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ORIGINAL RESEARCH

Reactive power capacity allocation technology of shore-based power supply system of offshore oil production platform under different network topology reliability measures

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Abstract

To improve the economy of offshore oil production platform shore-based power transmission mode, the reactive power capacity allocation technology of offshore oil production platform shore-based power supply system based on different network topology reliability measures was proposed. The optimization model of power supply system network topology and the structure model of voltage source converter high voltage direct current transmission system were established, the start and stop control scheme of flexible direct current (DC) transmission system was designed, and the operation parameters of converter station and DC line were monitored in real time. The topological structure of offshore oil production platform shore-based power supply system is constructed, the mathematical model of flexible DC transmission system is established when the alternating current side voltage is balanced, the reactive power capacity configuration of offshore oil production platform shore-based power supply system is optimized, and the life cycle cost results are calculated. The experimental results show that the algorithm proposed in this paper can obtain the optimal solution only after 26 calculations, with high optimization efficiency and good convergence effect. Reactive capacity configuration of shore-based power supply system for offshore production platform can reduce failure rate and life cycle cost.

1 | INTRODUCTION

With the increasing scale of offshore oil exploitation, the research on the power supply system of offshore oil exploitation platform has become an important research direction of power transmission and distribution of offshore oil exploitation platform. By constructing the reactive capacity configuration model of the shore-based power supply system of offshore oil exploitation platform, combined with the method of motor optimization control and power grid topology adjustment, transporting fossil fuels to offshore oil exploitation platform can provide sufficient and stable power for power grid. For offshore oil exploitation platform, because the power supply distance is greatly shortened, the construction difficulty, comprehensive cost and safety factor of the scheme of supplying power to the platform from the land power grid are all in an acceptable range, and the impact on the environment is better than that of transporting fossil fuels to the platform by sea. For offshore oil production platform, because the power supply distance is greatly shortened, it is necessary to build a shore-based power supply platform. Combined with the optimal design of the capacity configuration of the shore-based power supply system of offshore oil production platform, the generator set is effectively used to improve the system reliability and reduce the reserve capacity of the system [1]. By the optimal design of the technical scheme, topological structure and operation control strategy of the power supply system of offshore oil production platform, the construction difficulty, comprehensive cost, and safety factor of the scheme that the onshore power grid supplies power to the platform are all in an acceptable range [2]. Therefore, the reactive power capacity configuration technology of the shore-based power supply system of offshore oil production platform is studied, and the coordinated operation and dispatching ability between the oil production platform and the onshore power grid is improved by combining the design of offshore power transmission modes suitable for different offshore distances and voltage levels [3].

At present, the offshore oil production platform is mainly powered by diesel generated by the platform, and the generator terminal voltage, grid voltage, and load voltage of the offshore oil production platform power system are mostly at the same voltage level. In the traditional method, the reactive power capacity allocation of the offshore oil production platform shore-based power supply system is determined by evaluating the load level, offshore distance, feasibility of shore-based power technology scheme, and investment in shore-based power facilities. Taking the offshore platform in Suizhong Oilfield as an example [4], by analyzing the power grid structure, transmission mode, electrical main wiring, cable selection and other aspects, and considering the reliability and economy of the platform operation, the networking scheme of offshore oil production platform is designed. The built control system can realize seamless switching of ship power supply, and the optimization scheme of the control strategy can improve the dynamic response performance of inverter and improve the stability of power grid. Tsinghua University Gao Kecun put forward the control strategy of shore power supply based on virtual synchronous generator [5]. The mechanical motion equation of the generator is introduced into the control loop of shore power inverter, and the second-order electromechanical transient model of the generator is adopted. Through the introduction of the moment of inertia J in the model, the inverter has similar electrical and mechanical characteristics as the diesel generator. Through the introduction of power frequency controller module and excitation controller module, the inverter side of shore power supply has similar output droop characteristics as diesel generator. Simulation and experimental results verify the effectiveness of the control strategy. It has certain significance for the network topology research of large-scale oil production platform [6]. Wu Zhenfei, an engineer of Jiangsu Zhen'an Electric Power Equipment Co., Ltd., analyzes the problems of power supply mismatch and power supply system disunity of ship shore power technology, compares and analyzes the shore power technologies with different voltage levels and frequencies [7], and points out the power supply technical problems that need to be solved in the emerging stage of ship shore power technology, which is also of important guiding value for the research of power transmission mode of offshore oil production platform. Eaton Electric Co., Ltd. analyzes the influence of power distribution system on the power supply reliability of oil production platform, studies the power quality, load flow, protection setting and transient stability of offshore platform [8], and gives suggestions on the operation mode of the platform. Li Yang of the School of Electric Power Engineering, Northeast Dianli University proposed a two-step method to achieve multi-objective reactive power optimal scheduling in power systems. Multi-objective Optimization (MOO) algorithm is used to find well-distributed Pareto optimal solutions (POSs), and Fuzzy C-means algorithm (FCM) is combined with grey relational projection method (GRP) to make an integrated decision [9]. This scholar also proposed a two-stage method to solve the multi-objective optimal power flow problem for hybrid AC/DC grids containing voltage source converter based high voltage direct current (VSC-HVDC) [10]. In 2005, Asea Brown Bover (ABB) put into operation Troll-A, the world's first high-power power supply system for offshore oil production platform. The offshore distance of the platform is 70 km, and the two-level converter DC transmission technology was adopted [11]. In 2015, ABB doubled the capacity of the project, and its capacity expansion was limited by the synchronization technology of power electronic devices. To sum up, the research at home and abroad is currently focused on electricity, and most of them are analyzed from a single aspect, but the impact is not comprehensively analyzed from the overall standpoint, and the covering framework is not established, and the theoretical support for the coordination evaluation of power grid development is still not perfect. At present, offshore oil production platforms mainly adopt spontaneous self-use power supply, which has poor expansibility, weak impact resistance, low power supply reliability and guarantee, and large pollutant discharge. Therefore, it is urgent to study the power supply from shore to offshore oil production platforms [12].

In order to solve the above problems, this paper proposes reactive power capacity allocation technology for shore-based power supply system of offshore oil production platform based on different network topology reliability measures. Firstly, the optimization model of network topology of power supply system for large-scale oil production platform is established, and the operating parameters of the converter station and the DC line are monitored in real time with the detection and control constraints of voltage, current, and information state of control system itself. The topological structure of the shore-based power supply system for offshore oil production platform is constructed by using different network topology reliability measurement methods, and then the mathematical model of flexible DC transmission system with AC side voltage balance is established. Combined with the mathematical model analysis of VSC-HVDC system when the AC side of the converter station has an asymmetric fault, the reactive capacity configuration optimization of the shore-based power supply system of offshore oil production platform is realized. Finally, the experiment verifies that the proposed algorithm can obtain the optimal solution only after 26 calculations, with high optimization efficiency and good convergence effect, which shows the superiority of this method in improving the reactive power capacity allocation capability of shore-based power supply system of offshore oil production platform.

The innovation of the method in this paper is that it not only considers the energy demand of the oil production platform, but also combines the quantity of the number of platforms, which provides an important basis for building a more economical and efficient shore-based power supply system. Aiming at the reactive power capacity allocation problem of onshore power supply system of offshore oil production platform, the corresponding model is established in this study, and the reliability measures of different network topologies are analyzed and optimized, which is conducive to realizing the rational distribution of reactive power in the system, so as to improve the reliability and operation efficiency of the system. The start and stop control scheme of the flexible DC transmission system is designed, and the operating parameters of the converter station and the DC line are monitored in real time by the detection and control constraints of voltage, current, and information state. This flexible DC transmission system is more flexible and controllable, and can better adapt to different workloads and fault conditions, and improve the stability and reliability of the power supply system. By using different network topology reliability measurement methods, the topological structure of the shore-based power supply system of offshore oil production platform is constructed, and the mathematical model of the flexible DC transmission system when AC side voltage is balanced is established. This network topology reliability measurement method can accurately evaluate the reliability level of power supply system under different conditions, and provide a basis for the optimization of reactive power capacity allocation.

2 | MATERIALS AND METHODS

2.1 | Preparing materials

The actual operation data of a number of shore-based power supply systems of offshore oil production platforms are collected, including various parameters such as current, voltage, power factor etc., as well as the historical records of system operation status. This paper will use the obtained data as input to carry out application research. Professional power system simulation software is used to model and simulate the network topology and structure of shore-based power supply system of offshore oil production platform, such as power system simulator for engineering (PSS/E), power systems computer-aided design (PSCAD), digital simulation, and evaluation of power systems in an interactive laboratory environment (DIgSILENT PowerFactory) etc. These software have powerful calculation and analysis capabilities. Evaluate the impact of different configuration schemes on system reliability and reactive power capacity. Obtain the specifications and technical parameters of various power supply equipment in the shore-based power supply system of offshore oil production platforms, including generators, transformers, switchgear etc. By understanding the technical characteristics of the equipment, you can better understand the operation of the system and provide references for optimizing the configuration.

2.2 | Network topology and system structure model of power supply system

2.2.1 | Optimization model of network topology of power supply system

Firstly, the main topological structure of the flexible low-frequency power transmission system of shore-based power supply system of offshore oil production platform is analyzed. The impact of power failure on offshore oil production plat-

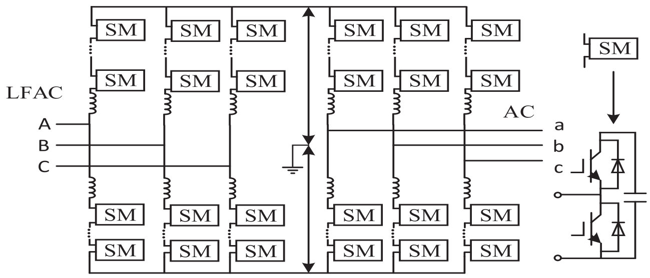

FIGURE 1 BTB-MMC flexible AC/AC converter structure of shore-based power supply system of offshore oil production platform. BTB-MMC, back-to-back modular multilevel converter.

forms can be reduced by a reasonable shore-based power supply system topology. When a certain part of the power supply fails, the other parts can be quickly supplemented to ensure the normal operation of the production platform. This structure helps to improve the stability of the power supply system and reduce the production interruption caused by power failure. The system structure includes flexible alternating current to alternating current (AC/AC) converter, low-frequency transformer, low-frequency circuit breaker, and low-frequency cable. The flexible AC/AC converter based on large-capacity turn-off devices is the core device to realize power conversion. Two-level and three-level inverter devices have insufficient withstand voltage and power, so it is difficult to achieve consistent triggering and complete voltage sharing by directly connecting switching devices in series [13]. Flexible AC/AC converter based on large-capacity turn-off devices is the core device to realize power I/F conversion. The voltage withstand capability and power of two-level and three-level inverter devices are insufficient, so it is difficult to achieve consistent triggering and complete voltage sharing by directly connecting the switching devices in series, which cannot meet the requirements of high-voltage and large-capacity flexible low-frequency transmission. The structure of back-to-back modular multilevel converter (BTB-MMC) flexible AC–AC converter in the shore-based power supply system of offshore oil production platform is shown in Figure 1.

The voltage level is adjusted by AC transformer. The induced electromotive force of transformer is shown in Formula (1):

$$E = 4.44 fNB_{sat}A_{core} \tag{1}$$

where f is the frequency, N is the number of turns of transformer winding, B_{sat} is the magnetic flux density, A_{core} is the cross-sectional area of the core.

Assuming that the transmission frequency is reduced from 50 to 50/3 Hz, and the line resistance is ignored, according to the formula of line static stability limit power and voltage drop shown in Formulas (2) and (3), the theoretical static stability limit power will be increased by three times and the voltage fluctuation will be reduced accordingly because the reactance of the line is reduced to 1/3 of the power frequency.

$$P_{\max} = \frac{U^2}{X} \tag{2}$$

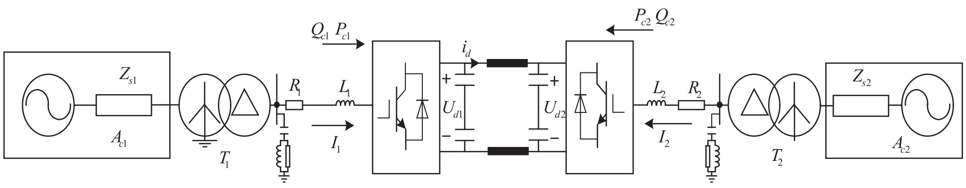

FIGURE 2 Structure diagram of HVDC transmission system of voltage source converter. HVDC, high-voltage direct current.

$$\Delta U = \frac{QX}{U^2} \times 100\% \tag{3}$$

where $P_{\max}$ is the static limit power of the line, which represents the limit power that the line can transmit while ensuring the stability of small interference; X is the line reactance, which is proportional to the transmission frequency; U is the line voltage; ΔU is the line voltage drop; Q is reactive power of the line.

However, for actual lines, especially cables, the transmission capacity is mainly limited by the charging power. According to Formula (4) and Formula (5), reducing the frequency will theoretically reduce the charging reactive power by 2/3, and release a lot of line capacity for active transmission:

$$Q_c = 2\pi fClU^2 \tag{4}$$

$$P_R = \sqrt{S_N^2 - Q_c^2} \tag{5}$$

where Q_c charges reactive power for cable, C is the cable capacitance, l is the cable distance, S_N is the apparent power, P_R is the maximum active transmission capacity. The power load of the platform is connected to the DC bus in parallel after rectification, which is similar to the DC grid two-stage converter system with converter station, with only two voltage levels. Due to the early boosting, the DC bus loss is reduced and the transmission efficiency is improved, so the optimization model of the network topology of the power supply system is established [14].

2.2.2 | Structural model of HVDC transmission system with voltage source converter

The grid-connected mode of DC transmission of offshore oil production platform is often the grid-connected mode of line-commutated converter-based high voltage direct current (LCC-HVDC), and the structure of the designed voltage source converter HVDC transmission system is shown in Figure 2.

The two-stage converter system with converter station is suitable for the situation that the export voltage level of offshore oil production platform is high and the voltage transmission level is relatively low. The two-stage converter system without converter station has the same two-stage structure as the two-stage converter system with converter station, and its reliability is higher than that with converter station. The converter stations at both ends adopt two-level voltage source topology. It can be seen from the figure that the VSC-HVDC system is composed of converter transformer, AC filter, converter reactor, voltage source converter station, DC side capacitor, and DC transmission cable. After introducing the structural model, the operation principle and characteristics of the HVDC transmission system of the voltage source converter can be understood more clearly. The structural model is the most suitable network topology structure of the power supply system for this paper, which can improve the efficiency and stability of the power supply system. Through the exploration of the basic composition and functional modules of the voltage source converter HVDC transmission system, the interaction and dependence between each component can be clarified, which provides basic information for the optimization of the network topology of the power supply system. By simulating and analyzing the system behaviour under different conditions, the stability and reliability of the system can be deeply understood, which provides a basis for the optimization of the network topology of the power supply system. The structure and function of each part are briefly introduced below [15].

(1) Converter transformer: Three-phase transformers are installed in most practical projects, and the secondary winding of the transformer is provided with tap switches. Its functions are as follows: firstly, it can adjust the maximum transmitted active power and reactive power of converter station, which is often obtained by adjusting the secondary voltage of transformer with tap changer. Secondly, the converter transformer converts the AC voltage of the system to the secondary voltage matching the DC voltage of the converter, so as to ensure that the switching modulation degree is not too small, so as to reduce the harmonic amount of the output voltage and current, thereby reducing the capacity of the AC filter device and the operating loss of the converter. Usually, the transformer is connected to the winding (primary side) on the AC system side by star connection, while the winding (secondary side) near the converter side is connected by triangle connection. It can reduce the harmonic component and DC component of the system, and when the secondary side of the transformer adopts triangle connection, it isolates the path of zero sequence component and avoids the influence of zero sequence component on the AC system [16].
(2) AC filter: Because of the high switching frequency of VSC, its output AC voltage and current contain more higher harmonics. Nowadays, countries are making more and more

efforts to control network harmonic sources. For the VSC-HVDC system, AC filter devices must be installed in order to meet the relevant harmonic standards. In practical engineering, an AC filter is usually installed at the converter bus to suppress harmonics.

(3) Converter reactor: Converter reactor is an important component of the VSC converter, which is the link between VSC and AC system and can determine the power transmission capacity of VSC. In addition, the converter reactor can effectively suppress the harmonics in the current and voltage output by VSC, as well as the surge current during fault.

(4) Two-level VSC converter station: At present, the high-power insulated gate bipolar transistor (IGBT) switching devices are used to further improve the rated voltage and rated power of the converter station under bipolar structure, and the converter station can be connected with the weak AC system or even passive network because of the advantages of VSC's not easy commutation failure and no commutation voltage. VSC adopts the control method based on pulse width modulation (PWM) technology, which can flexibly and independently control active power and reactive power, and can limit the generated low-order harmonics. With the continuous improvement of device integration, a compact and modular structure of VSC has emerged. VSC can be pre-assembled in containers and has been completely tested in the factory. The containers can be rearranged at different system connection points and quickly installed and debugged. Because it is modular, the project can be built by stages to meet the needs of different loads.

(5) DC-side capacitor: The advantages of DC-side capacitor are energy storage, buffering the impact current when the bridge arm is disconnected, filtering out the harmonics in DC voltage, providing voltage support for the receiving station etc. In addition, the size of DC-side capacitor will also affect the dynamic response characteristics of the VSC control system. However, when the DC circuit is grounded, a large amount of energy stored in DC-side capacitor will be released quickly, which will greatly increase the short-circuit point current and reduce the DC voltage, thus reducing the reliability of system operation.

(6) DC transmission line: In the projects that have been put into operation at present, the converters on both sides of the offshore oil production platform VSC-HVDC are generally connected by cables. In order to reduce the faults of transmission lines, cables are basically used as DC transmission lines. At present, a new type of cross-linked polyethylene extruded (XLPE) cable is widely used, and its insulation part is extruded by three layers, that is, the conductor shielding layer, insulation layer, and insulation shielding layer are extruded at the same time, so it has a solid structure. Therefore, this kind of cable is easy to be directly ditched and buried underground or used in undersea areas with harsh conditions. The working structure of the flexible DC transmission system is shown in Figure 3.

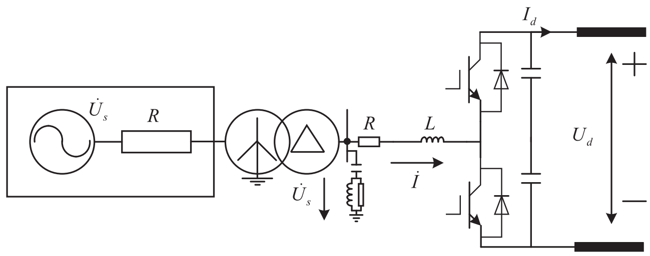

FIGURE 3 Working structure of flexible DC transmission system. DC, direct current.

2.3 | Optimization of reactive power capacity allocation for shore-based power supply system of offshore oil production platform

2.3.1 | Mathematical model of flexible DC transmission system when AC voltage is balanced

The optimization model of power supply system network topology of large-scale oil production platform is established, the structural model of voltage source converter HVDC transmission system is constructed, and the start-stop control scheme of flexible HVDC transmission system is designed. The mathematical model of flexible HVDC transmission system is established based on the detection and control constraints of voltage, current and information state of control system itself. If active power flows from the converter station side to the AC system side, it is positive; otherwise it is negative. If reactive power flows from the converter station side to the AC system side, it is positive; otherwise it is negative. Ignoring the losses generated on the converter reactor and the harmonic components in the voltage, it can be concluded that the active power P and reactive power Q transmitted between the converter and the AC power grid are respectively:

$$P = \frac{U_s U}{X} \sin \delta \tag{6}$$

$$Q = \frac{U_s (U_s - U \cos \delta)}{X} \tag{7}$$

where U is the fundamental component of converter output voltage, U_s is the fundamental component of AC voltage, the phase angle difference between U and U_s, and X is the reactance of converter reactor. From the above formula, it can be seen that the transmission of active power of VSC mainly depends on U. It can be seen from the above two formulas that the magnitude and direction of active power transmitted by the system can be controlled by control, and the magnitude of reactive power emitted (or absorbed) by the system can be controlled by control of U. However, when controlling sum U alone, due to the coupling between active power and reactive power, adjusting sum U within a certain control range can control active power and reactive power, but beyond the control range, the above control method cannot realize independent control of active power and reactive power. When the DC voltage is constant, the amplitude of VSC output voltage is

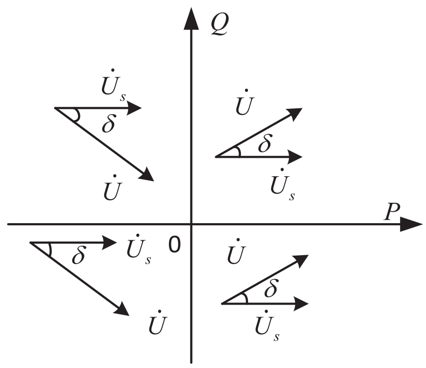

FIGURE 4 Voltage phasor diagram of VSC converter station in steady operation. VSC, voltage source converter.

determined by the modulation degree of sinusoidal pulse width modulation (SPWM), while the phase and frequency of VSC output voltage are determined by the phase and frequency of the modulation wave. Therefore, the magnitude and direction of active power and reactive power transmitted by VSC can be controlled by controlling the phase and modulation degree of SPWM modulation wave. In the VSC-HVDC system, the VSC converter usually adopts SPWM technology, and the voltage phasor diagram of the VSC converter station in steady operation is shown in Figure 4.

Each phase current of VSC is determined by three-phase switching function, so it is a non-linear time-varying system coupled with each other. According to the high frequency mathematical model of VSC obtained from the above analysis, the AC side and DC side of converter station can be represented by the high frequency equivalent circuit of VSC in the three-phase static coordinate system respectively. The equivalent high-frequency models of the AC and DC sides of VSC in the three-phase static coordinate system are shown in Figure 5.

In Figure 5, voltage-controlled current source (VCCS) represents a controlled voltage source jointly determined by three-phase switching function, and current-controlled current source (CCCS) represents a controlled current source jointly determined by three-phase switching function and three-phase current. It can be seen that VSC can be equivalent to a three-phase controlled voltage source on the AC side and a controlled current source on the DC side. In the three-phase three-wire system, there is $i_{sa} + i_{sb} + i_{sc} = 0$; when the voltage of the three-phase AC system is symmetrically balanced, there is $u_{sa} + u_{sb} + u_{sc} = 0$, which can be obtained.

$$u_{NO} = -\frac{1}{3}u_{dc} \cdot (S_a + S_b + S_c) \tag{8}$$

$$L\frac{di_{sa}}{dt} + R \cdot i_{sa} = u_{sa} - \frac{1}{3}u_{dc} \cdot (2S_a - S_b - S_c) \tag{9}$$

$$L\frac{di_{sb}}{dt} + R \cdot i_{sb} = u_{sb} - \frac{1}{3}u_{dc} \cdot (2S_b - S_a - S_c) \tag{10}$$

$$L\frac{di_{sc}}{dt} + R \cdot i_{sc} = u_{sc} - \frac{1}{3}u_{dc} \cdot (2S_c - S_a - S_b) \tag{11}$$

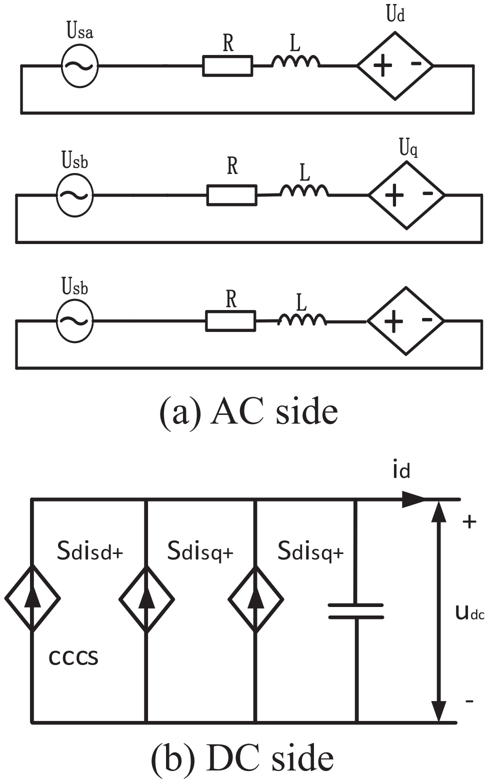

FIGURE 5 Equivalent high frequency models of AC and DC sides of VSC in three-phase static coordinate system. (a) AC side, (b) DC side. AC, alternating current; DC, direct current; VSC, voltage source converter.

On the DC side of the converter station, the following differential relation holds, namely:

$$L\frac{du_{dc}}{dt} = (S_a \cdot i_{sa} + S_b \cdot i_{sb} + S_c \cdot i_{sc}) - i_d = i_{dc} - i_d \tag{12}$$

To sum up, the high-frequency mathematical model of VSC is formed. It can be seen that each phase current of VSC is determined by the three-phase switching function, so it is a coupled non-linear time-varying system [17]. The start and stop control scheme of the flexible DC transmission system designed in this paper can reduce the impact on the AC grid, reduce the risk of system oscillation, and improve the reliability of power supply by controlling the stability of DC voltage. Under the premise of meeting the power demand, the energy consumption of the equipment can be reduced, the energy efficiency can be improved, and the energy waste can be reduced by starting and stopping the equipment reasonably. It can also be adjusted flexibly according to the actual operation of the power supply system network topology.

2.3.2 | Network topology reliability measurement and system reactive power capacity configuration

Combined with the mathematical model analysis of the VSC-HVDC system when the AC side of converter station has asymmetric fault, the reactive capacity configuration optimization of the shore-based power supply system of offshore oil production platform is realized. By comparing and analyzing the LCC of the transmission system, in order to establish a mathematical model of VSC suitable for controller design, the harmonic component generated by switching action is ignored, that is, only the fundamental component is considered [18]. Let u represent the fundamental voltage component at the midpoint of each leg of the converter, and the low-frequency dynamic model of VSC in the three-phase static coordinate system can be obtained:

$$\begin{cases} L\dfrac{di_{sa}}{dt} + R \cdot i_{sa} = u_{sa} - u_a \\ L\dfrac{di_{sb}}{dt} + R \cdot i_{sb} = u_{sb} - u_b \\ L\dfrac{di_{sc}}{dt} + R \cdot i_{sc} = u_{sc} - u_c \\ C\dfrac{du_{dc}}{dt} = i_{dc} - i_d \end{cases} \tag{13}$$

As can be seen from the above formula, the physical quantities of the AC side of the VSC low-frequency dynamic model are all time-varying, which is not conducive to the design of the controller, and it is difficult to realize the independent adjustment of the active and reactive power of the VSC-HVDC system. The D axis rotates counterclockwise with synchronous angular velocity. When the initial phase angle between the A axis and the D axis is zero, the transformation relationship between the three-phase abc stationary coordinate system and the synchronous d q rotating coordinate system is as follows:

$$\begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} = \begin{bmatrix} \cos(\omega t) & -\sin(\omega t) \\ \cos\left(\omega t - \dfrac{2\pi}{3}\right) & -\sin\left(\omega t - \dfrac{2\pi}{3}\right) \\ \cos\left(\omega t + \dfrac{2\pi}{3}\right) & -\sin\left(\omega t + \dfrac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} f_d \\ f_q \end{bmatrix} \tag{14}$$

Considering the coordinate transformation relationship, the mathematical model of VSC in the synchronous dq rotating coordinate system can be obtained by transforming the equation

$$\begin{cases} L\dfrac{di_{sd}}{dt} + R \cdot i_{sd} = u_{sd} - u_d + \omega L i_{sq} \\ L\dfrac{di_{sq}}{dt} + R \cdot i_{sq} = u_{sq} - u_q + \omega L i_{sd} \\ C\dfrac{du_{dc}}{dt} = i_{dc} - i_d \end{cases} \tag{15}$$

In the above formula, u_{sd}, u_{sq} respectively represent the d, q axis components of the voltage at the converter buses on both sides; u_d, u_q respectively represent the d, q axis components of the fundamental wave voltage at the midpoint of the converter bridge arms on both sides; i_{sd}, i_{sq} represent the d, q axis components of the AC system current on both sides respectively. After synchronous dq rotation coordinate transformation, the three-phase time-varying AC becomes two-phase direct current, which is beneficial to the controller design of the VSC-HVDC system. When an asymmetric fault occurs in the AC side of VSC-HVDC converter station, the negative sequence component will make the three-phase voltage and three-phase current asymmetric, and the asymmetric three-phase quantity can be decomposed into two symmetrical components, positive sequence and negative sequence, and the value circuit diagram of the AC side system of voltage source converter station is shown in Figure 6.

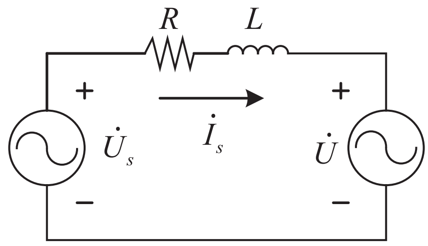

FIGURE 6 Value circuit diagram of AC side system of voltage source converter station. AC, alternating current.

When the AC side of converter station in the VSC-HVDC system has asymmetric fault, the voltage phasor, current phasor, and AC voltage output $\dot{U}_s$ by converter station in the above formula are all composed of positive sequence component and negative sequence component. Then in the two-phase stationary coordinate system, the voltage phasor and current phasor in the above formula can be expressed as

$$\dot{U}_s = \dot{U}_s^+ + \dot{U}_s^- = \left(u_{s\alpha}^+ + u_{s\alpha}^-\right) + j\left(u_{s\beta}^+ + u_{s\beta}^-\right) \tag{16}$$

$$\dot{I}_s = \dot{I}_s^+ + \dot{I}_s^- = \left(i_{s\alpha}^+ + i_{s\alpha}^-\right) + j\left(i_{s\beta}^+ + i_{s\beta}^-\right) \tag{17}$$

$$\dot{U} = \dot{U}^+ + \dot{U}^- = \left(u_{\alpha}^+ + u_{\alpha}^-\right) + j\left(u_{\beta}^+ + u_{\beta}^-\right) \tag{18}$$

By separating the real part from the imaginary part, the mathematical model of VSC in the two-phase static coordinate system can be obtained when the voltage of the AC system is unbalanced:

$$\begin{cases} u_{s\alpha}^+ = R \cdot i_{s\alpha}^+ + L\dfrac{di_{s\alpha}^+}{dt} + u_{\alpha}^+ \\ u_{s\beta}^+ = R \cdot i_{s\beta}^+ + L\dfrac{di_{s\beta}^+}{dt} + u_{\beta}^+ \end{cases} \tag{19}$$

$$\begin{cases} u_{s\alpha}^- = R \cdot i_{s\alpha}^- + L\dfrac{di_{s\alpha}^-}{dt} + u_{\alpha}^- \\ u_{s\beta}^- = R \cdot i_{s\beta}^- + L\dfrac{di_{s\beta}^-}{dt} + u_{\beta}^- \end{cases} \tag{20}$$

When the number and average failure rate of each key equipment in the internal collection network of offshore oil production platform are known, the failure rate, repair time, estimated power loss, load utilization rate, and other related parameters of the transmission system can be calculated according to the following formulas respectively:

TABLE 1 Initial input cost price of different transmission systems.

Price	AC	DC	Frequency division
Csub (thousand yuan)	78,415.997	352,871.986	235,247.991
Ccab (thousand yuan /km)	11,762.400	4704.960	5645.952
Cirs (thousand yuan /km)	2666.144	1685.944	1960.400
Ccom (thousand yuan)	2117.232	0.000	1019.408
Cland (thousand yuan)	101,940.796	188,198.392	25,0931.190

$$\lambda_F = \sum N_i \lambda_i \tag{21}$$

$$h_F = \sum N_i \lambda_i h_i \tag{22}$$

$$W_{F,loss} = \lambda_F h_F P_{F,rated} \tag{23}$$

$$\eta_F = \frac{W_{F,rated} - W_{F,loss}}{W_{F,rated}} \tag{24}$$

where λ_F, h_F are the average annual failure rate and failure repair time of the whole offshore oil production platform respectively; N_i, λ_i, h_i are the number, average annual failure rate, and failure repair time of each key equipment I in the internal collection network of offshore oil production platform respectively; $W_{F,loss}$, W_F, η_F are the estimated capacity loss, estimated energy consumption, and electric energy conversion rate of offshore wind farm, respectively. LCC of transmission system refers to the whole process cost of transmission system from construction to scrapping in the economic life cycle of the project, including the expenses incurred in the whole process of equipment purchase, installation and debugging, operation management, overhaul and maintenance, transformation and scrapping. According to the above design, the reactive capacity allocation of the shore-based power supply system of offshore oil production platform is realized through different network topology reliability measures.

3 | EXPERIMENTAL TEST

In the experiment, the maximum number of iterations is set to 100 generations; the population number is 200; the crossover rate is 0.6; the variation rate is 0.3; case study of life cycle cost of shore-based transmission system Life cycle cost comparison under different transmission systems, the main prices of initial input costs of different systems are shown in Table 1.

In Table 1, 'Csub' represents the sub-station cost of each transmission system, which is $78,415.997 thousand for AC transmission system, $352,871.986 thousand for DC transmission system, and $235,247.991 thousand for frequency division transmission system. Ccab 'represents the cost per kilometre of transmission line, the transmission line cost of AC transmission system is 11,762.400 thousand yuan/km, DC transmission system is 4,704.960 thousand yuan/km, frequency division transmission system is 5,645.952 thousand yuan/km'. Cirs 'represents the cost per kilometer of cable lines, the cable line cost of AC transmission system is 2666.144 thousand yuan/km, the DC transmission system is 1685.944 thousand yuan/km, and the frequency division transmission system is 1960.400 thousand yuan/km'. Ccom 'stands for communication cost, in this comparison, the communication cost of the AC transmission system is 2117.232 thousand yuan, the DC transmission system is 0 thousand yuan, and the frequency division transmission system is 1019.408 thousand yuan'. 'Cland' refers to the land lease cost, the land lease cost of the AC transmission system is 101,940.796 thousand yuan, the DC transmission system is 188,198.392 thousand yuan, and the frequency division transmission system is 250,931.190 thousand yuan.

According to the life cycle cost model of the offshore oil production platform transmission system, the calculated life cycle cost results are shown in Table 2.

In Table 2, 'C1' represents the unit energy consumption cost of the transmission system, 'Co' represents the initial investment of the transmission system, 'CM' represents the daily operation and maintenance cost of the transmission system, 'CF' represents the repair cost of the transmission system due to failure, and 'CD' represents the depreciation cost of the transmission system. 'CLCC' represents the total cost of the entire transmission system over its lifetime. At various distances (20, 40, 80, 120, and 160), whether AC, DC, or FFTS transmission systems, the life cycle cost (CLCC) increases with distance. This shows that as the transmission distance increases, the cost of the transmission system also increases. For each distance, AC transmission systems typically have a lower lifecycle cost, while DC transmission systems are a higher lifecycle cost option. The cost of an FFTS transmission system is somewhere between AC and DC. In a comparison between different transmission systems, it can be observed that at shorter distances (20 and 40), the life cycle cost of an AC transmission system is relatively low, while at longer distances (80, 120, and 160), the life cycle cost of an FFTS transmission system may be similar to or close to that of an AC transmission system.

It can be seen that if only based on the comparison of initial investment cost, when the offshore oil production platform is 40 km away from the land, the AC system is the most uneconomical choice, which is also in line with the equivalent distance of general cross-sea power transmission. However, according to the analysis results of the whole life cycle, it is still the most economical to adopt AC system at this time. When the distance is more than 80 km, the advantages of FFTS are gradually reflected. As for the VSC-HVDC system, some studies believe that it is only suitable for ultra-long-distance offshore oil platforms from the perspective of loss. From the perspective of life cycle cost, although the annual operating cost within 160 km is higher than the other two transmission systems, the life cycle cost after 80 km is more economical than that of the AC system, and it will become the most economical choice after 120 km. See Table 3 for the calculation results of life cycle cost of transmission systems with different capacities at a transmission distance of 120 km.

TABLE 2 LCC comparison of transmission systems with different distances.

	Transfer system	C1	Co	CM	CF	CD	CLCC
20	AC	471.437	199.059	95.550	91.472	−13.605	843.903
	DC	669.869	495.795	135.699	129.975	−19.271	1412.066
	FFTS	640.737	474.231	129.798	124.319	−18.428	1350.667
40	AC	818.820	506.538	165.948	91.472	−23.642	1559.145
	DC	797.687	590.394	161.596	129.975	−22.946	1656.705
	FFTS	792.864	586.826	160.616	124.319	−22.809	1641.825
80	AC	1337.150	564.585	271.006	91.472	−38.600	2225.603
	DC	1151.343	809.537	233.239	129.975	−33.121	2290.982
	FFTS	1097.118	812.017	222.260	124.319	−31.562	2224.152
120	AC	1914.291	808.273	387.973	91.472	−55.264	3146.746
	DC	1308.959	968.810	265.173	129.975	−37.649	2635.258
	FFTS	1401.372	1037.208	283.895	124.319	−40.306	2806.479
160	AC	2488.581	2463.164	504.362	91.472	−71.839	5475.740
	DC	1701.647	1133.503	344.727	129.975	−48.951	3260.900
	FFTS	1821.780	1348.363	369.055	124.319	−52.401	3611.125

FFTS, frequency division transmission; VSC, voltage source converter.

TABLE 3 LCC comparison of different transmission systems under different capacities.

	Transmission system	C1	Co	CM	CF	CD	CLCC
50	AC	334.287	289.512	243.903	91.472	−15.438	943.737
	DC	401.147	347.422	192.041	129.975	−12.115	1058.459
	FFTS	367.712	318.467	200.029	124.319	−12.625	997.912
200	AC	601.715	677.465	257.450	91.472	−23.162	1604.940
	DC	802.294	694.834	202.715	129.975	−18.183	1811.635
	FFTS	668.575	579.034	211.145	124.319	−18.937	1564.134
400	AC	1337.150	1158.057	271.006	91.472	−38.600	2819.075
	DC	1053.323	740.619	213.380	129.975	−30.298	2107.008
	FFTS	1097.118	812.017	222.260	124.319	−31.562	2224.152
600	AC	1872.005	1621.280	379.406	91.472	−54.038	3910.125
	DC	1579.984	1110.929	320.074	129.975	−45.452	3095.520
	FFTS	1755.391	1299.226	355.607	124.319	−50.490	3484.052
800	AC	2620.810	2269.790	531.161	91.472	−75.662	5437.581
	DC	2369.976	1666.399	480.112	129.975	−68.173	4578.289
	FFTS	2633.082	2078.759	568.977	124.319	−80.788	5324.348

CLCC, life cycle cost; FFTS, frequency division transmission; LCC, line-commutated converter.

In Table 3, for each transmission system, life cycle costs increase as capacity increases. When the transmission capacity increases from 50 to 800, the life cycle cost shows a gradually increasing trend. Regardless of the capacity, AC transmission systems typically have relatively low lifecycle costs. The life cycle costs of DC transmission systems and FFTS transmission systems are generally higher compared to AC. Under the same transmission capacity, the life cycle cost of the DC transmission system and the FFTS transmission system may be close to or not different. To sum up, it can be inferred from the tabular data analysis that at this transmission distance, increasing transmission capacity may lead to an increase in life cycle costs. For different transmission system choices, AC transmission systems may have relatively low life cycle costs.

According to the life cycle cost changes of different offshore distances and different capacities, the appropriate transmission modes of different offshore oil production platforms can be obtained, that is, the life cycle cost comparison of different transmission systems, as shown in Figure 7.

As can be seen from Figure 7,

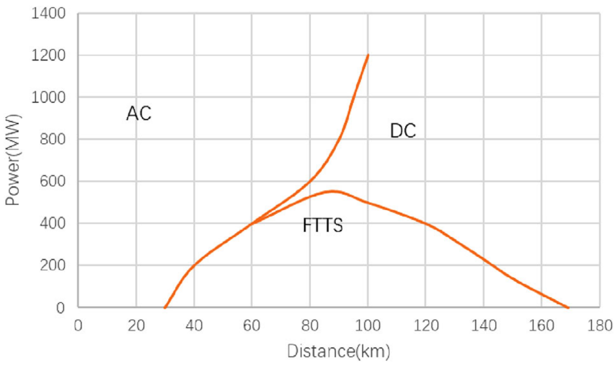

FIGURE 7 LCC comparison of different oil transportation systems. LCC, line-commutated converter.

(1) The AC system is suitable for short-distance and large-capacity offshore oil production platforms, and the AC system should be adopted for offshore oil production platforms within 30 km; the AC system is recommended for large offshore oil production platforms with transmission distance of 30 to 100 km and capacity of more than 500 MW.
(2) The DC system is suitable for offshore oil production platforms with long distance and different capacities, and it has obvious advantages when applied to oil production platforms with transmission distance over 100 km and capacity over 560 MW, or super-large oil production platforms with transmission distance over 180 km.
(3) The FFTS system is suitable for medium-distance and medium-small capacity offshore oil production platforms, and it has obvious advantages when applied to medium-sized oil production platforms below 560 MW and 30 to 169 km.

Taking W area as an example, there are five offshore oil production platforms in this area, namely w1#, w2#, w3#, w4#, and w5#, each with a capacity of 300 MW and a total capacity of 1500 MW. The offshore distance is between 48 and 48 to 64 km, the rated voltage is 6.6 kV or 10 kV, and the frequency is 60 Hz. There are two access points on the shore, which are adopted. The algorithm proposed in this paper and the traditional single-parent genetic algorithm were used for experimental testing. The traditional single-parent genetic algorithm screened individuals with higher fitness through selection operation, that is, a reactive power capacity allocation scheme was adopted. Then, through the cross operation, the excellent characteristics of the two individuals are combined to generate a new reactive power capacity configuration scheme. It can search and optimize the reactive capacity configuration of shore-based power supply system of offshore oil production platform more quickly and effectively, thus improving the performance and reliability of the power supply system. However, this method is easy to fall into local optimization, and it may be difficult to find the best solution for high dimensional and complex problems.

Based on the above optimization results, it can be seen from Figure 8 that:

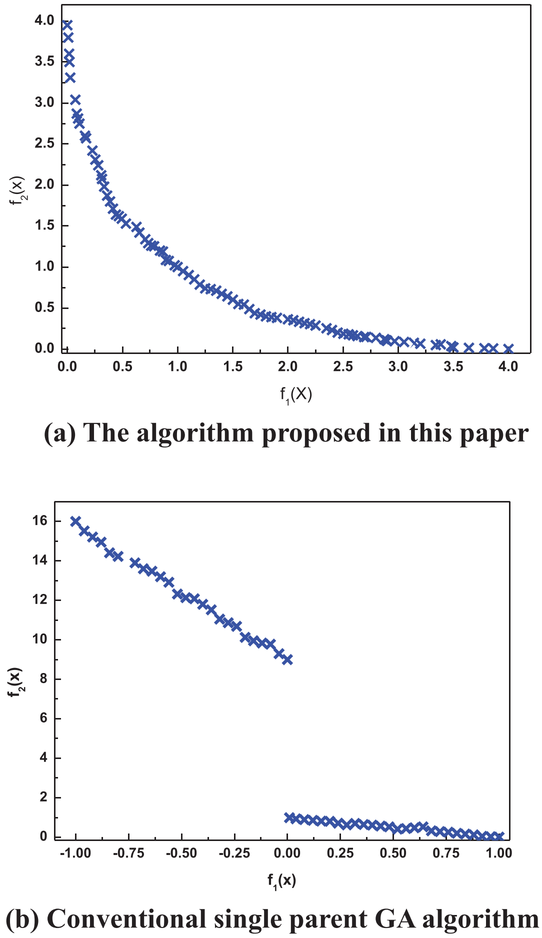

FIGURE 8 Optimization results of reactive power capacity configuration of shore-based power supply system of offshore oil production platform. (a) The algorithm proposed in this paper. (b) Conventional single-parent Genetic Algorithm (GA) algorithm.

1) Based on the FCM method, the fans in the offshore oil production platform can be conveniently grouped according to the demand, and the geographical orientation of the offshore booster substation can be obtained by calculating the group centre position.
2) Based on the optimization model of offshore power collection system, the optimal wiring scheme with comprehensive economy and reliability can be easily obtained on the basis of setting the evaluation weight of wiring scheme.
3) Compared with the conventional parthenogenetic algorithm, the algorithm proposed in this paper only needs 26 calculations to get the optimal solution, with higher optimization efficiency and better convergence effect.
4) According to the Euclidean distance between the oil production platform units and the cluster centre, a method of regional division of offshore oil production platform units based on the FCM algorithm is proposed, so as to achieve the purpose of scientific regional division of units with close geographical positions.
5) Considering the investment cost of each part of the offshore oil production platform and the reliability of the components and equipment of the collection system, the

optimization model of the power collection system of the offshore oil production platform is constructed, which can set the weights of economy and reliability, so as to obtain the topology optimization objectives under different emphases.

6) The improved partheno-genetic algorithm is used to iteratively solve the optimization model of the offshore oil production platform. Compared with the traditional genetic algorithm, it can achieve higher optimization efficiency and better convergence effect, thus providing design reference for the topology optimization of the power collection system in the construction of large offshore oil production platforms.

4 | CONCLUSIONS

In this paper, the reactive power capacity allocation model of the offshore oil production platform shore-based power supply system is constructed, and the reactive power capacity allocation technology of the offshore oil production platform shore-based power supply system based on different network topology reliability measures is proposed. After practical application, it is found that the scheme with the best initial investment cost or the least loss is not necessarily the best scheme in the whole life cycle, and the evaluation based on the whole life cycle cost will be more scientific and comprehensive than the traditional method, and has a higher practical value. In the experiment, the method only needs 26 calculations to obtain the optimal solution, which has high optimization efficiency and good convergence effect, indicating that the method has superior performance in improving the reactive power allocation capability of shore-based power supply system of offshore oil production platform.

AUTHOR CONTRIBUTIONS

Wenle Song: Conceptualization; data curation; resources; software; writing—original draft; writing—review and editing. **Lei Wang**: Conceptualization; data curation; formal analysis; resources; software; supervision; writing—original draft; writing—review and editing. **Xiangyu Hao**: Data curation; formal analysis; methodology; resources; software; writing—original draft; writing—review and editing. **Le Wan**: Writing—original draft; writing—review and editing. **Chenyang Li**: Formal analysis; resources; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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