Medium frequency diode rectifier unit based HVDC transmission for offshore wind farm integration

Zheren Zhang | Yingjie Tang | Zheng Xu

Abstract
The offshore wind farms are the main trend of the wind power development in the future. The medium frequency diode rectifier unit based high voltage direct current transmission system is proposed here for offshore wind farm integration. Unlike conventional high voltage direct current solutions, the rated frequency of the offshore alternating current (AC) grid is increased to about 100∼400 Hz in the proposed system. Besides, a grid-forming control scheme for the wind turbine converters is also proposed in this paper, where the machine side converter controls the direct current (DC) voltage and the grid side converter controls its output alternating current voltage in the global unified reference coordinate system. As a result, smaller and lighter passive components, such as the transformers, alternating current filters and reactive power (VAR) compensators, could be adopted in the offshore grid, which is beneficial for achieving higher economic efficiency. The small stability analysis and the time domain simulation of the proposed system are carried out based on a simplified model and power systems computer aided design/ electromagnetic transients including DC (PSCAD/EMTDC) respectively, and the feasibility of the proposed schemes is verified.

1 | INTRODUCTION
Offshore wind energy exploitation now has attracted a lot of attention from academia and industry, since the offshore wind resources are abundant and more reliable [1]. Theoretically, there exist two schemes for offshore wind farm integration: the high-voltage alternating current (HVAC) link or the high-voltage direct current (HVDC) link. The HVAC link is the preferred choice in commissioned small scale offshore wind farms close to the land, due to its rich operational experience and high technical maturity [2, 3]. However, some drawbacks of the HVAC scheme should be noted: (1) the capital investment and the power losses of AC transmission lines increase rapidly with distance [4]; (2) the high capacitive charging currents seriously limit the available active power transmission capacity of the submarine cables [5]; (3) AC faults in the onshore AC grid might directly affect the stable operation of the offshore wind turbines. Previous studies have proved that the HVDC link is a better option when supposed to transmit more than 100 MW offshore wind power over a distance of more than 90 km [6].

The selection of the HVDC system topology is an important part for the offshore wind farm integration scheme design. The offshore converter station and its control scheme should be in accordance with the wind turbine operation mode. Up to now, most commissioned offshore wind farm HVDC integration projects adopt the voltage source converter based HVDC (VSC-HVDC) scheme. The AC voltage and frequency of the offshore grid is regulated by the offshore converter station controlled in the islanded mode [7]. In this way, the wind turbines could operate as current sources (in the grid-following mode) [8]. After years of development, modular multilevel converter (MMC) outperforms other VSC topologies due to its high efficiency, excellent output waveforms and good scalability, and the MMC-HVDC has become the mainstream of the offshore wind power HVDC integration scheme. However, MMC-HVDC also has some insuperable defects, such as expensive switching devices and high power losses.

References [9–11] selected the line commutated converter based HVDC (LCC-HVDC) to interconnect the offshore wind farm and the onshore grid. Further, a hybrid HVDC topology composed of the LCC rectifier and the current source inverter
was proposed for offshore wind farm integration to achieve a more flexible reactive power control capability that is appreciated by utility grids [12]. Compared to the MMC-HVDC, the LCC-HVDC scheme represents lower cost, and lower power losses and higher reliability; but when an LCC rectifier is adopted, a static synchronous compensator (STATCOM) of large capacity is usually installed to support the commutation voltage for the LCC rectifier [11], and the equipment investment is consequently increased. Reference [13–15] studied another type of hybrid HVDC topology called as MMC-LCC HVDC, where the offshore wind farm and the onshore grid interface with the HVDC link by the MMC rectifier and the LCC inverter respectively. Although no STATCOM is required and the investment cost of the onshore inverter could be reduced about 30% [16], the DC side short circuit of the MMC rectifier caused by the commutation failure in the LCC inverter is troublesome. Reference [17] introduced a variant of the above MMC-LCC HVDC, where the LCC rectifier and the MMC inverter are combined and so called as LCC-MMC HVDC, and the commutation failure is avoided. Besides, the rectifier side STATCOM is cancelled in [17], but the voltage and frequency control for the offshore grid is not clearly explained.

In recent years, the application of the diode rectifier unit (DRU) for offshore wind farm integration has become a hot research topic [18, 19]. Compared with thyristor based LCC, the diode rectifier unit has smaller power losses, smaller investment cost and higher reliability, and the application of diode rectifier unit for the offshore wind farm integration has become a promising alternative to conventional MMC-HVDC [20]. It is estimated that the investment cost of the offshore diode rectifier unit platform would be 65% lower compared to current MMC technology [21, 22]. Some derivation topologies based on the diode rectifier unit are also proposed, such as the diode rectifier unit with a paralleled auxiliary converter [23] and the DRU-MMC HVDC with a parallel AC transmission line [24]. However, the derivation topologies are not as economically efficient as the original DRU-MMC HVDC, due to the auxiliary electrical equipment.

The operating frequency is an important attribute which has considerable influence on the electrical system performances. Considering that the offshore wind farm is connected to the onshore AC grid via the HVDC link, its operating frequency can be selected more flexible. Reference [25] proposed to transmit electricity produced from renewable energy generation units through the high frequency AC microgrid for the power quality improvement. Reference [26] studied the effect of the operating frequency on the capital expenditure of the offshore AC grid; and the optimal frequency choice was found at 93 Hz for the minimum cost. Further, the applications of the medium frequency AC distribution grid and the DC distribution grid to offshore wind farms were compared in [27], and the results show that the former is superior to the latter in terms of costs and efficiency. Reference [28–30] explored the feasibility of adopting the common high-frequency or medium-frequency link to integrate wind energy conversion systems and photovoltaic generation units. A new transmission system structure based on the medium-frequency AC bus and the MMC-HVDC link was shown in [31] to supply deep-sea facilities. Generally speaking, the introduction of medium frequency leads to smaller circuit components such as transformers and filters, while the energy transmission distance is further limited due to the capacitive effect and the increased power losses.

The contributions of the paper are as follows:

(1) A medium frequency diode rectifier unit based HVDC transmission system is proposed, where the offshore AC grid operating frequency is much higher than the power frequency (50/60 Hz). One of the main factors affecting the project cost is the offshore platform, of which the size and weight are dependent on the carried equipment including converter valves, converter transformers, and AC filters. The increased operating frequency can decrease the volume of converter transformers and AC filters, thus a smaller and lighter offshore platform is required with the system economic efficiency improved. Since only short cables are used to make up the offshore AC collector system, the slightly increased capacitive effect and transmission power losses does not matter. Thus, the medium frequency operation is actually an economically attractive solution for the HVDC-based offshore wind farm integration system.

(2) A novel control scheme for the offshore wind turbines in the medium frequency diode rectifier unit based HVDC scheme is proposed. All wind turbines are operated in the grid-forming mode and then set up a stable AC voltage in the offshore grid together. In this way, extra equipment for voltage control such as STATCOM are unnecessary. Moreover, the phase locked loop (PLL) is cancelled in the proposed grid-forming control scheme, and consequently the instabilities originated from the dynamics of the PLL observed in conventional control schemes [32–35] could be avoided.

The rest of this paper is organized as follows. In Section 2, the medium frequency diode rectifier unit based HVDC scheme is introduced. Section 3 discusses the technical characteristics of the medium frequency diode rectifier unit. The corresponding control strategies for the wind turbines and the HVDC transmission system are elaborated in Section 4. The case studies have been conducted on a 1000 MW/±320 kV medium frequency DRU-MMC HVDC system in Section 5. Section 6 is the concluding section.

2 | TOPOLOGIES OF PROPOSED DRU-MMC HVDC FOR OFFSHORE WIND FARM INTEGRATION

2.1 | Wind turbines for offshore wind farm

In the past two decades, the doubly fed induction generator based wind turbines (DFIG-WTs) have become the mainstream in onshore wind farm. In normal operation, the electromagnetic torque and reactive power of the WT could be regulated by the rotor side VSC.
From 2010 and later, the wind turbines with fully-rated converter (FRC-WTs) have gradually developed to be the dominant choice in the commissioned offshore wind farms. Compared with the DFIG-WTs, the generator is isolated from the offshore AC grid and the dynamic performance is enhanced with the fully-rated back-to-back converter.

Among the wind turbines with fully-rated converter, the permanent magnet synchronous generator based FRC-WT (PMSG-FRCWT) is the optimal solution for offshore wind farm, due to its elimination of the gearbox. In the PMSG-FRCWTs, the machine side converter (MSC) could operates in the DC voltage control mode, and thus the grid side converter could operate in the grid forming mode and regulates its output AC voltage. This feature makes the PMSG-FRCWT suitable for the offshore wind farm connecting to the diode rectifier unit converter station.

### 2.2 The proposed medium frequency DRU based HVDC

For almost all the commissioned offshore wind farms, the rated frequency of the offshore AC grid is 50 Hz. Theoretically, the rated frequency of the offshore AC grid could be increased to about 100–400 Hz range [25–29] in the proposed medium frequency DRU based HVDC system, as plotted in Figure 1. However, the exact frequency should be optimized in consideration of the advantages and the side effects by increasing the frequency, such as the investment cost, the operation cost, and the manufacture of the medium frequency equipment.

The benefits of the medium frequency diode rectifier unit based HVDC transmission system includes three aspects: (1) the reliability and economic efficiency of the offshore diode rectifier unit based HVDC system are higher than the conventional MMC-HVDC system [18]; (2) the weight and volume of all the offshore transformers are smaller when the operating frequency is increased, including the step-up transformer in the wind turbines, the step-up transformer in the offshore AC substations and the converter transformer in the offshore rectifier platform [26]; (3) the weight and volume of the rectifier side AC filters and VAR compensators are also smaller when the operating frequency is increased, which will be explained in Section 3.

However, there are some side effects with the increase of the offshore AC grid frequency [36]:

1. **The maximum transferable length of the AC submarine cable is approximately in inverse proportional relationship with the AC frequency due to the capacitive effect.** As a result, the cable feeders in the medium frequency offshore AC collector system cannot be too long. Considering that offshore wind turbines are usually located not far away from each other and a small scale offshore grid with feeders at the length of several kilo-meters can satisfy the lay-out requirement, the maximum transferable length would not be a crucial constraint for the proposed medium frequency based DRU transmission scheme.

2. **The operating frequency increase brings higher power losses,** including the transmission losses of AC cables, the iron losses of offshore transformers, and the switching losses of wind turbine converters and the HVDC rectifier.

3. **For the project construction of the medium frequency DRU based HVDC offshore wind farm integration system,** current electrical equipment, such as the AC submarine cables, offshore power transformers, wind turbines and power electronic converters, are designed and manufactured for the operating frequency of 50/60 Hz. The development of medium frequency equipment still need much more researches and experiments, which are time-demanding and cost-consuming.

### 3 OPERATION CHARACTERISTICS OF DRU STATION

#### 3.1 Active and reactive power characteristics

Theoretically, the DRU is mathematically equivalent to an LCC with firing angle equal to 0. Figure 2 shows the circuit configuration of a DRU based converter station, which is made up of a 12-pulse converter. Here, $U_c$ is the converter...
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FIGURE 2  Schematic circuit of DRU based rectifier station

FIGURE 3  Schematic diagram of the power characteristics at DRU

transformer line side voltage; \( U_{dcr} \) is the DC voltage of the diode rectifier unit; \( I_{dcr} \) is the DC current; \( X_{r1} \) is the commutating reactance; \( P_{dr} \) and \( Q_{dr} \) are the active power (also the DC power) and the reactive power respectively. Assuming the commutation reactance is \( X_{r1} \) and the overlap angle is \( \mu \), the mathematical model of the DRU can be expressed as [37]:

\[
U_{dcr} = \frac{6\sqrt{2}}{\pi} U_r - \frac{6}{\pi} X_{r1} I_{dcr} \quad (1)
\]

\[
P_{dr} = U_{dcr} I_{dcr} \quad (2)
\]

\[
Q_{dr} = P_{dr} \tan \phi_r \quad (3)
\]

\[
\tan \phi_r = \frac{2\mu - \sin 2\mu}{1 - \cos 2\mu} \quad (4)
\]

Based on Equations (1)–(4), the relationship between the active power and the reactive power of the diode rectifier unit is plotted in Figure 3. It is noted that the consumed reactive power \( Q_{dr} \) of the diode rectifier unit is about 0.4 p.u. if the active power \( P_{dr} \) is 1.0 p.u. When the active power decreases, the value of \( Q_{dr}/P_{dr} \) also decreases. In fact, the reactive power compensation devices are necessary in the DRU converter station, in order to make full use of the transmission capability of the off-shore AC cable.

3.2 Harmonics and AC filters

The harmonic characteristics of the diode rectifier unit is similar to the LCC, and could be derived using the switching function [38]. Theoretically, the AC side characteristic harmonic currents are mostly of the order \((12k \pm 1)\), and the DC side characteristic harmonic voltage are mostly of the order \(12k\). The AC filters should be installed to filter the characteristic harmonic currents and provide reactive power compensation.

There are three types of AC filters in practical projects, namely the single tuned filter (ST), the double tuned filter (DT) and the triple tuned filter (TT). According to [39], a double tuned filter is equivalent to two parallel connected single tuned filters, and a triple tuned filters is equivalent to three parallel connected single tuned filters. Regardless of the damping resistors, all the three type filters are plotted in Figure 4, including the original structure and the equivalent structure.

Here in Figure 4, \( C_i \) and \( L_i \) \((i = 1, 2, 3)\) are the actual capacitors and the actual inductors in the AC filters; \( C_j \) and \( L_j \) \((j = a, b, c)\) are the equivalent capacitors and the equivalent inductors of the AC filters. The resonant frequency \( \omega_1 \) and the capacitive reactive power \( Q_0 \) at fundamental frequency \( \omega_0 \) could be derived as in Equation (5):

\[
\begin{align*}
\omega_1 &= \frac{1}{\sqrt{L_1 C_1}} \\
Q_0 &= \frac{U_{ac}^2}{1/(\omega_0 C_1) - \omega_0 L_1} = \frac{\omega_0 C_1 U_{ac}^2}{1 - \omega_0^2 L_1 C_1}
\end{align*}
\]

where \( U_{ac} \) is the r.m.s. voltage at the converter AC bus.

In practical projects, the resonant frequency is chosen near the characteristic harmonic, and \( \omega_1 \) could be written in the form of \( \omega_1 = n_1 \times \omega_0 \) \((n_1 \text{ is the tuning order, } n_1 > 1)\). Besides filtering the AC side harmonics, the AC filters could behave like VAR compensators to supply the reactive power consumed by the DRU as in the LCC-HVDC system. Suppose the capacitive reactive power \( Q_0 \), the fundamental frequency \( \omega_0 \), the converter AC bus r.m.s. voltage \( U_{ac} \) and the tuning order \( n_1 \) are already
known, the actual capacitor $C_1$ and the actual inductor $L_1$ of the single tuned filter could be calculated by solving Equation (5):

$$
\begin{align}
C_1 &= \frac{Q_0\left[1 - \left(\frac{\omega_0}{\omega_1}\right)^2\right]}{\omega_0U_{2ac}} \\
L_1 &= \frac{1}{\omega_2^2C_1} = \frac{\omega_0^2U_{ac}^2}{\omega_0^2Q_0\left[1 - \left(\frac{1}{n_1}\right)^2\right]}
\end{align}
$$

It is noticed from Equation (6) that $C_1$ and $L_1$ are both approximate inversely proportional to $\omega_0$ if the tuning order $n_1$, the fundamental frequency reactive power $Q_0$ and the converter AC bus voltage $U_{2ac}$ are fixed. Therefore, the dimension of the single tuned filter for medium frequency diode rectifier unit is smaller than the ordinary power frequency schemes. With the same assumptions and the help of dimensional analysis, it could also be concluded that the actual capacitors and the actual inductors in double tuned filters and triple tuned filters are also approximate inversely proportional to $\omega_0$. Therefore, the dimension of the double tuned filters and triple tuned filters for medium frequency diode rectifier unit is also smaller than the ordinary power frequency schemes, which is beneficial and could directly decrease the size and the weight of the offshore rectifier platform.

# 4 CONTROL SCHEME OF THE PROPOSED HVDC

## 4.1 Control scheme for wind turbine

The critical factor for effective implementation of the proposed medium frequency diode rectifier unit based HVDC system depends on whether the frequency and voltage of the offshore AC power grid could be effectively controlled. Because the rectifier station adopts uncontrolled diode rectifier unit, the control of the offshore AC system voltage and frequency has to be realized by the grid side converter in the grid forming mode.

The complete controller structure of the PMSG-FRCWT for the proposed HVDC scheme is shown in Figure 5. The turbine blade drives the permanent magnet rotor, and the stator could generate AC output voltage. Therefore, the machine side converter could regulate its DC voltage and absorb the electromagnetic power from the generator. The grid side converter absorbs the DC power from the machine side converter, and transmits it to the collector system. With the help of the diode rectifier unit based HVDC system, the wind power is collected and then transmitted to the onshore AC grid.

In Figure 5, $\psi_r$ is the rotor flux-linkage; $U_{2ac}$ is the DC voltage of the back-to-back converter; $L_{d}$, $L_{q}$ and $C_{f}$ are the stator leakage inductance, the inductance and capacitance of the LC filter; $u$, $u_{2ac}$ and $u_{f}$ are the AC voltage of the machine side converter, the AC voltage of the grid side converter and the AC voltage at the valve side of the wind turbine transformer; $i$, $i_{2ac}$ and $i_{f}$ are the AC current of the machine side converter, the AC current of the grid side converter and the AC current at the valve side of the wind turbine transformer. $P_{2ac}$ and $Q_{2ac}$ are the output power of the grid side converter; $P_{r}$ and $Q_{r}$ are the active and reactive power at the valve side of the wind turbine transformer. $\omega_m$ and $\theta_m$ are the angular speed and the angle of the rotor; $\omega_0$ and $\theta_0$ are the rated angular speed and the angle position generated by the global reference phase angle generator [40]. Subscript ‘$d$’ and ‘$q$’ stand for the $d$-axis and the $q$-axis components; superscript ‘*’ represents the reference value of a certain variable.

## 4.1.1 Control scheme of MSC

The machine side converter directly connects to the stator of the PMSG, and the zero $d$-axis current control scheme could be adopted. With this method, the electromagnetic torque of the rotor is equal to the $q$-axis current component; the
electromagnetic power from the PMSG is totally absorbed by the machine side converter and then transmitted to the grid side converter. As the machine side converter is supposed to regulate its DC voltage, the q-axis current component is generated from the DC voltage controller as in Equation (7):
\[
\begin{align*}
\xi_q &= (k_{dip} + k_{di}/s)(U_{dcw}^s - U_{dcw}), \quad \xi_d = 0 \\
\mu_d &= (\xi_d - i_d)(k_{ipm} + k_{im}/s) - \omega_m L_{di} i_q \\
\mu_q &= (\xi_q - i_q)(k_{ipm} + k_{im}/s) + \omega_m \psi_f + \omega_m L_{di} i_d
\end{align*}
\]
where \( k_{dip} \) and \( k_{di} \) are the proportion gain and the integral gain of the DC voltage controller; \( k_{ipm} \) and \( k_{ipm} \) are the proportion gain and the integral gain of the current controller.

### 4.1.2 Control scheme of GSC

The \( abe-dq \) transform of all the grid side converters is based on a single global reference coordinate system with the rated angular speed \( \omega_0 \) in the medium frequency. The angle position \( \theta_0 \) of the reference coordinate system is given by the broadcast signal or generated by the GPS signal, which is represented by the global reference angle generator in Figure 5.

The controller of the grid side converter consists of three layers. The first layer is the power controllers. The behaviour of the DRU is directly determined by its AC voltage, which is closely related to all the output voltage of the wind turbine grid side converters. Assuming the DC voltage of the MMC and the DC line resistance are \( U_{dcw} \) and \( R_{dc} \), the DC power of the DRU could be calculated as:
\[
P_{dt} = \frac{\left(6\sqrt{2}/\pi R_{dc} U_{t} + 6/\pi X_{dc} U_{dcw}\right) \left(6\sqrt{2}/\pi U_{t} - U_{dcw}\right)}{(6X_{dc}/\pi + R_{dc})^2} (8)
\]

Obviously, the active power (DC power) of the DRU converter is directly determined by the AC voltage magnitude of the grid side converter, which is closely related to the AC voltage of the GSC. Therefore, the AC voltage magnitude of the grid side converter could be generated by the active power controller as in Equation (9):
\[
U_{im} = (k_{ipm} + k_{pi}/s)(P_{r}^s - P_t) (9)
\]
where the reference active power is obtained by the optimum relationship-based maximum power point tracking (MPPT) [41]. With this method, the reference active power of the grid side converter is proportion to the third power of the rotor speed \( \omega_m \).

Since the reactive power in the offshore AC grid is shared by all wind turbines in the wind farm, the reactive power reference of each wind turbine is allocated based on the proportion that the reactive power is distributed in equal proportion to the wind turbine capacity. In this way, the reactive power overload could be prevented, and the AC voltage phase angle of the grid side converter could be generated by the reactive power controller as in Equation (10):
\[
\delta = (k_{qip} + k_{qi}/s)(Q_r^s - Q_t) (10)
\]
where the reference reactive power \( Q_r^s \) is calculated by gathering the reactive power of all wind turbines and allocating it in equal proportion to the wind turbine capacity.

According to the reactive power share strategy, the steady-state reactive load allocated to each wind turbine obeys the following rule:
\[
Q_r^s = \sum S_n \times \sum Q_t (11)
\]
where \( S_n \) is the rated capacity of the concerned wind turbine; \( \sum S_n \) and \( \sum Q_t \) are the total rated capacity and the total reactive power of all wind turbines in the offshore wind farm.

The second layer and the third layer of the grid side converter controller are the AC voltage controller and the current controller, which are as described in Equations (12) and (13):
\[
\begin{align*}
\xi_{wd} &= (\xi_{wd} - i_{wd})(k_{vp} + k_{vi}/s) + i_{wd} - \omega_0 C_i i_{wd} \\
\xi_{wq} &= (\xi_{wq} - i_{wq})(k_{vp} + k_{vi}/s) + i_{wq} + \omega_0 C_i i_{wq} \\
\mu_{wd} &= (\xi_{wd} - i_{wd})(k_{ipw} + k_{iq}/s) + i_{wd} - \omega_0 L_i i_{wq} \\
\mu_{wq} &= (\xi_{wq} - i_{wq})(k_{ipw} + k_{iq}/s) + i_{wq} + \omega_0 L_i i_{wd}
\end{align*}
(12)
\]
\[
\begin{align*}
\mu_{wd} &= (\xi_{wd} - i_{wd})(k_{ipw} + k_{iq}/s) + i_{wd} - \omega_0 L_i i_{wq} \\
\mu_{wq} &= (\xi_{wq} - i_{wq})(k_{ipw} + k_{iq}/s) + i_{wq} + \omega_0 L_i i_{wd}
\end{align*}
(13)
\]

In the control scheme, the actual AC voltage of the grid side converter is generated by the current controller, and the grid side converter could output the desired AC voltage with pulse width modulation (PWM).

In conventional VSCs with \( dq \)-frame based controller, PLLs are always needed to generate the reference angle for \( dq \) transform [32]. With PLL, the reference angle is generated by making the \( q \)-axis voltage track the zero reference signal [33]. For scenario of multiple VSCs connected to weak grid, the issues of the self-synchronization, the cross-synchronization, and the grid-synchronization should be taken into account, and the parameters of PLLs should be carefully selected [34]. Otherwise, the small signal instability would appear. On the other hand, the synchronization of PLL would be lost during current injection to very low voltage faults in some specific conditions [35]. To avoid the instability caused by the PLLs, the PLLs are cancelled in this paper, and the grid side converter is controlled in the global reference coordinate. The phase angle \( \theta_0 \) of the global reference coordinate is generated by the global reference phase angle generator with a fixed angular speed \( \omega_0 \). \( \theta_0 \) could either be sent to every wind turbine through broadcast signal or be set through GPS signal. A communication system with high reliability need to be established for the correct implementation of the global reference coordinate. The voltages and currents in \( abe \)-frame could be transformed to \( dq \)-frame based on \( \theta_0 \).
4.2 Control scheme for the MMC

The control objective of the MMC is to maintain the DC voltage of the DRU based HVDC system. As the onshore AC grid is usually with large short circuit ratio (SCR), the conventional vector current control strategy could be adopted in the MMC. Considering the diode rectifier unit is uncontrollable, the MMC could operate in the DC voltage and AC voltage/reactive power control mode.

4.3 Energy dissipation for AC fault ride through capability

When a short-circuit fault occurs in the offshore AC grid, the grid side converter could not output the wind power captured by the wind turbine, and the surplus wind power results in severe DC overvoltage of the fully-rated back-to-back converter. Thus, the braking resistor is usually installed on the DC side of the back-to-back converter, which can be used to maintain the DC voltage stability when the power output of the grid side converter is blocked [42]. When a short-circuit fault occurs in the onshore AC system, the AC bus voltage of the MMC station drops rapidly and the DC power transmission is blocked, which results in the rapid rise of the DC voltage in the DRU-MMC HVDC system. Thus, a DC chopper is also installed at the DC side of the MMC station to help dissipate surplus DC power during onshore AC grid faults [43]. The braking resistor and the DC chopper are supposed to be inserted when the DC voltages exceed the preset upper threshold values.

4.4 Black start of offshore wind farm

The black start of offshore wind farm is essentially the black start of PMSG-FRCWTs. Usually, internal power supply (like a UPS) are installed in the wind turbines [44]. The internal power supply (IPS) is capable of supplying power to critical components, especially the controllers (both the mechanical and the electrical). Therefore, the internal power supply is the black start source for the wind turbine and the offshore wind farm in this paper.

However, it is also pointed out that the internal power supply is intended to supply power for less than an hour [44]. In offshore wind farms, usually the offshore substation is equipped with a diesel generator in HVDC connected offshore wind farms [45]. If there is not enough power in the internal power supply, the diesel generator installed at the offshore substation can be used to power up the internal power supply in the wind turbines. When the internal power supply is fully charged, the diesel generator can be disconnected, and the PMSG-FRCWTs enter into the black start stage.

The black start of the PMSG-FRCWT (also the offshore wind farms) consists of two stages as plotted in Figure 6. Before the black start of offshore wind farms, the DRU-MMC HVDC is supposed to be energized, and its DC voltage is controlled to the rated voltage.

The first stage is to control the mechanical parts, including releasing the rotor mechanical brake, controlling the yaw drive and enabling the blade pitch control. In this way, the mechanical torque gathered from the blade will drive the rotor, and the rotor speed will keep increasing. In the first stage, the machine side converter and the grid side converter keeps blocked.

The second stage is to control the electrical parts. The machine side converter and the grid side converter are deblocked and switched into normal operation schemes. The machine side converter regulates the DC voltage of the back-to-back converter, and the grid side converter operates in the grid forming mode. In this way, the PMSG-FRCWT (also the offshore wind farms) is black started, and the power transmission will be resumed after a certain period.

5 CASE STUDY

5.1 System parameters

To verify the feasibility of the proposed medium frequency diode rectifier unit based HVDC integration system, an offshore wind farm HVDC integration system is built as plotted in Figure 7. The total rated power of the whole wind farms is 1000 MW, and there are two sub wind farms which are represented by two equivalent aggregated wind turbines. The DRU-MMC HVDC system is a 1000 MW/±320 kV symmetrical monopolar system, as most commissioned practical projects. The star-connected inductor grounding device is installed at the valve side of the converter transformer in the MMC station.

In the MMC, each arm was made up of 320 submodules (SMs), and the rated voltage of the onshore AC grid is 220 kV. The main circuit parameters are listed in Table 1, and the controller parameters in Table 2.
5.2 Small signal stability analysis

In this section, the small signal stability analysis of the proposed medium frequency diode rectifier unit based HVDC system is presented. Two aggregated wind turbines are modelled. Considering the DC voltages of GSC1 and GSC2 are maintained by the machine side converters, the machine side converters and the PMSG are reduced to ideal DC voltage sources $U_{dcWT1}$ and $U_{dcWT2}$, and the equivalent wind turbine is represented by the grid side converter connecting to $U_{dcWT1}$ or $U_{dcWT2}$. The similar simplification is also applied to the diode rectifier unit based HVDC system, and the MMC is replaced by an ideal DC voltage source $U_{dcI}$. Both the AC cable and the DC cable are represented by the $\pi$ section model. The equivalent circuit for the small signal stability analysis is plotted as Figure 8.

In the derivation of the linearized small signal model of the diode rectifier unit, the quasi-steady state model of the diode rectifier unit as (1)–(4) is adopted, and the corresponding linearized small signal model could be derived as Equation (14). Since there is no dynamic process in the adopted quasi-steady state model, the linearized small signal model in Equation (14) only consists of algebraic equations:

\[
\begin{align*}
\Delta U_{dcr} &= (U_{rd0}\Delta U_{rd} + U_{rq0}\Delta U_{rq})/\sqrt{U_{rd0}^2 + U_{rq0}^2} - R_\mu \Delta I_{dcr} \\
I_{dcr0}\Delta U_{dcr} + U_{dcr0}\Delta I_{dcr} &= I_{rd0}\Delta U_{rd} + U_{rd0}\Delta I_{rd} \\
+ I_{rq0}\Delta U_{rq} + U_{rq0}\Delta I_{rq} \\
\frac{2\mu_0 - \sin 2\mu_0}{1 - \cos 2\mu_0} (I_{dcr0}\Delta U_{dcr} + U_{dcr0}\Delta I_{dcr}) &= I_{rd0}\Delta U_{rq} + U_{rq0}\Delta I_{rd} \\
- I_{rq0}\Delta U_{rd} - U_{rd0}\Delta I_{rq}
\end{align*}
\]

Here in Equation (14), all variables are nominalized, and the subscript ‘0’ stands for the steady state value of the concerned operating point; $R_\mu$ is the nominalized commutation resistance.

Except for the diode rectifier unit with the converter transformer, the other components are either conventional AC device or conventional DC device, and their detailed small signal models are not presented here. After combing the small signal model of all the components and eliminating the intermediate variables, the linearized small signal model for the whole integrated system is listed in Equation (15):

\[
d\Delta X_{sys}/dt = A_{sys}\Delta X_{sys} + B_{sys}\Delta U_{sys}
\]
TABLE 1 Parameters of equivalent aggregated wind turbines

| Items                    | Parameters   | Values               |
|--------------------------|--------------|----------------------|
| Aggregated wind turbines | Rated power/MW | 400(#1), 600(#2)    |
|                          | Transformer ratio | 0.69 kV/35 kV      |
|                          | Transformer leakage inductance | 0.07 p.u. |
|                          | Inductance in LC Filter | 0.15 p.u. |
|                          | Susceptance in LC Filter | 0.1 p.u. |
|                          | Rated DC voltage/kV | 1.2                 |
|                          | Rated AC frequency/Hz | 100                |
|                          | Equivalent rotary inertia/s | 2.5               |
|                          | Braking resistor upper threshold /kV | 1.32       |
|                          | Rated wind velocity/(m/s) | 12               |
| AC station               | Transformer ratio | 35 kV/220 kV        |
|                          | Transformer leakage inductance | 0.1 p.u.  |
| Rectifier Station       | Converter transformer ratio | 220 kV/237 kV     |
|                          | Transformer leakage inductance | 0.18 p.u.  |
|                          | L1 in DT/mH       | 0.5972              |
|                          | C1 in DT/uF       | 11.7864             |
|                          | L2 in DT/mH       | 0.3369              |
|                          | C2 in DT/uF       | 32.7852             |
| Inverter Station        | Converter transformer ratio | 220 kV/320 kV     |
|                          | Transformer leakage inductance | 0.18 p.u.  |
|                          | Arm reactor/mH    | 47.49               |
|                          | SM capacitor/mF   | 13.333              |
|                          | Chopper upper threshold/kV | 704            |
| AC cable                | R/(mΩ km⁻¹)       | 12.8                |
|                          | Ls/(mH km⁻¹)      | 0.43                |
|                          | Cs/(uF km⁻¹)      | 0.233               |
|                          | Length/km         | 3.5                 |
| DC cable                | R/(mΩ km⁻¹)       | 7.9                 |
|                          | Ls/(mH km⁻¹)      | 0.85                |
|                          | Cs/(uF km⁻¹)      | 0.188               |
|                          | Length/km         | 100                 |

TABLE 2 Controller parameters of Gsc

| Items                  | Parameters      | Values |
|------------------------|-----------------|--------|
| Active power control loop | The proportional gain $k_{pp}$ | 0.5     |
|                        | The integral gain $k_{pi}$ | 33.33  |
| Reactive power control loop | The proportional gain $k_{qp}$ | 0.3     |
|                        | The integral gain $k_{qi}$ | 33.33  |
| Voltage control loop   | The proportional gain $k_{vp}$ | 2       |
|                        | The integral gain $k_{vi}$ | 20      |
| Current control loop   | The proportional gain $k_{ug}$ | 1.1     |
|                        | The integral gain $k_{ug}$ | 20      |

FIGURE 9 Root locus of the test system with different active powers. (a) $P_{wt1}$ from 0.1 to 1.0 p.u. while $P_{wt2} = 1.0$ p.u. (b) $P_{wt2}$ from 0.1 to 1.0 p.u. while $P_{wt1} = 1.0$ p.u.

where $\Delta X_{sys} = [\Delta X_{WT1}^T, \Delta X_{WT2}^T, \Delta X_{ACL1}^T, \Delta X_{ACL2}^T, \Delta X_{DRL}^T, \Delta X_{ACF}^T, \Delta X_{DCL}]^T$, $\Delta u_{sys} = [\Delta P_s^*, \Delta Q_s^*, \Delta U_{dc}]^T$; $\Delta X_{WT1}$, $\Delta X_{ACL1}$, $\Delta X_{WT2}$, $\Delta X_{ACL2}$, $\Delta X_{DRL}$, $\Delta X_{ACF}$, $\Delta X_{DCL}$ are state variables of component ①–⑦.

Substituting the control parameters as listed in Table 2 into $A_{sys}$, the small signal stability analysis is carried out based on calculating the eigenvalues of $A_{sys}$, with different active power. To better illustrate the calculated results, only the roots near the y axis are plotted in Figure 9. It is noted that the real parts of all the eigenvalues are negative, which proves the small signal stability when working at these typical operating points.

5.3 Time-domain simulation

In this section, the large disturbance stability analysis of the proposed system is discussed based on time-domain simulation. Three scenarios are taken into account, namely the wind speed fluctuation, onshore AC system fault and offshore AC system fault. The simulation model as depicted in Figure 7 is built in PSCAD/EMTDC. In the simulation, the wind speed of WT #1 and WT #2 are supposed as 11 and 12 m/s, respectively.

In the scenario of offshore wind farm black start, the control process of the mechanical parts is neglected, and only the control process of the electrical parts is simulated. WT #1 and WT #2 begin black start at 0.5 s.

In the scenarios of the wind speed fluctuation, the onshore AC system fault and the offshore AC system fault, the wind turbines have already entered into steady state before 2.0 s, and about 880 MW wind power is transmitted to the onshore AC grid.
5.3.1 | Black start of offshore wind farm

Supposed the initial rotor speed of WT #1 and WT #2 are 0.7 p.u., and the DC voltage of the DRU-MMC HVDC has been controlled to the rated voltage before 0.5 s. The system response is plotted in Figure 10.

As plotted in Figure 10, the DC voltage of the wind turbine converters can be gradually regulated to 1.2 kV by the machine side converter when the machine side converter and the grid side converter is deblocked. At the same time, the grid side converter regulates its output active power and reactive power by controlling its output AC voltage.

The steady-state active powers offered by the two wind turbines are about 292 and 598 MW; The steady-state reactive powers offered by the two wind turbines are about 31 and 47 Mvar. As a result, the active power transmission of about 880 MW in
At the moment when the wind speed increases, the mechanical power of the generator in WT #1 is increased. Due to the imbalance between the electromagnetic power and the mechanical power, the generator inevitably speeds up. Noted the optimum relationship-based MPPT, the reduction of the generator rotational speed makes the grid side converter reference active power increase, and the wind turbine could eventually enter to a new stable operation state.

As plotted in Figure 11, the rotational speed of WT #1 smoothly increases from about 0.9 to 1.0 p.u., and the output active power also increases from about 0.7 to 1.0 p.u. At the same time, the rectifier r.m.s. AC voltage gradually increases from 236 to 237 kV, so as to enlarge the DC power of the rectifier. As a result, the DC voltage at the rectifier side and the DC current also increase to a new steady-state value.

The steady-state reactive powers offered by the two wind turbines are 31 and 47 Mvar at first. After the step change of wind speed, the steady-state reactive powers offered by the two wind turbines are 57 and 86 Mvar, respectively. Such reactive load allocation proves the reactive power control target of equal proportion allocation to the wind turbine capacity. In the transient process, the DC voltage of the wind turbine converter almost keeps constant.

5.3.3 Onshore AC system fault

Supposed a metallic three-phase short circuit fault occurs at the PCC of the onshore MMC station at 2.0 s, and it is isolated at 2.1 s. The system response is plotted in Figure 12.

When the fault occurs, the active power transmission of the MMC is blocked because of the AC voltage drop. Since the wind power keeps transmitting to the rectifier, the DC voltage of the DRU based HVDC system increases rapidly until 1.1 p.u at the beginning of the fault. Then, the DC chopper is inserted to consume the surplus active power from the wind turbines, and the DC voltage is maintained so as to prevent severe DC overvoltage. As a result, the DC current at the MMC side drops significantly.

It is noticed that the short-circuit fault at the onshore grid has little influence on the offshore wind turbines. The active power and the rotor speed of the wind turbines almost keeps unchanged. However, small fluctuation is observed in the reactive power of the wind turbines. When the fault is cleared, the active power transmission of the MMC is resumed. The DC voltage of the diode rectifier unit based HVDC system returns to the rated value after a short transient process, and the whole system could be restored quickly.

5.3.4 Offshore AC system fault

Supposed a metallic three-phase short circuit fault occurs at the PCC of the offshore rectifier station at 2.0 s, and it is isolated at 2.1 s. The system response is plotted in Figure 13.

Compared with the onshore AC fault, the impact on the WTs is greater in the offshore AC fault. When the fault occurs, the
power transmission of the wind turbines is blocked, and the DC voltage of the wind turbine converter and the rotor speed increased rapidly, due to the surplus wind power gathered by the generator. When the DC voltage of the wind turbine converter reaches the upper threshold, the wind turbine braking resistor is inserted. With the help of the braking resistor, the surplus wind power is dissipated, and the wind turbine DC voltage is limited at 1.1 p.u.

During the offshore AC fault, the AC voltage of the diode rectifier unit drops to zero, and the DC current of the diode rectifier unit suddenly drops to zero. However, due to the DC side equivalent reactance and capacitance in the diode rectifier unit based HVDC system, oscillations of both the DC current and the DC voltage could be observed in the diode rectifier unit based HVDC system. When the fault is cleared, the DC voltage of the wind turbines restored quickly, and the whole system could be fast resumed to the pre-fault state.

6 | CONCLUSION

A medium frequency (about 100–400 Hz) diode rectifier unit based HVDC scheme is proposed in this paper to improve the economic efficiency of the offshore wind farm integration system. Compared with the conventional DRU-MMC HVDC solutions, there are two advantages of the proposed system:

1. In the offshore AC collector system operated at the medium frequency, passive components including the transformers and AC filters can be made smaller and lighter, which is beneficial to reduce the capital investment cost both for the electrical equipment and the offshore platform.

2. To establish a stable AC voltage in the offshore grid interfaced with the diode rectifier unit, this paper proposed a grid-forming control strategy for the installed PMSG-FRCWTs, in which the machine side converter regulates the DC voltage and the grid side converter operates in the grid forming mode with fixed frequency. In this way, the auxiliary equipment for the offshore AC grid voltage control can
be eliminated. Besides, the PLL is moved out from the grid side converter control system to avoid system instabilities arising from its dynamics.

The techno-feasibility of the proposed system together with the proposed control scheme is proved with the small-signal stability analysis and the time domain simulation. The small-signal stability analysis proves that the operating points with small signal stability exist. The time domain simulation is performed with PSCAD/EMTDC in the scenarios of wind farm black start, wind speed fluctuation, onshore and offshore AC faults. The time domain simulation results show that the system could operate stably in the concerned scenarios with large disturbance.

DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon reasonable request.

CONFLICT OF INTEREST
The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS
Z.Z.: Investigation; software; writing-original draft. Y.T.: Data curation; validation; visualization. Z.X.: Conceptualization; project administration; supervision

NOMENCLATURE
\[ \mu \] commutation overlap angle
\[ * \] superscript for the reference value
\[ C_1, L_1, C_2, L_2, C_m, L_a \] capacitors and inductors of AC filters
\[ d, q \] subscripts for the \( d \)-axis and the \( q \)-axis component
DFIG doubly fed induction generator
DFIG-WT DFIG-based wind turbine
DRU diode rectifier unit
DT double tuned filter
GSC (wind turbine) grid side converter
HVC high voltage converter
HVDC high voltage direct current
\( i, i_{dr}, i_{wt} \) AC current of the MSC and the GSC
IPS (wind turbine) internal power supply
\( i_s \) wind turbine transformer valve side current
\( k_{d0}, k_{d1} \) parameters of MSC DC voltage controller
\( k_{dms}, k_{dpm} \) parameters of the MSC AC current controller
\( k_{ip0}, k_{ip1} \) parameters of GSC DC current controller
\( k_{ip0}, k_{ip1} \) parameters of GSC AC current controller
\( k_{pp0}, k_{pp1} \) parameters of GSC active power controller
\( k_{qp0}, k_{qp1} \) parameters of GSC reactive power controller
\( k_{q0}, k_{q1} \) parameters of GSC AC voltage controller
LCC line commutated converter
\( L_d, L_t \) stator leakage inductance
\( I_d, I_f \) inductance and capacitance of the LC filter
MMC modular multilevel converter
MPPT maximum power point tracking
MSC (wind turbine) machine side converter
\( n_1 \) tuning order of AC filter
\( P_{dr}, Q_{dr} \) active power and reactive power absorbed by DRU
PLL phase locked loop
PMSG permanent magnet synchronous generator
PMSG-FRCWT PMSG-based wind turbine
\( P_{dr}, Q_{dr} \) wind turbine active and reactive power
\( P_{wt}, Q_{wt} \) active and reactive power of GSC
\( \phi_0 \) fundamental frequency reactive power provided by filters
\( R_{dc} \) DC line resistance
SCR short circuit ratio
\( u_d, u_q \) AC voltages of the MSC and the GSC
\( U_{dc0} \) DC voltage of the MMC inverter
\( U_{dc1}, I_{dc1} \) DC voltage and current of DRU
\( U_{dcw0}, I_{dcw0} \) DC voltage of back-to-back VSC
\( U_i \) wind turbine transformer valve side voltage
UPS uninterruptible power supply
\( U_i \) converter transformer line side voltage
VSC voltage source converter
\( X_{r1} \) commutation reactance
\( \varphi_r \) power factor angle
\( \omega_0, \omega_1 \) fundamental frequency and tuning frequency
\( \omega_0, \omega_1 \) rated angular speed and the reference angle position
\( \omega_m, \theta_m \) angular speed and angle of rotor
\( \psi_r \) rotor flux-linkage

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ORSID
Zheng Xu https://orcid.org/0000-0003-1283-6238

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