Topologies and control of low-frequency alternating current for offshore wind farms based on modular multilevel matrix converter

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Abstract: As a new alternative to power transmission, low-frequency alternating current (LFAC) transmission system has a bright future for offshore wind power transmission. As a core equipment for LFAC system, modularised multi-level matrix converter (M3C) is a direct electric energy conversion device, which can achieve bi-directional power flow and provide any value of the power factor. In this study, the application of LFAC transmission system based on M3C (M3C-LFAC) for offshore wind farms is studied. For the characteristics of LFAC transmission system for offshore wind power, four types of LFAC offshore wind power grid-connected topological structure are proposed, and related control strategies are designed. By use of PSCAD/EMTDC to verify the feasibility of the proposed schemes, the advantages of the proposed topologies are verified through different working conditions.

1 Introduction

Offshore wind power has attracted more and more attention due to the advantages of abound resources, no occupation of land resources and the annual utilisation of wind turbines [1, 2]. With the development of wind power technology, large-capacity and long-distance offshore wind power will be the trend of future development.

Low-frequency transmission technology is a new transmission technology that can increase the capacity of transmission without increasing the classification of voltage [3]. It provides a new choice for offshore wind power transmission. The application of low-frequency alternating current (LFAC) transmission technology to the offshore wind power grid has the following advantages. First of all, low-frequency transmission can effectively reduce the capacitive charging capacity of the cables, which can effectively improve the transmission capacity and distance. Secondly, because offshore wind turbines can directly send out low-frequency AC power, only one converter station on land is needed to transmit LFAC power to the power grid. Therefore, the low-frequency transmission system of offshore wind power has obvious advantages over the high-voltage DC (HVDC) system in the number of converter stations and the maintenance cost. In offshore 30–150 km, the economy of low-frequency transmission systems for offshore wind power is better than that of high-voltage AC and HVDC [4]. In addition, the accumulation of space charge is disappearing while the current frequency of the crosslinked polyethylene cable is >1 Hz. Therefore, the power supply reliability of the line is further improved by the low-frequency transmission technology [5].

The frequency conversion device is the core of the low-frequency transmission system. With the development of high-voltage and large-capacity power electronic equipment, the AC–DC–AC type frequency converter of the multilevel modular converter (MMC) is gradually applied to the power system. However, the fluctuating power of the bridge arm of such an inverter device increases with the decrease of the frequency. In addition, the current of the bridge arm flowing through the back-to-back MMC (BTB-MMC) is unevenly distributed at a low frequency, that resulting in a lower utilisation rate of the semiconductor device [6]. Modular multilevel matrix converter (M3C) is a new type of direct AC–AC converter topology, which is suitable for lower frequency applications. When systems operation frequency is <25 Hz, the performance of M3C is better than that of BTB-MMC [6, 7].

At present, many scholars have done some research work on low-frequency transmission system, their research is based on one offshore wind farm connected to a one grid topology. For the power grids, different topologies can improve grid stability and offshore wind power transmission capacity. Therefore, in order to improve the wind energy capture rate and power transmission efficiency of the entire wind farm, and enhance the stability of grid access to offshore wind power, this paper focuses on the topologies of low-frequency grid-connected for offshore wind power transmission based on modular multi-level matrix converter and the corresponding control strategies. Finally, the simulation verifies the feasibility and effectiveness of the proposed scheme, and verifies the advantages of the proposed topologies through different grid operating conditions.

2 Offshore wind power LFAC system topology

For the above characteristics of the low-frequency offshore wind farm, Fig. 1 shows several transmission grid-connected topologies of LFAC for an offshore wind farm. Fig. 1a shows one offshore wind farm connected to single grid topology (single-input single-output). The offshore wind turbine generates low-frequency power, and then the converter station will be converted to 50 Hz/60 Hz power into the grid. This topology is suitable for the relative concentration of the entire wind farm. All the wind turbines in the wind farm form the same fleet, and both operate at the same speed to generate the same frequency of power. When the distance between several wind farms is close or the scale of the wind farm is large, in order to improve the wind energy capture rate of the entire wind farm, the wind turbines in the wind farm will be divided into several units. This large-scale wind farm can adopt the multi-terminal input low-frequency offshore grid topology (multi-input single-output) as shown in Fig. 1b. This topology enables the power from the wind farm to be integrated into the same set of busbars and is integrated into the same converter station to the power grid.

For large-scale offshore wind farms, the network topology of multi-port transmission can be used as shown in Figs. 1c and d. Fig. 1c is a topology for the different transmission frequencies of multiple offshore wind farms connected to the same power grid (multi-frequency input into a single grid). When the scale of the
wind farm is large, in order to improve wind power capture capability of wind farms, the wind turbines in the wind farm will be divided into several unit groups, each group can operate at different speeds and send different frequencies of power. This topology enables the different wind farms to operate at their best working frequencies and obtain the maximum power output. Fig. 1d is a multi-port topology, where two power grids are interconnected by low-frequency offshore wind farm (multi-input and multi-output). The control of multi-port systems is complex, but it brings greater flexibility and adjustment to large-scale wind farms. By sharing the AC transmission bus, large-scale wind farms can be connected to multiple shore power grids, so as to achieve optimal dispatching of power flow and enhance the stability of a large power grid. A summary of the four topologies is shown in Table 1.

3 Modelling and control of M3C-LFAC

3.1 Mathematical model of the M3C-LFAC system

The establishment of the mathematical model of the M3C-LFAC system is the basis for the study of its control system. It is very important to establish a mathematical model of the M3C-LFAC system correctly.

3.1.1 M3C-LFAC mathematical model in three-phase rest coordinates: The establishment of a mathematical model for the AC side of a converter: the M3C topology is shown in Fig. 2, and the grid three-phase voltage

\[
\begin{align*}
U_1^a &= U_{1a} \cos(w_1 t - \delta) \\
U_2^a &= U_{2a} \cos(w_2 t + 2\pi/3) \\
U_3^a &= U_{3a} \cos(w_3 t + 2\pi/3)
\end{align*}
\]

is the phase voltage amplitude of the power grid and the \(w_1\) is the phase voltage angle frequency of the power grid.

The three-phase voltage of the low-frequency side is

\[
\begin{align*}
U_{M1}^a &= U_{M1a} \cos(w_M t + \delta_1) \\
U_{M2}^a &= U_{M2a} \cos(w_M t + \delta_2 - 2\pi/3) \\
U_{M3}^a &= U_{M3a} \cos(w_M t + \delta_2 + 2\pi/3)
\end{align*}
\]

\(U_{M1a}\) is low-frequency side phase voltage amplitude, and \(w_2\) is low-frequency side phase voltage angle frequency. \(\delta_1\) is the difference between the angle of the frequency side and the low-frequency side.

The bridge arm voltage of the converter can be regarded as the superposition of power-frequency AC component and low-frequency AC component. \(U_{dc}\) is the DC voltage of H-bridge module of the converter, then the voltage of \(A\)-phase bridge can be expressed as

\[
\begin{align*}
\bar{u}_1^a &= \bar{u}_1^a + \bar{u}_{1M}^a \\
\bar{u}_2^a &= \bar{u}_2^a + \bar{u}_{2M}^a \\
\bar{u}_3^a &= \bar{u}_3^a + \bar{u}_{3M}^a
\end{align*}
\]

The subscript \(S\) is power-frequency component of converter bridge arm voltage, \(K_{S1}\) is the power grid side DC voltage utilisation coefficient, \(K_{M1}\) is the LFAC side DC voltage utilisation coefficient, \(\delta_M\) is the phase difference between the output voltage of the cascaded H-bridge module and the power-frequency side grid voltage.

The bridge arm current of the converter can be expressed as

![Fig. 1 M3C-LFAC topological structures](http://creativecommons.org/licenses/by-nc/3.0/)

(a) Single-input single-output, (b) Multi-input single-output, (c) Multi-frequency input into a single grid, (d) Multi-input and multi-output
Table 1  Topological features and applications

| Topology type            | Topological characteristics | Application                                      |
|--------------------------|-----------------------------|--------------------------------------------------|
| single-input single-output |                             | one offshore wind farm connected to one grid     |
|                          | 2. same frequency           |                                                  |
| multi-input single-output | 1. multiple offshore wind farms | multiple offshore wind farms connect to a single grid |
|                          | 2. same frequency           |                                                  |
|                          | 3. shared AC bus            |                                                  |
| multi-frequency input    | 1. connect different wind farms | wind farm is far away, operate at different frequencies and connect the same power grid |
| into a one grid           | 2. multi-frequency          |                                                  |
|                          | 3. connect the same power grid |                          |
| multi-input multi-output | 1. multiple offshore wind farms | low-frequency interconnection of different power grids |
|                          | 2. connect the different power grid |                          |

According to Kirchoff’s Voltage Law, the mathematical equation of the converter station can be expressed as

\[
L_L \frac{d}{dt} \begin{bmatrix} \theta_a \\ \theta_b \\ \theta_c \end{bmatrix} = \begin{bmatrix} \frac{2}{3} \theta_a \\ \frac{2}{3} \theta_b \\ \frac{2}{3} \theta_c \end{bmatrix} - \begin{bmatrix} (\cos(w_2 t + \delta_a) + \frac{2}{3} \cos(w_3 t + \frac{2\pi}{3})) \\ \cos(w_2 t + \delta_a + \frac{2\pi}{3}) \\ \cos(w_3 t + 2\pi/3) \end{bmatrix} - \begin{bmatrix} \frac{\theta_a}{3} \cos(\theta_a - \theta_c - \frac{\pi}{3}) \\ \frac{\theta_a}{3} \cos(\theta_a - \theta_b - \frac{\pi}{3}) \\ \frac{\theta_a}{3} \cos(\theta_a - \theta_c - \frac{\pi}{3}) \end{bmatrix} - \begin{bmatrix} \frac{\theta_a}{3} \cos(\theta_a - \theta_b - \frac{\pi}{3}) \\ \frac{\theta_a}{3} \cos(\theta_a - \theta_c - \frac{\pi}{3}) \\ \frac{\theta_a}{3} \cos(\theta_a - \theta_b - \frac{\pi}{3}) \end{bmatrix}
\]

Substituting (2) and (3) into (8), we can obtain

\[
\frac{1}{3} L_L \frac{d}{dt} \begin{bmatrix} i_{M1} \\ i_{M2} \end{bmatrix} = \begin{bmatrix} \frac{\theta_a}{3} \cos(\theta_a - \theta_c - \frac{\pi}{3}) \\ \frac{\theta_a}{3} \cos(\theta_a - \theta_b - \frac{\pi}{3}) \end{bmatrix} - \begin{bmatrix} \frac{\theta_a}{3} \cos(\theta_a - \theta_b - \frac{\pi}{3}) \\ \frac{\theta_a}{3} \cos(\theta_a - \theta_c - \frac{\pi}{3}) \end{bmatrix}
\]

The establishment of a mathematical model for the DC side of the module: the internal loss of the converter is not considered, and the power balance between the AC side and the DC side can be obtained

\[
9N \frac{d}{dt} \left( \frac{1}{2} C \frac{U_{dc}^2}{2} \right) = \begin{bmatrix} u_{dc}^a \\ u_{dc}^b \\ u_{dc}^c \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}
\]

The establishment of the mathematical model of LFAC submarine cable: taking the A-phase as an example, the equivalent circuit diagram of the phase cable is shown in Fig. 3.

From Fig. 3, the mathematical equations of A-phase cable are as follows:

\[
C_L \frac{d}{dt} i_a = i_M + i_a - \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}
\]

Therefore, a mathematical model of M3C-LFAC in a three-phase stationary coordinate system can be obtained. The number of unknowns and the number of equations of the mathematical model

\[
L_M \frac{d}{dt} \begin{bmatrix} i_{M1} \\ i_{M2} \end{bmatrix} = \begin{bmatrix} \frac{\theta_a}{3} \cos(\theta_a - \theta_c - \frac{\pi}{3}) \\ \frac{\theta_a}{3} \cos(\theta_a - \theta_b - \frac{\pi}{3}) \end{bmatrix} - \begin{bmatrix} \frac{\theta_a}{3} \cos(\theta_a - \theta_b - \frac{\pi}{3}) \\ \frac{\theta_a}{3} \cos(\theta_a - \theta_c - \frac{\pi}{3}) \end{bmatrix}
\]

In the same way, the corresponding mathematical equations of the other two phases can be obtained.

The analysis of the U-phase is taken as an example, so the mathematical equation of the low-frequency side of the converter station can be expressed as

\[
L_M \frac{d}{dt} \begin{bmatrix} i_{M1} \\ i_{M2} \end{bmatrix} = \begin{bmatrix} \frac{\theta_a}{3} \cos(\theta_a - \theta_c - \frac{\pi}{3}) \\ \frac{\theta_a}{3} \cos(\theta_a - \theta_b - \frac{\pi}{3}) \end{bmatrix} - \begin{bmatrix} \frac{\theta_a}{3} \cos(\theta_a - \theta_b - \frac{\pi}{3}) \\ \frac{\theta_a}{3} \cos(\theta_a - \theta_c - \frac{\pi}{3}) \end{bmatrix}
\]

The establishment of the mathematical model of M3C-LFAC in a three-phase stationary coordinate system can be obtained. The number of unknowns and the number of equations of the mathematical model.
are 13. If the initial values of the 13 unknowns are given, the law of change of the 13 variables with time can be obtained by solving the differential equations. However, because the coefficients of the differential equations are constantly changing, it is very difficult to solve them, so we can transform them into constant coefficient differential equations and reduce the difficulty of solving them.

3.1.2 M3C-LFAC mathematical model of dq rotating coordinates: The mathematical model of LFAC system is transformed into a two-phase rotating coordinate system. The definition of coordinate transformation relation and orientation is shown in Fig. 4.

Due to the different frequencies of the power-frequency side and the low-frequency side voltage angle, the transformation is needed on both the sides, respectively. \(d_S-q_S\) is a synchronous rotating coordinate under the power frequency and revolves counterclockwise at the angular velocity of \(\omega_0\). When \(t=0\), the \(d_S\) axis coincides with the \(A\)-axis; \(d_M-q_M\) is a synchronous rotating coordinate at low frequency, revolving counterclockwise rotation at the angular velocity of \(\omega_L\), and the \(d_M\) axis coincides with the \(ot=0\) axis at the time of \(t=0\).

The equivalent Park transformation matrix \(P_{abc-dq}\) and its inverse transformation matrix \(P_{dq-abc}\) can be expressed as

\[
P_{abc-dq} = \begin{bmatrix}
\cos \omega t & \cos (\omega t - \frac{2\pi}{3}) & \cos (\omega t + \frac{2\pi}{3}) \\
\sin \omega t & \sin (\omega t - \frac{2\pi}{3}) & \sin (\omega t + \frac{2\pi}{3})
\end{bmatrix}
\]

\[
P_{dq-abc} = \begin{bmatrix}
\cos \omega t & \sin \omega t \\
\sin \omega t & \cos \omega t
\end{bmatrix}
\]

At the power-frequency side \(\omega = \omega_0\); at the low-frequency side \(\omega = \omega_L\).

For the converter station power frequency side \(dq\) rotating coordinate transformation, the calculation method is to multiply formula (6) by formula (12), to get

\[
\frac{1}{3}L_a \frac{d}{dt} \begin{bmatrix} \delta_1 \\ \delta_3 \end{bmatrix} = \begin{bmatrix} U_{dS} \\ U_{qS} \end{bmatrix} - \begin{bmatrix} 0 \\ \delta_1 \end{bmatrix} + \frac{1}{3}w_L \begin{bmatrix} \delta_1 \\ 0 \end{bmatrix}
\]

Since the direction of the voltage phase of the power-frequency side system is the same as the direction of the \(d_S\) axis, \(U_{dS}, U_{qS}\), \(U_{dS}^{ref}\) and \(U_{qS}^{ref}\) are obtained as follows:

\[
\begin{bmatrix} U_{dS}^{ref} \\ U_{qS}^{ref} \end{bmatrix} = \begin{bmatrix} U_{S} \\ 0 \end{bmatrix}
\]

In the same way, the formula (12) left multiplicative (9) can be obtained by the low-frequency mathematical equation

\[
\frac{1}{3}L_a \frac{d}{dt} \begin{bmatrix} \delta_1 \\ \delta_3 \end{bmatrix} = U_{dM} \cos \delta - \frac{1}{3}w_L \begin{bmatrix} \delta_1 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ \delta_1 \end{bmatrix} + \frac{1}{3}w_L \begin{bmatrix} \delta_1 \\ 0 \end{bmatrix}
\]

Similarly, the mathematical model of the DC side of the module and the mathematical model of the submarine cable in the \(dq\) coordinate system can be obtained

\[
\frac{dU_{dc}}{dt} = \frac{1}{6N} K_s (\cos \delta_1^{ref} + \sin \delta_1^{ref})
\]

To sum up, the mathematical model of M3C-LFAC in the \(dq\) rotating coordinate system can be obtained. It is a nine-order constant coefficient differential equation.

3.2 Design of M3C-LFAC control system

According to the previous mathematical deduction, the M3C-LFAC control system can be obtained. Take Fig. 1a topology as an example. This control method can be applied to other topologies. The reactive power control and constant DC voltage control are adopted at the low-frequency side.

3.2.1 Inner loop current control: Taking the input current as an example, formula (5) can be expressed as

\[
K_{Sl}i_{Sd} \cos \delta = \frac{v_1^{ref} - \frac{1}{3} \frac{d}{dt} U_{Sd}^{ref}}{\frac{1}{3} \omega_L L_i^{ref}} + \frac{1}{3} \omega_L L_i^{ref}
\]

The proportion integral is added to compensate the voltage landing on reactance

\[
\frac{d}{dt} (\delta_3^{ref} - \delta_3^{ref}) + K_{Sl} \int (\delta_3^{ref} - \delta_3^{ref}) dt
\]

\[
\delta_3^{ref} \text{ and } \delta_3^{ref} \text{ are the reference values of active and reactive current, respectively.}
\]

3.2.2 Outer loop voltage controller: The outer loop voltage controller can be obtained according to formula (10)

\[
9N \frac{d}{dt} \left( \frac{1}{2} C U_{dc} \right) = \frac{3}{2} V_{Sd}^{ref} - \frac{3}{2} (V_{Mdc}^{ref} + V_{Mdc}\delta_1^{ref})
\]
When the active power of the input side and the output side of the converter is not balanced, it will cause a fluctuation of the capacitance-voltage at the DC side. At this time, the active current of the input side will charge (or discharge) to the DC side capacitor until the DC side capacitance is stable at the set value. Therefore, the DC voltage controller is equivalent to an active balance node for the converter.

The controller in Fig. 5 is a constant DC voltage controller. The DC voltage and the DC voltage instruction deviations are adjusted by PI as the reference value of the active current $i_{\text{ref}}$.

### 3.2.3 Control of active power and reactive power of outer loop

The active power and reactive power of the low-frequency side in the $dq$ rotating coordinate can be expressed as

$$
\begin{align*}
\tilde{P_d} &= \frac{3}{2}(v_{dM}i_{dM} + v_{qM}i_{qM}) \\
\tilde{Q_d} &= \frac{3}{2}(v_{dM}i_{qM} - v_{qM}i_{dM})
\end{align*}
$$

As described in Sections 3.2.1–3.2.3, the control of the M3C-LFAC is shown in Fig. 6.

### 4 Case study

The Arklow Bank Offshore Wind farm has an installation capacity of 500 MW. The wind farm is made up of doubly fed induction generator wind turbines, whose rotor connects to the grid through an AC–DC–AC frequency converter. This connection is easily affected by the power grid. On the other hand, a large group of wind turbines already resemble a conventional power plant and has a significant impact on the stability of the main system. Research shows that the system events are most likely to cause wind turbine tripping off [8]. The LFAC-M3C system can avoid the above problems. As shown in Fig. 1a, because of the converter station, the offshore wind farm is isolated from the power grid, so that the power grid accident will not affect the wind farm. At the same time, the influence of wind farm on the stability of the power grid is reduced. In addition, the converter station based on M3C can realise the bidirectional flow of active power and makes the dispatching of the power grid more flexible. The simulation system of Fig. 1a is simulated in Section 4.1.

The serious faults in the power grid often destroy the safety and stability of the power grid. It is necessary to take some emergency control measures after the failure, such as emergency power support, cutting machine load shedding and so on. Taking Baoshan ~ TA Pu double phase fault in 2008 as an example, the interconnected power grid lost 1260 MW active power after the fault, and the corresponding load must be removed to maintain the stability of the interconnected system [9]. Fig. 1d shows two different power grids. When one of the power grids fail, the wind farms can be ensured of the reliability of users electricity. This topology can greatly improve the reliability of power supply and more reasonable allocation of power.

In January 2010, the Beihai SuperGrid program was announced in Europe, proposing Scotland offshore wind power, solar power, Germany, Belgium and Denmark waves can be connected with Norway hydroelectric power generation, to form the United power network from Beihai to Northern Europe. Fig. 1d topology can realise the interconnection between offshore wind power and the grid, so as to realic the complementary wind and other new energy cooperation and echo the Beihai SuperGrid plan.

Through the above analysis, the advantages of grid interconnection based on M3C-LFAC can be obtained. The following sections 4.1 and 4.2 take the topologies of Figs. 1a and d as examples to verify the effectiveness of the network topology and its control scheme proposed. Verification is based on PSCAD/EMTDC simulation platform.

#### 4.1 Offshore wind farm connected to the single grid

The simulation topology is shown in Fig. 1a and system parameters are shown in Table 2. The low-frequency side adopts the constant
of active power and reactive power control mode, and the power-frequency side adopts the constant reactive power and the constant DC voltage control.

Fig. 7 is the power change response of Fig. 1a topology. The subscripts 1, 2 and ref represent the parameters of the frequency side, the low-frequency side and the reference value, respectively. As shown in Figs. 7a and b, when 1–1.2 s, the wind farm sends 100 MW active power to the power grid. The active power of the M3C power-frequency side and the low-frequency side is \( P_2 = 100 \text{ MW} \) and \( P_1 = 100 \text{ MW} \). The M3C converter station absorbs the capacitive reactive power of \( Q_2 = 70 \text{ Mvar} \). Set the M3C power-frequency side to send the reactive power of 50 Mvar. When \( t = 1.2 \text{ s} \), the active power reverses, and the active power of 50 MW is provided by the power grid to the wind farm. At this time, the two sides of the M3C power imbalances, causing the DC side capacitor to charge and discharge. The excess power is consumed on the capacitor of the DC side, as shown in Fig. 7c. When the capacitance of the DC side is stable, the active power of the input and output of the M3C converter station is back to the balanced state. When \( t = 2.0 \text{ s} \), the M3C converter station sends out perceptual reactive power, and the low-frequency reactive power reverses.

It can be found that the active and reactive power of the system can trace the command accurately, and the mutual influence is small. In addition, the reactive power of the converter's power-frequency side is not affected by the inverting of the reactive power of the low-frequency side. It can be controlled independently. Therefore, the M3C-LFAC system can realise the bidirectional flow of power between the power grid and the wind power field according to the actual needs. The power control of the power grid is more flexible.

### Table 2 M3C-LFAC simulation system parameters

| Parameter                        | Value             |
|----------------------------------|-------------------|
| system voltage                   | 110 kV            |
| frequency of LFAC                | 19 Hz             |
| connection inductor              | 0.05 H            |
| cascade module                   | 3                 |
| module capacitance voltage       | 60 kV             |
| cable length                     | 150 km            |
| unit resistance of the cable      | 0.03837Ω/km       |
| unit inductor of cable           | 0.6576 mH/km      |
| unit capacitance of the cable    | 0.171 μF/km       |

4.2 Two power grids are interconnected by low-frequency offshore wind farm

The simulation topology is shown in Fig. 1d. Active power captured by the wind farm is transmitted to two power grids. According to the actual needs, the active power between the power grid 1 and the power grid 2 can be bidirectional flow, which helps to improve the stability and reliability of the whole power grid. This multi-port M3C-LFAC system provides a flexible scheme for the grid connection of offshore wind farms. The main parameters of the system are shown in Table 2.

Figs. 8 and 9 are the response of Fig. 1d topology power change. The subscripts 1, 2, W and ref represent the parameters of the power grid 1, the power grid 2, the offshore wind farm and the reference value. Before 1.8 s, the power grid 2 transported the active power of 100 MW to the power grid 1. After 1.8 s, the load of power grid 1 increased by 100 MW. At this time, the wind farm is put into operation, the active power of 100 MW is output by the offshore wind farm as shown in Fig. 8a, and the active power of the power grid 1 is unchanged. Active power from the power grid 2 and wind farms was absorbed by the power grid 1. After 0.4 s, the system is restored to the original value. There is no obvious fluctuation in the active power received by the power grid 1 and the DC side voltage of the converter station.

Figs. 10 and 11 are the power responses of the system when the wind farm is separated from the power grid. After 1.2 s, the active power of the wind farm is reduced to 0 MW. In order to compensate the power shortage, the power grid 2 increases the power output, so as to ensure the stability of the power grid 1. As shown in Fig. 10, the wind farm is removed from the power grid and the active power of the power grid 1 is basically stable as...
shown in Fig. 10b. The active power of the power grid 2 is changed as shown in Fig. 10c, and the stability is restored after 4 s. This indicates that this topology has good disturbance resistance and dynamic response when the power is changed at low-frequency side. The free dispatch of power flow can be realised, and the stability and reliability of the whole power system can be enhanced.

From the above cases, we can get that the proposed control method enables decoupling control of active power and reactive power in M3C-LFAC system, and the proposed multi-port system can achieve free dispatching of power flow. The power disturbance has a good dynamic response, and the stability and reliability of the whole power system are enhanced.

5 Conclusion
In this paper, the low-frequency transmission system based on modularised multilevel matrix converter is studied, and the following two contributions are made:

- Four kinds of M3C-LFAC topological structures are proposed, and then the mathematical model and control method of the topology are given.
- Two cases are used to verify the correctness of the control method and the advantages of the topology. The wind farm with M3C-LFAC transmission can realise decoupling control of wind power flow, and power step disturbance has a good dynamic response. It not only improves the wind energy capture rate and power transmission efficiency of the whole wind farm, but also enhances the stability of the grid connected to the wind power. The scheme proposed in this paper can provide an optimised and flexible solution for the grid-connected transmission of large capacity long distance offshore wind farm.

6 References
[1] Deng, W., Long, M., Li, H.: ‘HVDC transmission control strategy for offshore wind power generation based on reduced matrix converter’, Autom. Electr. Power Syst., 2013, 37, (8), pp. 34–40
[2] Xu, Q., Kang, C.: ‘A discussion on offshore wind power output characteristics and its accommodation’, Autom. Electr. Power Syst., 2011, 35, (22), pp. 54–59
[3] Wang, X.F.: ‘Fractional frequency power transmission system’, Electr. Power China, 1995, I, pp. 2–6
[4] Qin, N., You, S., Xu, Z. et al.: ‘Offshore wind farm connection with low frequency AC transmission technology’. 2009 IEEE Power & Energy Society General Meeting, IEEE, 2009
[5] Hao, W.: ‘Space charge behavior of liner Low density polyethylene doped with some types of inorganic nano powder’. Proc. Int. Symp. on Electrical Insulating Materials (ISEIM’08), Mie, Japan, 2008
[6] Korn, A.J.: ‘Direct modular multi-level converter for gearless low-speed drives’. Power Electronics and Applications, EPE 2011 Proc., Birmingham, UK, 2010
[7] Korn, A.J.: ‘Low output frequency operation of the modular multi-level converter’. IEEE Energy Conversion Congress and Exposition, ECCE 2010 – Proc., Atlanta, USA, 2015
[8] Lei, Y.: ‘An analysis on the interaction between arklow bank wind park and Irish grid’, Int. Electr. Power China, 2003, 7, (6), pp. 30–34
[9] Li, H.: ‘Simulation research on direct current emergency power support in regional AC interconnected power network’ (Huazhong University of Science and Technology, Wuhan, 2012), pp. 36–40

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