 33 kV transformers on a cost per rated MW basis in [17]. The cables required for higher inter-array cable voltage evaluation by [17] reports that the cable cost is more expensive for 66 kV cables compared to 33 kV cables. However, it is assured that the increase in the cable and the transformer costs can be outweighed by the increase in their power transmission capabilities.

AC collection systems with 66 kV inter-array cable voltage are already commercialized by Siemens, which is providing offshore direct drive wind turbines with a 66 kV option for turbines rated from 6–8 MW [20]. The 66 kV collection cables are available commercially by the cable manufacturers Prysmian Group [22] and Nexans [20]. ABB has introduced new 66 kV WindSTAR concept turbine transformers [23], which can fit into the wind turbine towers and facilitate higher inter-array cable collection voltages for large scale OWFs.

In the UK [20], Hornsea2, East Angelia one, Moray East, and Triton Knoll OWFs are using a 66 kV inter-array voltage.

C. DC Collection Systems

The DC collection system is preferable for large OWFs due to the following facts. The capacitive effect of AC cables reduces the active current carrying capacity and so longer distances cannot be covered using AC cables. This limits the active power transfer capability of AC cables and requires compensating devices. In order to address the power quality issues, bulk AC filter banks are installed [1], which can take up a lot of space in the offshore platform. The DC transmission is free from the cable charging current and compensating devices are not required as in AC systems.

The conventional approach to realizing AC collection systems within wind farms are primarily based on 50 Hz bulky transformers. These transformers are heavy and lead to high transportation and installation costs [12].

DC collection systems potentially eliminate the large AC transformers and save space in the offshore platform [11], [12]. The use of DC-DC converters enables the operation of offshore DC collection systems. The DC collection systems can be realized by a step-up DC-DC converters and medium frequency transformers [13]. Reduction in size and weight are the advantages of medium frequency transformers. The decision to use AC collection systems at 50 or 60 Hz frequency is primarily because of the cost of controlling and protecting DC systems. If cost effective DC protection is available, this limitation is no longer an issue [24].

DC collection network cables could also be cheaper than AC cables. This is due to the two core cables of DC instead of three in AC. It is reported in [25] that DC based systems can be expected to save probably from 25% up to possibly 50% of the cable weight of its AC counterpart. Thus, reduction in the size of the cables and magnetic components in achieving a smaller footprint and size are the expected advantages of the DC collection systems. The fault ride through capability of wind turbines is enhanced by decoupling the wind farm from the onshore grid by using HVDC transmission and DC collection systems [26].

Currently, OWFs are equipped with three phase AC grids. The DC collection systems are being considered with an aim to reduce the footprint and size of the offshore platforms. This section will provide an overview of different collection arrangements for OWFs with DC collection systems.

Different configurations of the DC collection systems [13] are possible depending on the collection system voltage and the number of DC-DC converters.

1) DC String Collection Systems

In this collection topology (Fig. 3(a)), individual wind turbines are connected to a medium voltage DC-DC converter and another DC-DC converter is used on the offshore platform.

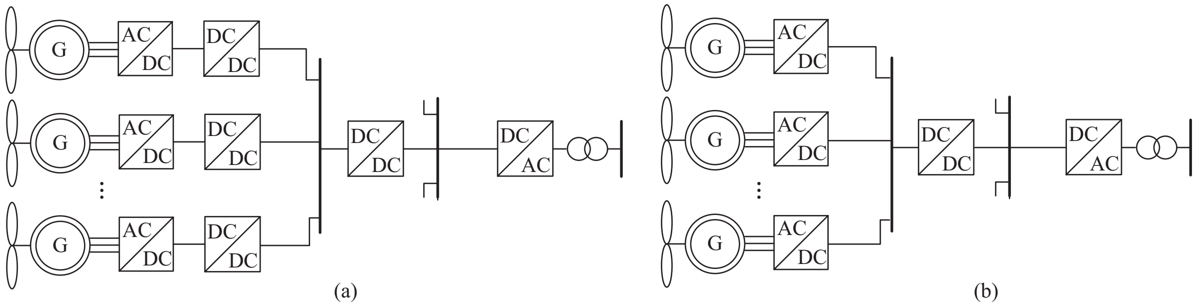
This configuration is like the present-day full-scale converter configurations of the AC system. In this configuration, the turbines with low output voltage can be used. The advantage of this configuration is the direct step up of voltages after the turbine, which leads to reduced cable losses at the collection level. The fault withstand capability of the wind turbines is increased by the two voltage transformation stages between the wind turbines and the grid [13].

The comparison of different DC collection systems in [13], [14] shows that the DC string collection systems with (two DC-DC converters) have the lowest efficiency.

2) DC Cluster Collection Systems

Clustering involves all the turbines in the string to be connected to a common converter. A centralized converter controls all the wind turbines in a single string [27]–[33]. In DC string collection systems, each wind turbine can be controlled independently in order to extract the maximum power output by the generator side AC-DC converter provided in the individual wind turbines. A single large power converter is used to control a group of wind turbines in cluster collection systems. The cluster configuration is shown in Fig. 3(b). A method to control several wind power generators with a single VSC is developed for fixed speed wind turbines [30]. Following these ideas, in DC collection systems, a centralized DC-DC converter controls the wind turbines [29] in a single string and the power is transferred to the DC collection system at medium voltage. The idea behind these configurations is to eliminate the individual wind turbine converters and their associated controls, which can substantially improve the capital cost of the OWFs.

All the wind turbine generators within the single clusters will be operating at the same wind speed. Energy capture losses occur when the group of wind turbines is controlled together with a single converter rather than the individual converters. This is because the individual wind turbines cannot be controlled to extract the maximum power output [28].



(a) (b)

Fig. 3. DC collection systems. (a) DC string collection systems. (b) DC cluster collection systems.

The technical and economic assessment of the centralized power converters and the selection of main components of such topologies were analyzed in [28] for the case of a 300 MW wind farm. The specialized control methods of centralized power converter-based configurations are discussed in this paper, which analyzes the energy capture losses and shows the expected losses in the efficiency in the order of 2%–6% and savings in the capital cost is in the order of 5%–6% by using centralized power electronic converters, instead of the individual wind turbine converters.

Based on the clustering concept, the individual wind turbine converters can be removed and the idea of controlling the entire wind farm with a single large power converter concept is presented in [32]. Another cluster-based configuration, identified as a hybrid AC-DC OWF based on more converter platforms, is presented in [33] and its optimized design is carried out. Hybrid AC-DC refers to a cluster-based configuration, in which wind turbines are grouped and each group is connected to an AC-DC converter in the collector platform. This collector platform is different from HVDC offshore platform. This configuration is shown in Fig. 4. This paper showed that the cluster-based hybrid AC-DC wind farms were cost effective compared to the conventional AC radial collection system based wind farms and showed a total cost savings of 3.76% for hybrid AC-DC wind farms.

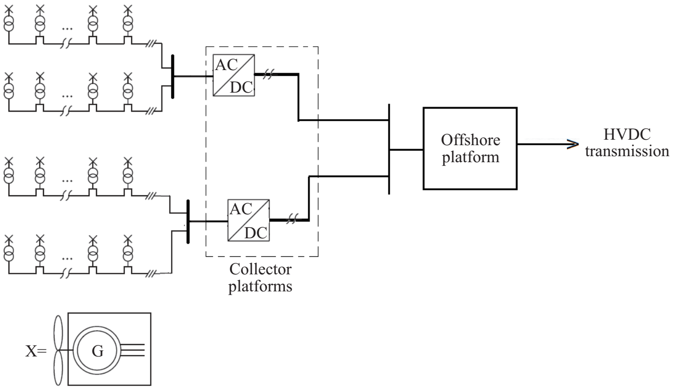


Fig. 4. Hybrid AC-DC collection system.

Another variation of cluster collection topology is proposed in [29] and identified as star topology. In this configuration, each wind turbine is connected to its own converter on a platform housing many converters. The idea behind this topology is to provide improved access to the converter platforms for maintenance purposes and also improved reliability. The study carried out in [29] compares the AC radial collection systems with centralized converter topologies. The centralized converter topologies are classified into star and cluster networks, which are compared with the standard radial collection systems. The results of this study indicate that the cost and losses in the centralized converter topologies (star and cluster networks) were reported to be higher in comparison with the radial collection systems. With star topology, higher losses were contributed by the more component counts. For cluster topology, the losses were due to the energy capture losses. This paper has estimated an energy capture loss of 1.5% for a 1 GW sized wind farm for cluster collection topology.

3) DC Series Collection Systems

In the DC series connection, the turbines with DC power output are connected in series. This series connection builds up the voltage to the transmission level and thus eliminates the offshore converter platforms [34]. The DC series-parallel collection systems configuration is shown in Fig. 5. Wind turbine generators are used with DC-DC converters. The number of wind turbines connected in series constitutes a single string. Numbers of strings are connected in parallel to realize a DC series-parallel configuration. Elimination of the offshore platform, line frequency transformers and power electronic converters reduces the size of the offshore installation and leads to considerable infrastructural cost savings [9], [10].

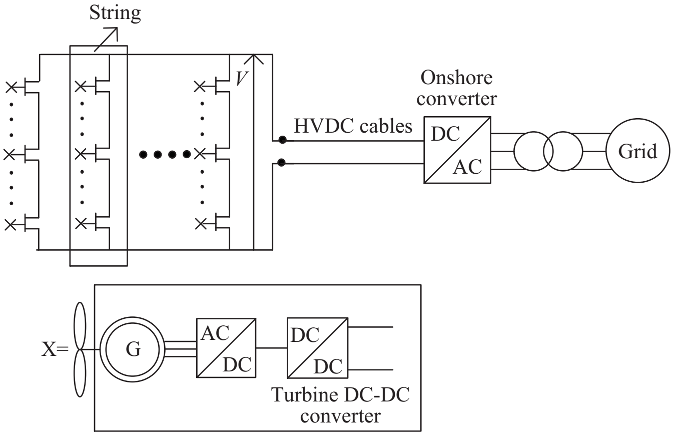


Fig. 5. DC series-parallel collection systems.

However, DC series–parallel collection systems have limitations in terms of their design and control challenges. The main design issue is the insulation requirements of wind turbine converters, which requires withstanding the transmission level voltage because of the series connection [35]. There should always be provisions for a closed path in order to enable the current flow in a string of series connected turbines. This requires special measures, such as diodes to be connected at the output of the wind turbines to by-pass the failed wind turbines [36]. The reliability of DC series-parallel wind farms was estimated to be lower than traditional AC alternatives due to series operations [37]. Special converter topologies and expensive protection requirements are also considered as great challenges for these collection systems. In [34], DC-DC converter requirements for DC series-parallel collection systems were identified.

The series connection of wind turbines causes complicated control for each turbine generator. In this configuration, different output power levels of adjacent turbines poses problems and requires complicated controls. The control of DC series collection systems with thyristors [38], onshore current source converters [39] and matrix converters [40] were proposed to regulate the string current. Therefore, DC series collection systems need to address considerable design and control challenges.

D. Low Frequency AC Collection Systems (LFAC)

LFAC systems are proposed as an alternative to conventional 50/60 HZ AC collection and transmission systems. LFAC refers to the adaptation of HVAC transmission to a lower frequency of 16.7 Hz [41]. LFAC is gaining significant interest in OWF integration for around 80–180 km from the shore. An LFAC collection system is shown in Fig. 6.

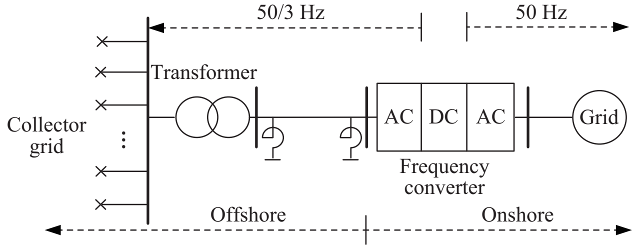


Fig. 6. LFAC collection systems.

One of the limitations of the HVAC cable is the cable charging current, which is a function of the length of the cable, capacitance and frequency. With LFAC collection systems, the cable charging current is reduced because of the reduced frequency and it also reduces the generated reactive power in the cables. This increases the current carrying capacity and enables maximum power transfer compared to the 50/60 Hz frequency AC systems [42]–[44].

In OWF collection systems using LFAC, wind turbines produce LFAC output, which is collected by LFAC cables. An LFAC transformer is used in the offshore platform with LFAC transmission cables. Onshore, a frequency converter is used to convert the low frequency AC into grid frequency. A LFAC collection and transmission system was proposed in [16] for interconnecting large scale offshore wind power. This is considered as an alternative to the conventional AC collection systems and VSC HVDC based AC collection and DC transmission systems.

There are two main advantages of LFAC in terms of reducing the complexity of the OWFs. One is the maximum transfer of active power through longer collection and transmission cables due to the reduced frequency of operations. The second is the elimination of offshore substation converters compared to the HVDC transmission systems of bulk power transfers. The study carried out in [16] compares the HVAC, HVDC and LFAC transmission systems for OWFs. It shows that the capital cost of LFAC is competitive for transmission distance in the range between 30–150 km.

III. CHALLENGES OF DC AND LFAC OWF COLLECTION SYSTEMS

A. Challenges of DC Collection Systems

1) DC-DC Converters

High-power DC-DC converters are considered to be the main components of the DC collection systems [27]. The basic topology of a DC-DC converter consists of an inverter, medium frequency transformer and passive rectifier (Fig. 7). High power DC-DC converters can be obtained by connecting several of these basic converter cells in series and parallel [5].

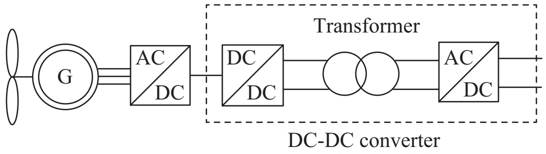


Fig. 7. DC-DC converter in DC based wind farms.

The DC-DC converter topologies can be classified into isolated type and non-isolated type converters [46]. The isolated DC-DC converters use medium frequency transformers. These converters need to be designed with high voltage transformation ratios. The medium frequency transformers require complicated design at high power levels which are discussed in [27]. The cost of DC-DC converters is increased by the construction complexity of the medium frequency transformers.

The energy efficiency of different types of DC-DC converters are compared in [47] for their application in DC collection systems. This paper suggests the full bridge converter as a suitable topology for DC collection systems by considering the energy production costs and converter control requirements. An improved Full-Bridge Three-Level DC-DC converter (IF-BTL) for DC collection systems is proposed in [48]. Novel topologies of DC-DC converters for high power applications have been proposed in [49]–[54].

DC string collection systems with resonant DC-DC converters were analyzed in [14]. The high frequency operation of resonant converters helps to reduce the size of the magnetic components. This paper has compared the AC radial collection systems with DC collection systems using single-phase and three-phase resonant DC-DC converters and reported that there are higher losses in the DC collection systems. However, the comparison of the cables and the magnetic component weights showed that the DC collection systems were beneficial. Resonant DC-DC converters [5] use resonant components and output filters without transformer isolation. They use soft switching concepts for all the diodes and switches. The possible requirements of DC-DC converters for offshore applications are specified in [5], which are expected to have an input voltage in the range of 1–6 kV, an output voltage in the range of 30–60 kV and a power rating of 10 MW.

The DC-DC converters will play an important role in wind power, solar power and energy storage applications. The feasibility of high-power DC-DC converters, taking into account their losses, harmonics, saturation levels in medium frequency transformers, response of high-power medium frequency transformers during wind farm system contingencies, faults and worst-case operating conditions, such as start-up and shut down of the wind farms, has not yet been identified. These are considered to be the greatest challenges for DC collection-based wind farms. As an alternative to these high power, high voltage DC-DC converters with high frequency medium frequency transformers, modular DC-DC converters are proposed in which, multiple DC-DC converters are connected in parallel at their input and series in their output [49] However, an experimental demonstration of the performance of wind turbine control with high power DC-DC converters is required to understand the operational issues. However, there is no commercially available high-power DC converter.

2) Fault Management and Cost Effective Protection Strategies

Fault management and developing cost effective protection methods are major challenges for DC collection systems. There is a need for high power DC circuit breakers [55], [56] capable of switching large DC currents and instantaneously disconnecting the faulty parts in DC collection and transmission systems. However, cost effective DC circuit breakers have not been commercially available yet. Some feasibility tests are being carried out in [57]. DC based transmission and collection systems are considered to be advantageous in terms of active power transfer capability and the reduced size of the collection cables. In addition to these advantages, the major disadvantage of the DC system is the cost of DC protection equipment. Novel solutions need to be developed for fault management and cost-effective protection of DC collection systems.

In multi-terminal DC (MTDC) networks, different protection zones are created to handle the DC faults. This reduces the number of DC circuit breakers. However, in the case of DC collection systems, the options are limited in determining the protection and isolation zones [58], [59].

3) Grid Code Compliances

DC based wind turbines and DC-DC converters must be controlled in order to comply with stringent grid code requirements, which might require novel control methods in DC based wind farms [60], [61].

B. Challenges of LFAC Collection Systems

The main challenge of the LFAC system is the effect of the non-standard frequency on the wind turbine generators, turbine transformers and substation transformers and reactors. The size of the offshore platform will increase as the size of the transformers and reactors will increase in LFAC systems due to their lower frequency. An analysis has been presented in [62] showing the effect of non-standard frequencies in OWF components. However, compared to the HVDC transmission systems of large-scale OWFs, an LFAC offshore platform will only contain the AC transformers and AC switch gears. In this way, complexity of the OWF is reduced by eliminating a power conversion stage in the offshore platform.

The LFAC cables are more efficient for power transmission compared to nominal 50/60 Hz cables due to low frequency. Since the frequency changers are required only at the onshore end, the maintenance cost is reduced compared to the offshore substation of DC collection and transmission systems.

The increase in the core cross sectional area of the substation transformer can be understood by (1), relating the transformer core size and the operating frequency f [42].

$$A_{\text{core}} = E/4.44fnB_{\text{sat}} \tag{1}$$

where E is the applied voltage, n is the number of turns, and B_{sat} is the saturation flux density.

It can be expected that the core cross sectional area of the offshore substation transformer will increase in the case of an LFAC collection system. However, it is not possible to quantify the size of the offshore substation with an increase in the core size of the transformer. What needs to be considered is the manufacturing and the installation cost of such low frequency AC transformers [42]. The circuit breaker requirements of LFAC collection systems are also expected to be larger in size and require longer fault clearance times compared to AC circuit breakers.

With conventional AC collection systems, the turbine transformers which raise the generator output voltage to inter-array collection voltages can be fitted inside the nacelle of the wind turbine, however, with LFAC collection systems, it might be a challenge to appropriately house the turbine transformers [43]

For LFAC collection systems, the wind turbines should also be based on LFAC. Fully rated PMSG or DFIGs [44] can be used for wind turbine generators; however, a fully rated PMSG is preferred for a relatively simpler adaptation of low frequency AC.

The number of different converter types, such as cycloconverters, back-back VSC converters and matrix converters [42], [63] are analyzed for the LFAC transmission topologies, which require AC-AC converters on the onshore substation for interconnecting the wind farm with the onshore grid operating at standard frequency.

The increase in the size of the transformers causes the LFAC system to be expensive [42]. The main drawback of LFAC collection systems are the size and cost of the low frequency components and the hesitancy of manufacturing markets towards accepting a non-standard frequency [42]. A comparison of transformer and LFAC collection platforms by [64] is shown in Table I. An LFAC collection system can be preferred if the transmission system is also LFAC.

TABLE I
LFAC COLLECTION SYSTEM TRANSFORMER AND SUBSTATION SIZE COMPARISON

Collection system compenents	Size
LFAC substation	1000 m^3
VSC substation	16000 m^3
50 Hz transformer	52.52 m^3
16.7 Hz transformer	157.24 m^3

The effect of low frequency on transformers, reactors and wind turbines are analyzed in [42] which are of critical importance. The lower frequency could increase the size of transformers and the space requirements of offshore platforms. The other issues with the non-standard collection frequency are discussed in [62].

IV. RELIABILITY AND COST ASPECTS OF OWF COLLECTION SYSTEMS

A. Cost Proportion of Collection Systems

The cost of OWFs is usually higher than their onshore counterparts. According to 2018 statistics from the International Renewable Energy Organization [65], the global offshore wind power cost per kilowatt-hour is 0.127 USD/kWh, which is 1% lower than in 2017, and 20% lower than in 2010. Offshore costs are coming down through technology innovation and economies of scale [66]. During the planning and evaluation of the collection systems, the minimum present value of total cost is usually taken as the objective function. Factors, such as topology of collection systems, location and quantity of offshore platforms, cable layout, number of circuit breakers, WT capacity and voltage level are used as variables to maximize the comprehensive economic benefits of collection systems [67], [68].

Cost comparative studies carried out in [69], [70] for HVAC, LFAC and HVDC transmission systems for a large scale OWF show that for a transmission distance between 125 km and 200 km, LFAC is shown to be 16%–17% less expensive than the HVDC transmission. The economic studies carried out in [64] show that HVDC is more expensive compared to LFAC transmission systems.

The components of collection systems considered include the wind turbines, power electronic converters used in wind turbines, collection cables and offshore platforms. Table II lists the cost proposition of collection system components based on the summary of the previous research.

The cost of wind turbines accounts for 30%–50% of the total cost of OWF [71], which has a greater impact on the collection system costs. Major wind turbine companies have been committed to the research and development of large-capacity offshore wind turbines. Increasing the single WT capacity can save space, increase power generation, reduce base construction costs and the total area of wind farms. Since the wind turbines considered in all the three collection systems are the same, it is not listed in Table II.

The cost of wind turbine transformers shown in Table II show that in [64], the cost of an LFAC transformer is higher than that of similar 50 Hz transformers. The cost of power electronic converters depends on specific wind turbine types [72]. The power electronic converters are usually high in cost. This is primarily because the majority of the converters are used with filters to improve the power quality, which are considered to be heavy and bulky. The construction complexities of the medium frequency transformers increase the cost of DC-DC power electronic converters of DC collection systems. Developments in new semiconductor devices and magnetic materials are required to bring down the cost of DC-DC converters used in large scale OWFs with DC collection systems. The cost of collection cables depends on the current and the voltage ratings of the cables. From the cost proportion analysis of collection cables shown in Table II, it is seen that the costs of DC cables are less expensive compared to AC and LFAC collection cables [64], [76]

The cost of an offshore platform depends on the amount of power processed. According to [72], offshore platform costs are 3.5% of LCOE. (Levelized Cost of Energy) and the electrical infrastructure costs are around 12%. In DC collection systems used with HVDC transmission, the offshore platform costs are estimated to be lower. This is because of the reduction in the size of the offshore platform, which houses DC-DC converters and the elimination of the line frequency transformers used in the AC collection and HVDC transmission systems. An LFAC collection system used with an LFAC transmission system is free of offshore platform converters, which is reflected in the cost of the LFAC offshore platform shown in Table II.

The failure rate of power electronic converters is usually higher than the line frequency transformers [73]. DC collection systems depend more on power electronic converters and this would cause the maintenance costs to be higher.

B. Reliability of Collection Systems

The reliability of electrical collection and transmission systems is of great importance. Extreme operating conditions in OWFs can lead to unexpected failures. Because of the high cost of the assets [74], the reliability aspect of an OWF is considered to be significant. The cost and reliability aspects are considered to be one of the main motivations behind the different collection configuration studies.

An OWF consists of several subsystems, including wind turbines and generators, internal collection cables, transmission platform, offshore cables and grid interconnections. The reliability model of the wind farm collection systems can be expressed in terms of the availability of the subsystems to generate and deliver power to the main AC grid. Failure rates and Mean Time to Repair (MTTR) of wind farm subsystem components are the reliability data used in calculating the reliability indices. The reliability data are usually obtained from the operational experiences of the commissioned wind

TABLE II
COST PROPORTION OF COLLECTION SYSTEMS

Collection system components	AC collection systems	DC collection systems	LFAC collection systems
Wind turbine power electronics converters	60 £/kVA [73]	165 £/kW [73]	60 £/kVA [64], [73]
Wind turbine transformer	112 k£ [64] (for a 5 MW wind turbine)	No separate wind turbine transformer, medium frequency transformer is part of DC-DC converter	LFAC transformer 313 k£ [64] (for a 5 MW wind turbine)
Collection cables	65.63 M£(33 kV inter array cable of a 200 MW wind farm from [73])	32.98 M£(30 kV inter array cable of a 200 MW wind farm from [73])	Inter-array cable cost models not available, can be considered approximately similar to the cost of AC collection cables. Reference [64] reports LFAC collection cables to be expensive than DC collection cables.
Offshore platform	52.05 M£(for a 200 MW wind farm, AC collection + HVDC transmission) [73] (including the cost of offshore platform converter – AC/DC converter)	45.94 M£(for a 200 MW wind farm, DC collection + HVDC transmission) [73] (including the cost of offshore platform converter – DC/DC converter)	25 M£ for a 200 MW wind farm with LFAC collection and LFAC transmission [64]. Not required to use an offshore platform converter and thus reduces offshore platform cost.

farms. The failure rates and MTTR data collected for the wind turbine converters, transformers, AC and DC collection cables, collection bus, platform converters and platform transformers are shown in Table III [8], [75], [76].

TABLE III
RELIABILITY DATA USED [8], [75], [76]

Components	Failure rate (failure/year)	Repair time (hours)
Power electronic converters	0.05	720
Wind turbine transformer	0.0131	240
Wind turbine circuit breakers	0.024	2160
AC collection cables	0.008/km	2160
DC collection cables	0.0706	1440
Collection bus	0.004	720
Platform transformers	0.02	4320

As wind farms are being planned to be installed for significant distances from the shore, the access to wind farms might be difficult for maintenance purposes. Normally longer repair times for offshore equipment are due to the additional delays caused by the waiting times for reparation during the winter seasons. Especially, the offshore platform transformers would require longer repair times due to lifting and transportation of spare units.

The reliability of offshore wind power collection systems can be evaluated in terms of reliability indices, such as EENS (Expected Energy Not Supplied) and Average System Availability Index (ASAI). Reliability indices can be evaluated by probabilistic methods by representing the system under consideration with the interconnection of several subsystems. These indices help to evaluate the efficiency of the wind farms based on both the component failure status and wind energy availability [76]. In order to perform accurate reliability analysis, the failure data is very crucial. However, there is little failure data existing in the public domain [74].

Different topologies of the collection systems can have different reliability indices depending on the components involved. This is because the equipment reliability of different components of collection systems might be different for various collection systems considered. The reliability of different collection systems is estimated using the reliability data of the different components for a specific type of collection system being considered. The variations in the failure rate and the MTTR of different components involved in a particular type of collection system yields variations in the reliability of the different collection systems being considered.

For example, in DC and AC collection systems used with HVDC transmission, the offshore platform includes a VSC-HVDC converter. However, in the case of LFAC collection systems using an LFAC transmission, VSC-HVDC converters are not present in the offshore platform. The failure rate and the downtime of the VSC-HVDC converters will impact the reliability performance indices of AC and DC collection systems used with HVDC transmission. Similarly, the differences in the failure rates and downtime of the MVAC, MVDC and LFAC collection cables would impact the reliability performance of each of the collection systems.

A reliability comparative study carried out in [8] for a 300 MW wind farm shows the ASAI of an AC radial collection system is 89.17 and that of a DC radial collection system is 76.69. The reliability difference is approximately 12% in terms of ASAI for the AC radial and DC radial collection systems. Similarly, a comparative study between VSC-HVDC and LFAC based collection and transmission systems shows that the unavailability of the VSC-HVDC converters to be higher. However, reliability figures focusing only on collection system components are not generally available. This is primarily due to the limited data on maintenance and repair times.

The reliability of the power electronic converters has been identified to be weak [8], [75], [76]. Such reliability considerations encourage the use of wind farm collection topologies with less power electronic conversion stages involved. In this aspect, the LFAC collection (LFAC collection + transmission), and AC collection system (AC collection + AC transmission) have more reliability compared to the DC collection systems (DC collection + HVDC transmission) [75]. In DC collection systems, the cluster-based converters control method, which controls a group of wind turbines with centralized converters, are proposed as a reliability improvement measure. However, they have inherent power capture losses because of controlling each wind turbine away from the maximum power point. The reliability of DC series wind farms was estimated to be lower than the AC radial collection systems due to the number of series connected wind turbines [37]. It is also to be understood that more mature technologies perform with higher reliability [77]. With the reduction in the number of power conversion stages, the reliability of the system can be expected to be improved.

There is a need for more proactive approaches to be developed for maintenance and reliable operation of the OWFs. The reliability assessment of collection systems helps to quantify the risks and helps to arrive at an optimal design. Failure of large wind farms will have a significant impact on the power balance in the power system. So, a reliability analysis is required to identify the largest contributor to the unreliability and evaluation of alternative designs with additional redundancy with respect to the collection system components.

The reliability analysis of different collection system configurations helps to determine the maintenance costs of the collection systems. The differences in the failure rate and down time of the collection system components cause variations in the maintenance costs of different collection systems [76]. The cost and reliability analysis of various collection systems is complex primarily because of the different factors which must be taken into consideration. Another major reason is that there are no commercial projects established with alternative collection system configurations, such as DC and LFAC collection systems, so as to verify the cost and reliability models developed based on well supported assumptions.

V. COMPARISON OF AC, DC AND LFAC COLLECTION SYSTEMS

There are many studies that have been reported comparing the AC and DC collection system configurations in terms of their energy losses, cost benefit analysis and reliability considerations [73], [78]–[80]. With an HVDC transmission configuration, the losses in the DC radial collection systems were reported to be higher than AC radial collection systems [73]. The number of power conversion stages remains the same in both AC and DC radial collection systems. In DC collection systems, the cost of DC– DC converters and DC protective devices outweighs the benefits of cost savings obtained by reduced cable size and elimination of reactive power losses. Also, from a reliability consideration, the use of more power electronic converters reduces the reliability of DC collection systems more than the AC counterparts. DC cluster collection systems with less power electronic conversion stages proposed can have more reliability; however, they would require additional platforms to incorporate the centralized converters.

The elimination of offshore platforms reduces the costs of DC series and DC series-parallel wind farms [8]. However, their operational challenges, in terms of insulation requirements, over-voltages and power curtailment losses caused by unequal wind speed conditions [81], need careful considerations.

Compared to LFAC, in DC collection systems, redesign of wind turbines is not required. The reduced number of cables in LFAC means reduction in breaker requirements [42]. This yields more savings in LFAC compared to AC collection systems. However, the size of the collection cables and the offshore substation transformers needs additional consideration. From a reliability point of view, LFAC systems were reported better in [42] because of the elimination of power electronic converters in offshore substations.

The problems associated with the DC technology are the cost of protection equipment and converter costs. LFAC could be considered as an option to increase the transmission capability and reduce the power conversion stages [42]. The cable losses of LFAC collection systems will be significantly lower than the AC collection cables, however, the increase in the size of the cables and reactors causes additional concerns.

The DC series collection systems are compared with the AC radial collection systems in terms of losses, cost and reliability in [8] based on a 300 MW wind farm with 150 kV transmission voltages. In this comparative study, the wind turbines with 2 MW ratings and 10 MW ratings are compared. This comparative study reported higher losses for DC series collection systems compared to the AC collection systems. This was primarily due to the DC-DC converters of the DC series collection systems. Higher rated wind turbines were suggested to obtain cost beneficent DC series collection systems.

In DC radial collection systems, the number of power conversion stages is almost the same as that of the AC radial collection systems. In order to reduce the number of power conversion stages, usage of higher rated wind turbines and high (step-up) voltage transformation ratio for DC–DC converters are suggested. A summary of comparisons between the collection system advantages and limitations of each collection system are shown in Table IV.

VI. Current Status of Offshore Wind Power Collection Systems

Currently, there are 146 OWFs operating in the world. The global cumulative offshore wind power capacity is shown in Fig. 8 [66]. China installed 2.652 GW of offshore wind capacity in 2018 alone. It has surpassed the UK as the world's leading offshore market in new installations in 2018 (Fig. 8).

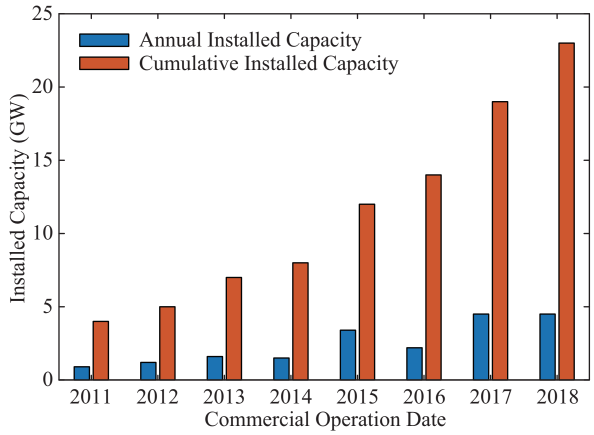


Fig. 8. Global cumulative offshore wind capacity in 2018 [66].

A. *Offshore Wind Power Collection Systems in China*

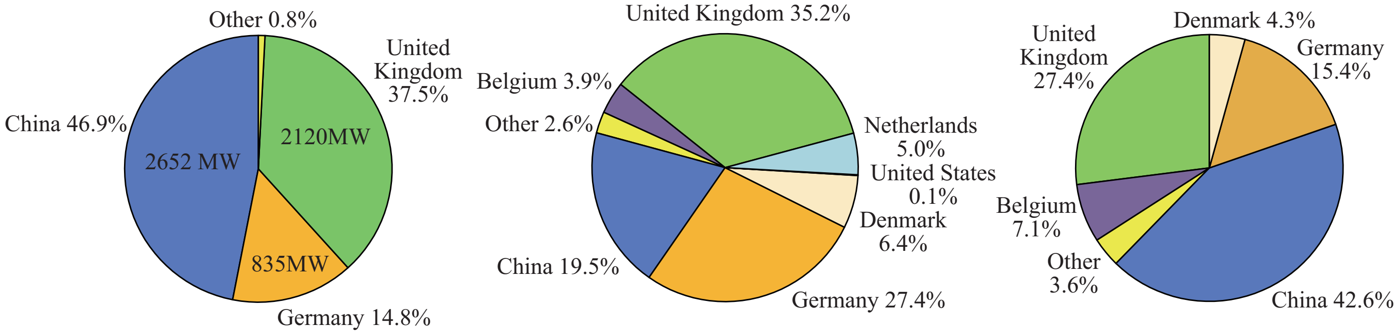
China's first OWF is located on the Shanghai Donghai Bridge. In recent years, Jiangsu, Shandong, Zhejiang, Guangdong and other coastal provinces have accelerated the development of offshore wind power, and several hundred-megawatts OWFs are beimg constructed. Among them, the H3#-H5# offshore wind power project in Sheyang, Jiangsu was launched in July 2019, with the planned installed capacity of 1000 MW and the adoption of the VSC HVDC transmission scheme. The largest OWF connected to the grid in China is the CGN Yangjiang Nanpeng Island Offshore Wind Power Project, with an installed capacity of 400 MW and collection cables of 35 kV.

In 2019, China approved 24 offshore wind power projects off the coast of Jiangsu province with a total capacity of 6.7 GW [66]. These developments made China the world's third largest offshore wind market and this accounts for 19.5% of installed capacity [66] behind the UK (35.2%) and Germany (27.4%) as shown in Fig. 9(a) and Fig. 9(b) Fig. 9(c) shows the offshore wind capacity under construction by country [66] and China shows a maximum of 42.6% wind capacity as being in under construction. It is forecasted that China will add 40 GW of offshore wind capacity by 2030 [82].

China's offshore wind power plants are currently primarily distributed near the coast with only a small distance from the shore. The commonly used voltage level of the collection system is 35 kV in China, such as the 300 MW offshore wind power project in Jiangsu Binhai and the Lingang Phase II offshore wind power project in Shanghai. The commonly used type of collection system cable is 35 kV three-core XLPE cable in China. The most common topology of collection system in China is radial topology.

TABLE IV
SUMMARY OF ADVANTAGES AND LIMITATIONS OF DIFFERENT COLLECTION SYSTEMS

Collection systems	Advantages		Limitations	Technology	Features
	Technical	Economical			
AC radial collection	Simple to control	Small cable length and lower cost.	Reliability– any cable failure prevents the downstream turbines exporting power.	Mature	Line frequency transformers (huge size, occupies large space in the offshore platforms, high transportation, maintenance and installation cost). Three-phase three-core submarine AC cables, size, limitations on active power transfer capability due to reactive power losses in AC cables. Protection aspects-AC circuit breakers-mature technology and widely available in the market.
AC radial loop collection	High reliability, since reconfiguration is possible.	Not advantageous	Cost of additional cables providing path for redundant power flow.	Mature	
AC star	Reduced cable ratings. High reliability.	Not advantageous	Cable losses and costs considerably higher compared to the radial configurations.	Mature	
DC string	Less weight, increased voltage level. Free from reactive power losses in collection cables. Decoupling wind farm from the onshore grid. Flexibility of power flow control [60]. High power density.	Potential elimination of large sized AC transformers, smaller size of MVDC cables.	Complicated fault and protection control strategies. High capital investments [64], [78]. High voltage DC-DC converters.	Research only	Medium frequency transformers (reduction in size, saves large space in the offshore platforms). Protection aspects- DC circuit breakers– (complex and costly, not widely available like the AC counterparts).
DC cluster	More reliability	Less number of power electronic converters	Power capture losses. Complicated control one or more centralized offshore collection platforms.	Research only	
DC series	Reduced footprint and size.	Elimination of offshore platforms	Insulation requirements. Fault management. Poor reliability. Voltage variation due to unequal wind speeds.	Research only	
LFAC collection	Less reactive power losses compared to AC collection systems.	Elimination of offshore converter stations. Reduced power conversion stages.	Sizes of the LFAC transformers and reactors. Increase in cable size. LFAC protection circuits. Frequency converters in the onshore platform Non-availability of specific standards [45].	Not widely available (LFAC transformers in railway power systems [45]).	LFAC transformer increase in size. Power electronic converters need to be reconfigured for low frequency. LFAC breakers bigger in size and take a longer time to break [42]. Not available widespread like the AC counterparts, still relatively easy to realize compared to DC breakers. Reference [15] suggests that 50 HZ breaker can be used with LFAC systems with suitable de-rating factors.



(a) (b) (c)

Fig. 9. (a) Installed offshore wind capacity by country in 2018. (b) Cumulative offshore wind installed capacity by country in 2018. (c) Offshore wind capacity under construction by country in 2018 [66].

B. Offshore Wind Power Collection Systems in Other Regions

Europe is targeting for a total offshore installed capacity of 100 GW by 2030 [83]. The total installed capacity in Europe is primarily contributed by the UK, Germany, Belgium, Denmark and the Netherlands. The United Kingdom is the world's largest offshore wind market in total capacity.

The 1.2 GW Hornsea Project in the United Kingdom is the largest OWF in the world [20]. Dogger Bank (UK, 4.8 GW) and Greater Changhuva (Taiwan, China, 2.4 GW) are the other projects in the planning stage.

In the US offshore industry, the total offshore wind procurement target is 25.4 GW in 2019 with upgrading in New York and New Jersey. 15 offshore projects are expected to be built by 2026 [66].

In Asian offshore markets, Taiwan Province in China is planning to install 5.6 GW of offshore wind to be in operation by 2025.

As far as the wind power collection systems are concerned, all the installed OWFs around the world use MVAC collection systems in the voltage range of 33–36 kV for inter-array cables. Some of the new installations in the UK are using 66 kV inter-array cables for offshore wind power collection systems [20]. Radial AC topology is the most commonly used collection system topology in the offshore plants.

VII. FUTURE PROSPECTS

As of now, no offshore wind power projects with DC or LFAC collection systems are available, as they are still limited by their technical challenges. However, significant research has been carried out for the key components of the collection systems with respect to DC-DC converters and DC circuit breakers. A CIGRE working group [60], [61] has been established for feasibility analysis of MVDC grids. As reported in [42], as there are no market requirements of LFAC equipment, there is a general hesitancy to accept new LFAC technology for OWFs.

There is more potential for commercial availability of LFAC components compared to DC collection components, considering the maturity of AC collection and transmission systems. However, site specific assessments need to be evaluated depending on the offshore area and the wind farm ratings.

The wind turbine ratings are also increasing in the range of 8 to 15 MW. There is an evolution of mega power projects in China and worldwide. These measures indicate the need for innovative electrical collection and transmission options for efficiently interconnecting the offshore wind energy to the grid.

Investigations regarding the transmission distance for AC, HVDC and LFAC transmission distances have been performed and distinct distances have been reported with respect to each transmission system [84]. However, such an analysis has not been done with respect to collection systems. Regarding the cost benefit of these topologies, because of the market unavailability of the few components of DC and LFAC collection systems, no definite conclusions have been drawn; results with the inclusivness of several sensitive factors are reported. However, consideration of the advantages of the novel collection systems, advancements in the direction of DC circuit breakers, DC-DC converter topologies, matrix converters for LFAC systems and fault tolerant converters [85], [86] are all being performed at a faster pace.

There is some infrastructural simplification with respect to the cable systems and DC-DC power electronic converters of the DC collection systems and reliability improvements with centralized collection systems. However, these advantages need to be evaluated against the research development and market availability of the DC-DC converters and DC protection circuits. Research advances in the high-power density DC-DC converters, bidirectional converters without magnetic core transformers, fault tolerant converters and fast DC circuit breakers can be expected to make a greater impact on the footprint and size of the DC collections systems. The cost effectiveness and the energy efficiency of such converters need to be improved in order to consider the full advantages of DC collection systems.

This study focused on the electrical components of the collection systems. The research developments in these areas are going to have a greater impact on the OWF collection and transmission [87] topologies, energy efficiency, cost and the reliability of the collection system configurations. The cost effectiveness of the collection topologies needs to be evaluated over the lifetime of a project, also taking into account the reliability considerations. Such an evaluation is not possible, given the lack of operational experience with the components of DC and LFAC collection systems. Since it can be considered as a potential challenge to analyze the cost benefits of each topology with the given amount of uncertainties involved with the different factors. An optimized electrical collection system is a vital requirement and arriving at such a system is also quite challenging.

The power collection systems of OWF are not a major technical issue as the technology involved is mature. However, optimization of these technologies for large scale and remote OWFs, considering of new grid codes and security standards, has become an important issue to be considered. As the OWF projects are significantly costly, the power collection systems must be optimized taking into account energy efficiency, cost and reliability. The challenges in the components of collection systems are presented here. These factors need due consideration in the process of evaluating the cost-effective electrical systems for large scale OWFs.

VIII. CONCLUSION

This paper has presented a review of the electrical collection system configurations of OWFs. The challenges of the novel power collection systems, such as DC and LFAC are summarized. This study developed a categorization of different offshore collection systems. It is expected that many other innovative electrical collection topologies will emerge due to the extensive ongoing research in this area. Further attention needs to be paid to finding innovative solutions of collecting the power from the OWFs in a cost-efficient and reliable way. The innovative solutions require filling the research gap in developing high power density power electronic converters with novel semiconductor devices, integrated fault tolerant measures and their flexible control methods. These technology barriers relating to electrical collection and transmission systems need special consideration in order to make use of the tremendous wind potential available worldwide. The key component requirements and grid integration challenges must be evaluated with each collection system configuration as an extension to this study. The commercial availability of LFAC and DC collection system components, and different power electronic converters involved would decide the competitiveness of these newer configurations. The concept of DC collection system topology does not exist today. However, it could become a viable alternative depending on the market availability and rapid development of the high-power DC-DC converters and cost-effective DC protective devices.

This categorization is useful to understand the advantages and limitations of each collection system configuration, challenges in the collection system components and further research needs to be considered for improving the energy efficiency, cost benefit and reliability of the different collection systems.

REFERENCES

[1] E. Apostolaki-Iosifidou, R. Mccormack, W. Kempton, P. Mccoy, and D. Ozkan, “Transmission design and analysis for large-scale offshore wind energy development,” *IEEE Power and Energy Technology Systems Journal*, vol. 6, no. 1, pp. 22–31, Mar. 2019.

[2] N. M. Kirby, L. Xu, M. Luckett, and W. Siepmann, “HVDC transmission for large offshore wind farms,” *Power Engineering Journal*, vol. 16, no. 3, pp. 135–141, Jun. 2002.

[3] G. Quinonez-Varela, G. W. Ault, O. Anaya-Lara, and J. R. McDonald, “Electrical collector system options for large offshore wind farms,” *IET Renewable Power Generation*, vol. 1, no. 2, pp. 107–114, Jun. 2007.

[4] K. Das, *Nicolaos Antonios Cutululis, Offshore Wind Power Technology Catalogue*, DTU, Denmark, 2017.

[5] W. Chen, A. Q. Huang, C. S. Li, G. Y. Wang, and W. Gu, “Analysis and comparison of medium voltage high power DC/DC converters for offshore wind energy system,” *IEEE Transactions on Power Electronics*, vol. 28, no. 4, pp. 2014–2023, Apr. 2013.

[6] P. Bauer, S. W. H. De Haan, C. R. Meyl, and J. T. G. Pierik, “Evaluation of electrical systems for offshore windfarms,” in *Conference Record of the 2000 IEEE Industry Applications Conference. Thirty-Fifth IAS Annual Meeting and World Conference on Industrial Applications of Electrical Energy (Cat. No.00CH37129)*, 2000, pp. 1416–1423.

[7] P. Gardner, L. Craig, and G. Smith, “Electrical systems for offshore wind farms,” in *20th BWEA Conf Wind Energy-Switch on to Wind Power*, Cardiff, UK, Sep. 1998.

[8] H. J. Bahirat, B. A. Mork, and H. K. Høidalen, “Comparison of wind farm topologies for offshore applications,” in *2012 IEEE Power and Energy Society General Meeting*, Jul. 2012, pp. 1–8.

[9] S. Lundberg, “Evaluation of wind farm layouts,” in *NORPIE’04*, 2008, pp. 1–8.

[10] S. Lundberg, “Wind farm configuration and energy efficiency studies—Series DC versus AC layouts,” Ph.D. dissertation, Chalmers University of Technology, Sweden, 2006.

[11] S. J. Shao and V. G. Agelidis, “Review of DC system technologies for large scale integration of wind energy systems with electricity grids,” *Energies*, vol. 3, no. 6, pp. 1303–1319, 2010.

[12] C. Zhan, C. Smith, A. Crane, A. Bullock, and D. Grieve, “DC transmission and distribution system for a large offshore wind farm,” in *9th IET International Conference on AC and DC Power Transmission (ACDC 2010)*, Jul. 2010, pp. 1–5.

[13] C. Meyer, M. Höing, A. Peterson, and R. W. De Doncker, “Control and design of DC grids for offshore wind farms,” *IEEE Transactions on Industry Applications*, vol. 43, no. 6, pp. 1475–1482, Nov./Dec. 2007.

[14] J. Robinson, D. Jovcic, and G. Joós, “Analysis and design of an offshore wind farm using a MV DC grid,” *IEEE Transactions on Power Delivery,* vol. 25, no. 4, pp. 2164–2173, Oct. 2010.

[15] M. Jafar, Y. Yang, and A. Yanushkevich, “Low frequency AC transmission for grid integration of offshore wind power,” in *Proceedings of the 13th Wind Integration Workshop*, Berlin, Germany, 2014.

[16] N. Qin, S. You, Z. Xu, and V. Akhmatov, “Offshore wind farm connection with low frequency AC transmission technology,” in *2009 IEEE Power & Energy Society General Meeting*, 2009.

[17] A. Ferguson, P. Villiers, B. Fitzgerald, and J. Matthiesen, “Benefits in moving the inter-array voltage from 33 kV to 66 kV AC for large offshore wind farms,” in *EWEA*, Denmark, Apr. 2012.

[18] D. Saez, J. Iglesias, E. Giménez, I. Romero, and M. Reza, “Evaluation of 72 kV collection grid on offshore wind farms” in *EWEA Annual Event*, Copenhagen, Apr. 2012.

[19] R. M. Dermott, G. Hassan, and P. Ltd, “Investigation of use of higher AC voltages on offshore wind farms,” in *EWEC*, France, Mar. 2009.

[20] Offshore Wind Farms Database. [Online]. Available: http://www. 4coffshore.com

[21] “66 kV systems for offshore wind farms,” TenneT Rep., 2015.

[22] “66 kV submarine cable systems for offshore wind,” Pyrsmian Group, 2016.

[23] https://www.hitachiabb-powergrids.com/

[24] C. M. Franck, “HVDC circuit breakers: a review identifying future research needs,” *IEEE Transactions on Power Delivery*, vol. 26, no. 2, pp. 998–1007, Apr. 2011.

[25] J. D. Herbst and A. L. Gattozzi, “MVDC and HFAC electric power system architectures for the transformable sea base connector (T-craft),” in *11th International Conference on Fast Sea Transportation FAST 2011*, Sep. 2011.

[26] Y. Q Lian and S. J. Finney, “DC collection networks for offshore generation,” in *2nd IET Renewable Power Generation Conference (RPG 2013)*, Beijing, 2013, pp. 1–4.

[27] C. Meyer, “Key components for future offshore DC grids,” Ph.D. dissertation, RWTH Aachen University, Germany, 2007.

[28] D. Jovcic and N. Strachan, “Offshore wind farm with centralised power conversion and DC interconnection,” *IET Generation, Transmission & Distribution*, vol. 3, no. 6, pp. 586–595, Jun. 2009.

[29] M. A. Parker and O. Anaya-Lara, “Cost and losses associated with offshore wind farm collection networks which centralise the turbine power electronic converters,” *IET Renewable Power Generation*, vol. 7, no. 4, pp. 390–400, Jul. 2013.

[30] L. Trilla, O. Gomis-Bellmunt, A. Sudrià-Andreu, and J. Liang, “Control of SCIG wind farm using a single VSC,” in *Proceedings of the 2011 14th European Conference on Power Electronics and Applications (EPE 2011)*, 2011, pp. 1–9.

[31] D. Jovcic, “Offshore wind farm with a series multiterminal CSI HVDC,” *Electric Power Systems Research*, vol. 78, no. 4, pp. 747–755, Apr. 2008.

[32] O. Gomis-Bellmunt, A. Junyent-Ferré, A. Sumper, and J. Bergas-Jané, “Control of a wind farm based on synchronous generators with a central HVDC-VSC converter,” *IEEE Transactions on Power System*, vol. 26, no. 3, pp. 1632–1640, Aug. 2011.

[33] M. De Prada, L. Igualada, C. Corchero, O. Gomis-Bellmunt, and A. Sumper, “Hybrid AC-DC offshore wind power plant topology: optimal design,” *IEEE Transactions on Power Systems*, vol. 30, no. 4, pp. 1868–1876, Jul. 2015.

[34] N. Holtsmark, H. J. Bahirat, M. Molinas, B. A. Mork, and H. Kr. Hoidalen, “An All-DC offshore wind farm with series-connected turbines: An alternative to the classical parallel AC model?” *IEEE Transactions on Industrial Electronics*, vol. 60, no. 6, pp. 2420–2428, Jun. 2013.

[35] E. Veilleux and P. W. Lehn, “Interconnection of direct-drive wind turbines using a series-connected dc grid,” *IEEE Transactions on Sustainable Energy*, vol. 5, no. 1, pp. 139–147, Jan. 2014.

[36] F. Tatsuta and S. Nishikata, “Dynamic performance analysis of a wind turbine generating system with series connected wind generators and bypass diodes using a current source thyristor inverter,” in *The 2010 International Power Electronics Conference-ECCE ASIA*, Sapporo, Japan, 2010, pp. 1830–1836.

[37] H. J. Bahirat, G. H. Kjolle, B. A. Mork, and H. K. Hoidalen, “Reliability assessment of DC wind farms,” in *2012 IEEE Power and Energy Society General Meeting*, 2012, pp. 1–7.

[38] S. Nishikata and F. Tatsuta, “A new interconnecting method for wind turbine/generators in a wind farm and basic performances of the integrated system,” *IEEE Transactions on Industrial Electronics*, vol. 57, no. 2, pp. 468–475, Feb. 2010.

[39] M. Popat, B. Wu, F. R. Liu, and N. Zargari, “Coordinated control of cascaded current-source converter based offshore wind farm,” *IEEE Transactions on Sustainable Energy*, vol. 3, no. 3, pp. 557–565, Jul. 2012.

[40] A. Garcés and M. Molinas, “Coordinated control of series-connected offshore wind park based on matrix converters,” *Wind Energy*, vol. 15, no. 6, pp. 827–845, Nov. 2012.

[41] H. Chen, M. H. Johnson, and D. C. Aliprantis, “Low-frequency AC transmission for offshore wind power,” in *2014 IEEE PES General Meeting | Conference & Exposition*, 2013.

[42] J. Ruddy, R. Meere, and T. O’Donnell, “Low Frequency AC transmission for offshore wind power: a review,” *Renewable and Sustainable Energy Reviews*, vol. 56, pp. 75–86, Apr. 2016.

[43] M. R. Islam, Y. G. Guo, and J. G. Zhu, “A review of offshore wind turbine nacelle: technical challenges, and research and developmental trends,” *Renewable and Sustainable Energy Reviews*, vol. 33, pp. 161–176, May 2014.

[44] C. N. Mau, K. Rudion, A. Orths, P. B. Eriksen, H. Abildgaard, and Z. A. Styczynski, “Grid connection of offshore wind farm based DFIG with low frequency AC transmission system,” in *2012 IEEE Power Energy Society General Meeting*, 2012.

[45] W. Fischer, R. Braun, and I. Erlich, “Low frequency high voltage

offshore grid for transmission of renewable power," in *2012 3rd IEEE PES Innovative Smart Grid Technologies Europe*, 2012.

[46] L. Max, "Design and control of a DC collection grid for a wind farm," Ph.D. dissertation, Department, Chalmers University of Technology, Sweden, 2009.

[47] L. Max and S. Lundberg, "System efficiency of a DC/DC converter-based wind farm," *Wind Energy*, vol. 11, no. 1, pp. 109–120, Jan. /Feb. 2008.

[48] F. J. Deng and Z. Chen, "Operation and control of a DC-grid offshore wind farm under DC transmission system faults," *IEEE Transactions on Power Delivery*, vol. 28, no. 3, pp. 1356–1363, Jul. 2013.

[49] N. Denniston, A. M. Massoud, S. Ahmed, and P. N. Enjeti, "Multiple-module high-gain high-voltage DC-DC transformers for offshore wind energy systems," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 5, pp. 1877–1886, May 2011.

[50] D. Jovcic, "Step-up DC–DC converter for megawatt size applications," *IET Power Electronics*, vol. 2, no. 6, pp. 675–685, Nov. 2009.

[51] D. Jovcic, "Bidirectional, high-power DC transformer," *IEEE Transactions on Power Delivery*, vol. 24, no. 4, pp. 2276–2283, Oct. 2009.

[52] D. Jovcic and B. T. Ooi, 'High-power, resonant DC/DC converter for integration of renewable sources," in *2009 IEEE Bucharest PowerTech*, Bucharest, Romania, Jun. 2009.

[53] S. D. Johnson, A. F. Witulski, and R. W. Erickson, "Comparison of resonant topologies in high-voltage DC applications," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 24, no. 3, pp. 263–274, May 1988.

[54] A. Garcés and M. Molinas, "Electrical conversion system for offshore wind turbines based on high frequency AC link," in *Proc of IX International Conference and Exhibition of Renewal Energy and Ecological Vehicles EVER2009*, Mar. 2009.

[55] G. Li, J. Liang, S. Balasubramaniam, T. Joseph, C. E. Ugalde-Loo, and K. F. Jose, "Frontiers of DC Circuit Breakers in HVDC and MVDC systems," in *2017 IEEE Conference on Energy Internet and Energy System Integration*, Beijing, China, Nov. 2017, pp. 1–6.

[56] M. Heidemann, G. Nikolic, A. Schnettler, A. Qawasmi, N. Soltau, and R. W. De Donker, "Circuit-breakers for medium-voltage DC grids," in *2016 IEEE PES Transmission & Distribution Conference and Exposition-Latin America (PES T & D-LA)*, Morelia, 2016, pp. 1–6.

[57] Twenties Project, "Alstom Grid Technologies. Feasibility tests of Direct Current Circuit Breaker prototype in DEMO3-DCGRID breaking test demonstration.

[58] J. P. Wang, B. Berggren, K. Linden, J. P. Pan, and R. Nuqui, "Multi-terminal DC system line protection requirement and high speed protection solutions," in *CIGRE 2015*, 2015.

[59] L. X. Tang and B. T. Ooi, "Protection of VSC-multi-terminal HVDC against DC faults," in *2002 IEEE 33rd Annual IEEE Power Electronics Specialists Conference*, 2002.

[60] G. Abeynayake, G. Li, J. Liang, and N. A. Cutululis, "A review on MVdc collection systems for high-power offshore wind farms," in *2019 14th Conference on Industrial and Information Systems (ICIIS)*, 2019, pp. 407–412.

[61] ENTSO, "ENTSO-E Draft network code on high voltage direct current connections and DC-connected power park modules," 2014.

[62] J. L. Domínguez-García, D. J. Rogers, C. E. Ugalde-Loo, J. Liang, and O. Gomis-Bellmunt, "Effect of non-standard operating frequencies on the economic cost of offshore AC networks," *Renewable Energy*, vol. 44, pp. 267–280, Aug. 2012.

[63] A. Garcés and M. Molinas, "A study of efficiency in a reduced matrix converter for offshore wind farms," *IEEE Transactions on Industrial Electronics*, ; ol. 59, no. 1, pp. 184–193, Jan. 2012.

[64] J. Ruddy, R. Meere, and T. O'Donnell, "A comparison of VSC-HVDC with low frequency AC for offshore wind farm design and interconnection," *Energy Procedia*, vol. 80, pp. 185–192, 2015.

[65] INENA, "Renewable Power Generation costs in 2019," IRENA, 2019.

[66] GWEC, "Global Offshore Wind Report," GWEC, Aspire Design, New Delhi, 2019.

[67] Y. Fu, H. L. Xu, and L. L. Huang, "Life-cycle cost analysis of power collection system in offshore wind farm," *Automation of Electric Power Systems*, vol. 40, no. 21, pp. 161–167, 2016.

[68] S. R. Wei, K. L. Liu, Y. Fu, Y. Y. Feng, H. Hu, and K. H. Zhang, "Optimization of power collector system for large-scale offshore wind farm based on topological redundancy assessment," *Automation of Electric Power Systems*, vol. 42, no. 18, pp. 84–90, 2018.

[69] E. Olsen, U. Axelsson, and A. Canelhas, "Low frequency AC transmission on large scale offshore wind power plants-achieving the best from two worlds," in *13th Wind Integration Workshop: International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants*, Nov. 2014.

[70] X. F. Wang, Y. F. Teng, L. H. Ning, Y. Q. Meng, and Z. Xu, "Feasibility of integrating large wind farm via Fractional Frequency Transmission System a case study," *International Transactions on Electrical Energy Systems*, vol. 24, no. 1, pp. 64–74, Jan. 2014.

[71] F. Blaabjerg, M. Liserre, and K. Ma, "Power electronics converters for wind turbine systems," *IEEE Transactions on Industry Applications*, vol. 48, no. 2, pp. 708–719, Mar. /Apr. 2012.

[72] "Report on guide to an offshore wind farm 2019 by BVG Associates,"

[73] P. Lakshmanan, J. Liang, and N. Jenkins, "Assessment of collection systems for HVDC connected offshore wind farms," *Electric Power Systems Research,* vol. 129, pp. 75–82, Dec. 2015.

[74] D. Cevasco, S. Koukoura, and A. J. Kolios, "Reliability, availability, maintainability data review for the identification of trends in offshore wind energy applications," *Renewable and Sustainable Energy Reviews*, vol. 136, pp. 110414, Feb. 2021.

[75] Ole Holmstrom, DONG Energy report on reliability of state of the art wind farms, 2007.

[76] B. Franken, "Analysis of electrical system within offshore wind parks," Elforsk Report, Stockholm, Sweden, Tech. Rep., 2007.

[77] D. B. Zhao, S. Meliopoulos, R. Fan, Z. Y. Tan, and Y. Cho, "Reliability evaluation with cost analysis of alternate wind energy farms and interconnections," in *2012 North American Power Symposium*, 2012, pp. 1–6.

[78] H. Díaz and C. Guedes Soares, "Review of the current status, technology and future trends of offshore wind farms," *Ocean Engineering*, vol. 209, pp. 107381, Aug. 2020.

[79] M. De Prada Gil, J. L. Domínguez-García, F. Díaz-González, M. Aragüés-Peñalba, and O. Gomis-Bellmunt, "Feasibility analysis of offshore wind power plants with DC collection grid," *Renewable Energy*, vol. 78, pp. 467–477, Jun. 2015.

[80] X. Xiang, M. M. C. Merlin, and T. C. Green, "Cost analysis and comparison of HVAC, LFAC and HVDC for offshore wind power connection," in *The 12th IET International Conference on AC and DC Power Transmission (ACDC 2016)*, 2016.

[81] P. Lakshmanan, J. L. Guo, and J. Liang, "Energy curtailment of DC series-parallel connected offshore wind farms," *IET Renewable Power Generation*, vol. 12, no. 5, pp. 576–5884, Apr. 2018.

[82] IEA, "China Wind Energy Development Roadmap 2050," IEA, 2018.

[83] E. P. P. Soares-Ramos, L. de Oliveira-Assis, Rú Sarrias-Mena, and L. M. Fernández-Ramírez, "Current status and future trends of offshore wind power in Europe," *Energy*, vol. 202, pp. 117787, Jul. 2020.

[84] X. Xiang, S. Fan, Y. Gu, W. Ming, J. Wu, W. Li, X. He and T. C. Green "Comparison of cost effective distance for LFAC with HVAC and HVDC connections of offshore and remote onshore wind energy, *CSEE Journal of Energy and Power Systems*, doi: 10.17775/CSEEJPES.2020.07000.

[85] M. M. C. Merlin, T. C. Green, P. D. Mitcheson, D. R. Trainer, D. R. Critchley, and R. W. Crookes, "A new hybrid multi-level Voltage-Source Converter with DC fault blocking capability," in *9th IET International Conference on AC and DC Power Transmission*, 2010, pp. 1–5.

[86] M. E. Baran and N. R. Mahajan, "Overcurrent protection on voltage-source-converter-based multiterminal DC distribution systems," *IEEE Transactions on Power Delivery*, vol. 22, no. 1, pp. 406–412, Jan. 2007.

[87] M. Wang, T. An. H. Ergun, Y. Lan, B. Andersen, M. Szechtman, W. Leterme, J. Beerten and D. V. Herten, "Review and outlook of HVDC syatems as Backbone of the transmission system," *CSEE Journal of Power and Energy systems*, doi: 10.17775/CSEEJPES.2020.04890.

Padmavathi Lakshmanan received the Ph.D. degree from Indian Institute of Technology, Madras, India in 2011. Currently, she is working as a Principal Scientist in CSIR - Central Electronics Engineering Research Institute (CEERI), Pilani, India. She was a postdoctoral Researcher at the Institute of Energy, Cardiff University, Cardiff, UK from 2011 to 2016. Her research interests includes control of power electronic converters and offshore wind energy.

Ruijuan Sun received the B.Eng degree in Electrical Engineering and Automation at Zhengzhou University, Zhengzhou, China, in 2017. She is currently pursuing the Master degree in Electrical Engineering in the School of Electrical Engineering, Zhengzhou University, Zhengzhou, China. Her research interests include new energy generation and transmission.

Jun Liang (M'02–SM'12) received the B.Sc. degree from Huazhong University of Science and Technology, Wuhan China in 1992, and the M.Sc. and Ph.D. degrees from China Electric Power Research Institute, Beijing China in 1995 and 1998 respectively. From 1998 to 2001, he was a Senior Engineer with China Electric Power Research Institute. From 2001 to 2005, he was a Research Associate at Imperial College, London, U.K. From 2005 to 2007, he was a Senior Lecturer at the University of Glamorgan, Wales U.K. Currently, he is a Professor at the School of Engineering, Cardiff University, Wales U.K. He is the Chair of IEEE PELS UK&I Chapter. His research interests include DC technologies, power system stability control, power electronics, and renewable power generation.