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Safety Analysis of Offshore Platform Power System Considering Low Voltage Crossing Capability

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ABSTRACT In the face of increasingly serious energy and environmental problems, the safety of offshore oil drilling and production platform, as a natural gas development platform, is of great significance. For offshore platforms, the offshore power system serves for oil and gas production, and the interruption or shutdown of oil and gas production caused by electric power is intrinsically unsafe; In addition, due to the weak interconnection between the offshore platform systems, with the characteristics of small unit, large load, wide application of frequency conversion equipment and poor environment, the security analysis of the offshore platform power system must take the power grid and gas network as a whole to analyze and take into account the low-voltage crossing capacity. For the coupling of power grid and gas network of offshore platform, multi-stage compression system and the ''power to gas'' system are proposed. For these voltage sag sensitive systems, the safe critical voltage and critical cut-off time are used to characterize the low-voltage crossing capability. The operation constraints considering the low-voltage crossing capability are also proposed, and the impact of voltage sag is taken into account in the safety analysis. The simulation results show the correctness of the safety analysis method considering the low voltage crossing capability, and the necessity of the safety analysis considering the gas network and the low crossing capability.

INDEX TERMS Offshore platform power system, low voltage crossing capability, safety analysis.

I. INTRODUCTION

In recent years, with the massive reduction of fossil energy on land and the development demand of modern smart grid and low-carbon society, energy and environmental problems have become increasingly prominent, while natural gas, with its clean and efficient characteristics, has gradually been concerned and applied [1], [2]. The ocean occupies 70% of the earth's area and has a large amount of oil and gas reserves. The exploration and development of marine oil and gas has developed rapidly and continuously discovered, becoming a hot spot of oil and gas exploration [3], [4]. In the process of offshore oil and gas exploitation, the power system of offshore platform is an important part, and its basic characteristics are determined by the attributes of oil and gas production. It provides the necessary energy and power for the whole process of oil and gas exploitation, and ensures the exploitation, transportation and normal operation of equipment. Therefore, the safe operation of the power system is directly related to the production, operation and economic benefits of the platform.

The power system of offshore platform ultimately serves for offshore oil and gas production. In addition to the safety analysis of traditional power grid, its safety analysis should pay more attention to the intrinsic safety goal of whether or not the oil and gas production is stopped. The gas production equipment in the power system transmits the collected natural gas to the land through pipelines and compressors, forming a simple gas network. At the same time, the gas electricity coupling of offshore platform is close, and the fault or power quality disturbance in the power grid is easy to shut down the gas production equipment and compressor, which leads to the natural gas production reduction or even shutdown. Similarly, oil and gas production in turn affects the output of power grid

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generators, thus forming a vicious cycle. It can be said that the shutdown of oil and gas caused by the power system of offshore platform can be regarded as unsafe. In short, "halt production is unsafe." Therefore, the gas network should be taken into account in the power system safety analysis of offshore platforms.

At present, literature [5] proposes a power system cascading fault model considering the influence of natural gas system, and evaluates the influence of natural gas random fault on power system fault; It is also found that the fault of natural gas pipeline and gas transmission block will lead to power block and emergency load cut of power system in [6]–[8], which further make the natural gas pipeline approach the ultimate operation state. In [9], considering the natural gas N-1 accident, the failure propagation mechanism of coupling elements is analyzed by using standard matrix model, and the key accidents and vulnerable parts are identified.

The above research results have some limitations in the safety analysis of offshore platform power system considering gas network. The interconnected power system of offshore platform presents the characteristics of small unit and large load. The load is mainly the large-scale electric load such as electric submersible pump, water injection pump and gathering and transmission pump. The load condition changes violently, which will have a great impact on the power grid when it is started and stopped, making the anti-voltage disturbance ability of the power system of offshore platform weak [10]. The environment of the offshore platform is relatively harsh. Too high relative temperature and humidity of the surrounding environment, salt fog, mold and so on will affect the performance of electrical equipment, and will increase the failure probability [11], [12]. In addition, the offshore platform fault type is special, so the protection cooperation is difficult; the restart process after the compressor shutdown is complex, and the restart time is long. The electric submersible pump, water injection pump, gathering pump and other pump loads in the equipment are mostly frequency conversion equipment, which is more sensitive to voltage sag. To sum up, because the power system voltage of offshore platform fluctuates frequently, the equipment has poor anti voltage sag capacity, and the equipment starts up for a long time after shutdown, which is easy to cause oil and gas production interruption. Therefore, in the safety analysis of offshore platform, the influence of voltage sag on the low voltage crossing capability of key equipment should be considered.

Considering the characteristics of offshore platform, this paper proposes a method to analyze the safety of offshore platform based on gas and electricity as a whole, and it is necessary to consider the voltage crossing capability of coupling equipment. The gas-electric interconnection model for safety analysis of offshore platform is established, and the voltage sag characteristics of coupling nodes are considered to realize the safety analysis.

This paper is divided into seven parts. The section I is the introduction part of the article; the section II briefly introduces the power system of offshore platform; the section III proposes the coupling elements of offshore gas-electric interconnection system, "power to gas" system and multi-stage compression system, and carries out modeling; the section IV introduces the calculation method of low-voltage crossing capacity of key coupling nodes of offshore platform; the section V proposes the expected accidents and operational constraints of offshore platforms, and the safety analysis is carried out. The section VI is example analysis, which simulates the traditional gas-electric interconnection system and the offshore platform system respectively to prove the necessity of considering the low voltage crossing capability of the key coupling nodes in the offshore platform; the section VII is the conclusion.

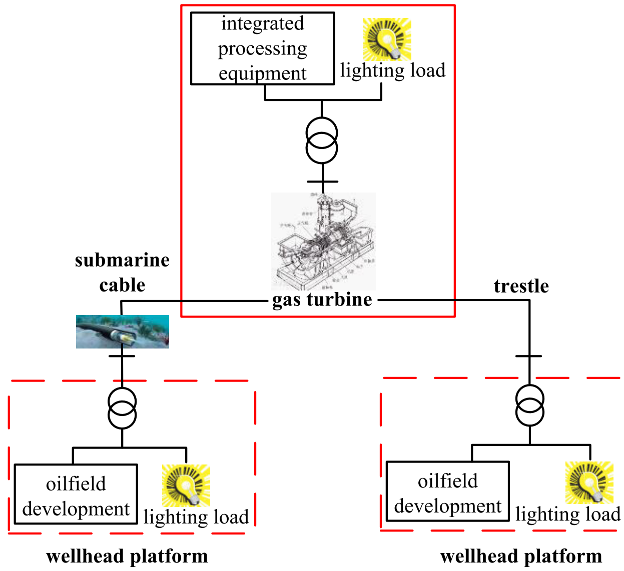

FIGURE 1. Typical offshore platform power system diagram.

II. OVERVIEW OF POWER SYSTEM OF OFFSHORE PLATFORM

Offshore platform oil and gas processing facilities have different uses. Generally, the platform is divided into offshore central platform (main platform, MP) and wellhead platform (WP). The main platform provides power to each wellhead platform and processes the well fluid. The wellhead platform simply measures, processes or directly transports the oil and gas extracted to the main platform for processing. Its power is provided by the main platform. The main platform transmits the electric energy to the remote and near wellhead platforms through submarine cable and trestle. The typical offshore platform power system schematic diagram is shown in Fig. 1.

The actual offshore oil and gas field includes multiple platforms. If the power system of each platform is independent of each other, there will be problems such as large investment and poor reliability of power supply [13]. Therefore, in order to enhance the supply reliability of the power system of the offshore platform, and ensure safe, stable and economic

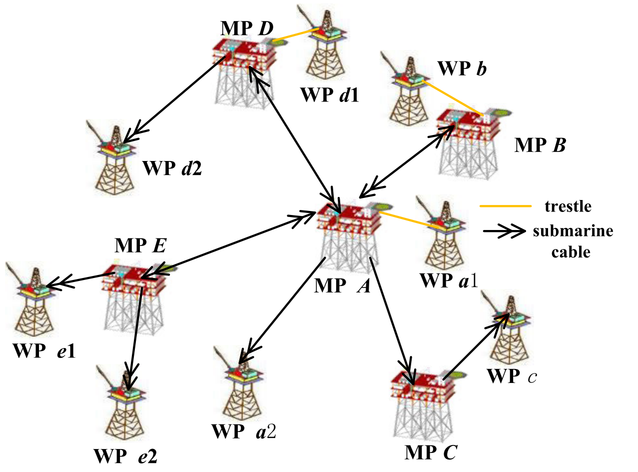

FIGURE 2. Schematic diagram of interconnected power system of offshore platform.

operation of production, the power system organizes into power networks to form weak interconnection power system of offshore platform, as shown in Fig. 2.

III. MODELING OF COUPLED SYSTEM OF OFFSHORE PLATFORM

The offshore power system provides a service for oil and gas production, and it will separate oil and gas, and transmit crude oil and natural gas to the land end respectively. However, the interruption and shutdown of oil and gas production caused by the power system can not meet the demand of natural gas load, which is the intrinsic insecurity of the power system of offshore platform. Therefore, the gas and electricity of offshore platform should be analyzed as a whole. In addition, after the power consumption process such as exploitation and treatment process, the natural gas network is formed by the transmission and interconnection between platforms. Therefore, the integrity of offshore platform power system and natural gas network is reflected in the special coupling between the two networks, that is, the process of natural gas processing. The platform is roughly divided into the following two process: 1) Platform oil and gas production process: through a series of treatment processes, crude oil and natural gas are separated and measured, and the relationship between electric power and natural gas flow is established. In the following, this process is briefly described as ''power to gas.'' 2) Natural gas compression: the purpose of multi-stage compressor is to remove condensate and boost natural gas (gas to gas), reduce volume, facilitate transmission and greatly reduce transportation cost.

A. ''POWER TO GAS'' SYSTEM OF PLATFORM

The main equipment of the ''power to gas'' system includes the electric submersible pump, slug catcher, separator and other process equipment. From the input of electric energy to the output of natural gas, a series of processes are encapsulated in the ''power to gas'' system. The whole electric gas production process is regarded as a coupling element, equivalent to the load in the power grid and the gas source in the gas grid. The specific process is shown in Fig. 3, which shows that the power system serves for oil and gas production.

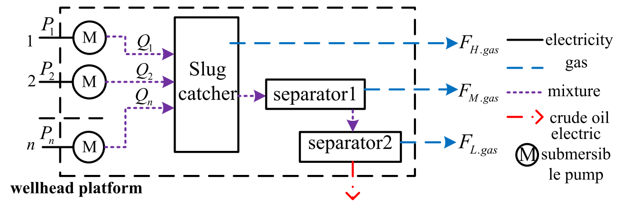

FIGURE 3. Schematic diagram of ''electric to gas'' system in the platform.

Electric submersible pump is a common production equipment in offshore oil production technology. It is a lifting equipment that lowers the motor and multi-stage centrifugal pump into the oil well below the liquid level to pump oil. The electric energy is converted into mechanical energy to lift the well fluid to the ground. Slug catcher and oil-gas separator have similar functions. They are mostly used to catch well fluid from multiphase pipeline of electric submersible pump, provide buffer volume for well fluid fluctuation, and achieve gas-liquid separation. In the ''power to gas'' system, the power consumption equipment, such as water injection pump and sewage pump, which has no obvious relationship with the content of natural gas, is regarded as constant power and is coupled in the ''power to gas'' system [14]. The coupling relationship between electric power and natural gas flow in the ''power to gas'' system is as follows (1):

$$\begin{bmatrix} F_{\text{H.gas}} \\ F_{\text{M.gas}} \\ F_{\text{L.gas}} \end{bmatrix} = \begin{bmatrix} \lambda \\ (1-\lambda)\cdot k_1 \\ (1-\lambda)\cdot(1-k_1)\cdot k_2 \end{bmatrix} \sum_{i=1}^{n} \frac{1000 P_i \mu}{\rho g H} \quad (1)$$

where, $F_{\text{H.gas}}$, $F_{\text{M.gas}}$ and $F_{\text{L.gas}}$ are respectively high pressure, medium pressure and low pressure natural gas flow; λ, k_1 and k_2 are the natural gas separation coefficients of slug catcher and separator 1 and 2, which are related to factors such as mixture density, pressure and temperature; μ is the working efficiency of electric submersible pump; P is the power consumed by electric submersible pump; H is the total dynamic pressure head of oil well; ρ is the density of well fluid mixture; g is the gravity acceleration.

B. MULTI-STAGE COMPRESSION SYSTEM

The natural gas output in the ''power to gas'' system shall be pressurized by multi-stage compressor for pipeline transportation to meet the demand of natural gas load, which is represented by multi-stage compression system, reflecting that the power system serves the transmission of oil and gas, as shown in Fig. 4.

The treatment process of natural gas generally adopts multi-stage compression, and its overall coupling is expressed as follows:

$$\begin{aligned} HP_{\sum} = {} & HP_{com}(F_{L.gas}) + HP_{com}(F_{L.gas} + F_{M.gas}) \\ & + n \cdot HP_{com}(F_{L.gas} + F_{M.gas} + F_{H.gas}) \end{aligned} \quad (2)$$

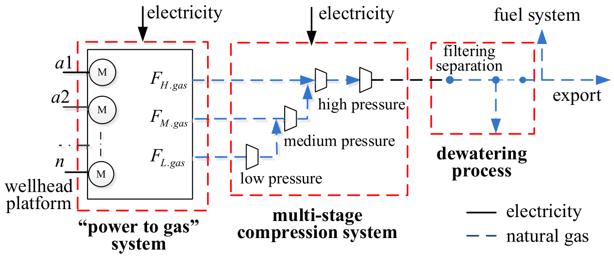

FIGURE 4. Schematic diagram of Natural gas multi-stage compression system.

where, $HP_{\sum}$ is the total power consumed in the multi-stage compression process; n is the number of high-pressure compressors; HP_{com} is the conversion relationship between the power consumed by the compressor and the natural gas flow through.

IV. LOW PRESSURE CROSSING CAPACITY OF KEY NODES OF OFFSHORE PLATFORM

Voltage sag of offshore platform is more frequent than other transient power quality problems, which may cause the platform to stop production, resulting in great economic loss and bad social impact [15], [16]. Therefore, the voltage sag has become one of the most important power quality problems of offshore platform. For petroleum and petrochemical enterprises, voltage sag will make the motor system out of operation, resulting in shutdown. However, "power to gas" system and multi-stage compression system are not only sensitive to voltage sag, but also crucial to the operation of power system and natural gas network. Therefore, considering the impact of gas network on the safety of offshore platform power system, the low-voltage crossing capability of "power to gas" system and multi-stage compression system should be considered.

A. EVALUATION OF LOW VOLTAGE CROSSING CAPABILITY OF ELECTRIC COMPRESSOR SYSTEM

In the marine electric compressor system, the frequency converter and the motor part of the compressor are sensitive to the voltage sag. Generally speaking, the low-voltage crossing capability of the electric compressor system is mainly determined by the frequency converter when there is a frequency converter, and by the motor when there is no frequency converter. For the low-voltage crossing capability of the variable frequency compressor system, please refer to the limit of DC capacitor low-voltage protection in the frequency converter manual.

For the compression system whose low voltage crossing capability is determined by the motor, this section uses the safe critical voltage and critical cut-off time (CCT) to characterize its low voltage crossing capability [17]. If the residual voltage is greater than the safe critical voltage, the motor will not lose stability no matter how long; if the residual voltage is less than the safe critical voltage and the voltage drop duration exceeds the CCT, the motor will lose stability even if the voltage is restored.

There are many types of natural gas compressors. Generally, piston compressors and centrifugal compressors are preferred for compressors used in natural gas production. The above two types of compressors are generally considered as constant torque loads [18]. The mechanical torque model of constant torque load can be expressed as follows:

$$T_{l,ConT}(s) = T_0 \tag{3}$$

where, $T_l, ConT$ is mechanical torque; T_0 is constant torque.

According to [19], the safe critical voltage and CCT of constant torque load are shown in (4) and (5).

$$u_{crit,ConT} = u_n\sqrt{\frac{1}{k_m}\frac{T_0}{T_n}} \tag{4}$$

$$t_{crit,u_{sag}} = 2H\int_{s_0}^{s_c}\left[T_l(s) - T_n\left(\frac{u_{sag}}{u_n}\right)^2 \frac{2k_m}{{s}/{s_m} + {s_m}/{s}}\right]^{-1} ds \tag{5}$$

where, u_{crit}, $ConT$ is the safe critical voltage for mechanical torque; t_{crit}, $ConT$ is the CCT; u_n is rated voltage; T_n is rated torque; k_m is the ratio of rated torque to maximum torque at rated voltage; s_m is critical slip; u_{sag} is residual voltage; H is the moment of inertia of the motor; s_0 and s_c are the slip of the balance point when the motor works under rated voltage, which s_0 is the stable slip of the balance point and s_c is the unstable slip of the balance point.

The natural gas compression process in the gas-electric interconnection system of offshore platform includes three stages of compression: low pressure, medium pressure and high pressure. The low-pressure crossing capacity of each stage of compressor is different. The voltage sensitivity and weakness of the electric compressor system are reflected in that if one compressor is shut down, the whole compressor system will be out of operation. Therefore, the judgment principle of the low-pressure crossing capacity of the compressor system on the offshore platform is: the minimum of the safety critical voltage of the multi-stage compressor is taken as the safety critical voltage u_{crit}^{min}, and the minimum of the CCT of the multi-stage compressor is taken as the CCT $t_{crit,u_{sag}}^{min}$.

B. EVALUATION OF LOW VOLTAGE CROSSING ABILITY OF "POWER TO GAS" SYSTEM

The "power to gas" system of offshore platform is obviously different from the traditional P2G. "Power to gas" system is a collection of gas production equipment, including frequency conversion equipment such as electric submersible pump and water pump, which belongs to voltage sag sensitive load. Its low voltage withstand characteristic is the comprehensive characteristic of all frequency conversion equipment in the "power to gas" system, which is generally described by the withstand curve, as shown in Fig. 5. The area composed of residual voltage and duration is divided into action area and

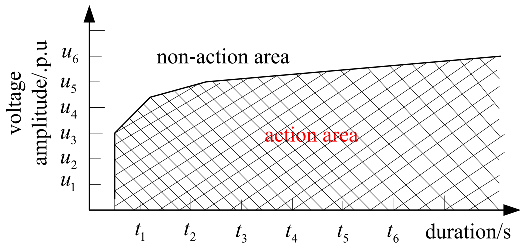

FIGURE 5. Voltage sag tolerance curve of conversion equipment.

non-action area by the tolerance curve. The voltage on the tolerance curve is expressed by u_{vf}, $crit$, and the "power to gas" system in the non-action area keeps normal operation state; the action area is the shadow part in Fig. 5, and the "power to gas" system will show abnormal operation state, or even exit from operation [20].

V. SAFETY ANALYSIS

A. OPERATION CONSTRAINTS AND EXPECTED ACCIDENT SET

The safety operation constraints of offshore platform system include power system and natural gas system. Taking the offshore platform voltage compressor as an example, during the production and operation period, it is required that there should be no shutdown of the compressor, the outlet pressure should not be too low or too high, which should meet the standard requirements, that is, the pressure rise ratio should also meet the requirements. Similarly, the key variables in each system, including voltage amplitude, branch power flow, generator output, node pressure, pipeline flow and pressure rise ratio of compressor, are taken as the main variables. The safety operation constraints of this interconnected system include:

1) OPERATION CONSTRAINTS OF POWER SYSTEM

$$U_i^{\min} \le U_i \le U_i^{\max} \tag{6}$$

$$\left|P_{l,i-j}\right| \le P_{l,i-j}^{\max} \tag{7}$$

$$0 \le P_{G,i} \le P_{G,i}^{\max} \tag{8}$$

where, $U_i^{\min}$and $U_i^{\max}$are the upper and lower limit of voltage amplitude; $P_{l,i-j}^{\max}$is the limit of active power of branch current; $P_{G,i}^{\max}$is the upper limit of active power of generator.

For nodes considering low-pressure crossing capacity, the safety constraints are:

$$frequencyconverter \begin{cases} operational \\ constraints \quad : U_i^{\min} \le U_i \le U_i^{\max} \\ low-pressure \\ crossingcapacity : \begin{cases} U_i \ge U_{crit} \\ (U_i > U_{vf,crit})\, t \le t_{crit}\ (U_i \le U_{crit}) \end{cases} \end{cases}$$

$$\text{non-}frequencyconverter \begin{cases} operational \\ constraints : U_i^{\min} \le U_i \le U_i^{\max} \\ low-pressure \\ crossingcapacity : \begin{cases} U_i \ge U_{crit} \\ t \le t_{crit}\ (U_i \le U_{crit}) \end{cases} \end{cases} \tag{9}$$

2) OPERATION CONSTRAINTS OF OFFSHORE PLATFORM NATURAL GAS SYSTEM

$$p_i^{\min} \le p_i \le p_i^{\max} \tag{10}$$

$$\left|f_{ij}\right| \le f_{ij}^{\max} \tag{11}$$

$$k_{com}^{\min} \le k_{com} \le k_{com}^{\max} \tag{12}$$

$$S_{dcq.\min} \le S_{dcq} \le S_{dcq.\max} \tag{13}$$

where, $p_i^{\min}$and $p_i^{\max}$ are the upper and lower limit of node pressure of gas network;$f_{ij}^{\max}$ is the upper limit of pipeline flow;k_{com} is the pressure rise ratio of compressor, which is equal to the ratio of compressor outlet pressure and inlet pressure,$k_{com}^{\min}$and $k_{com}^{\max}$are the upper and lower limit of compressor pressure rise ratio. S_{dcp} is the gas production of the "power to gas" system; $S_{dcp.min}$ is the minimum gas production of the "power to gas" system, which needs to meet the requirements of the natural gas load of the offshore platform; $S_{dcp.max}$ is the upper limit of the gas production of the "power to gas" system, which needs to consider the power of the electric submersible pump, water injection pump and other equipment in the "power to gas" system, and no equipment can exceed the upper limit of its power.

In the integrated energy system, the expected accident set of static safety analysis generally includes the disconnection of main components, such as 1) the disconnection of transmission lines, transformers and generators in the power system; 2) the disconnection of gas transmission pipelines in the natural gas system; 3) the withdrawal of coupling components, such as compressors and gas turbines in the interconnected system. The disconnection of coupling elements will affect the two systems at the same time, and the influence is generally large. However, the disturbance of uncoupled elements may indirectly lead to the decommissioning of the coupling elements, and further expand the influence of the disturbance through the function of the coupling elements. Because the offshore platform system has the characteristics of small unit, large load, voltage sensitive frequency conversion equipment, closely linked with power grid and gas network, the impact is particularly obvious. In this paper, the "grid fault" is considered as a cause, and the fault propagation of coupling components is considered. Therefore, the expected fault set is constructed for the power system branch disconnection caused by short circuit and protection action.

B. SAFETY ANALYSIS CONSIDERING VOLTAGE SAG

Taking the voltage sag sensitive coupling element as an example, the specific steps of the safety analysis of the gas- electric interconnection system considering the low-voltage crossing

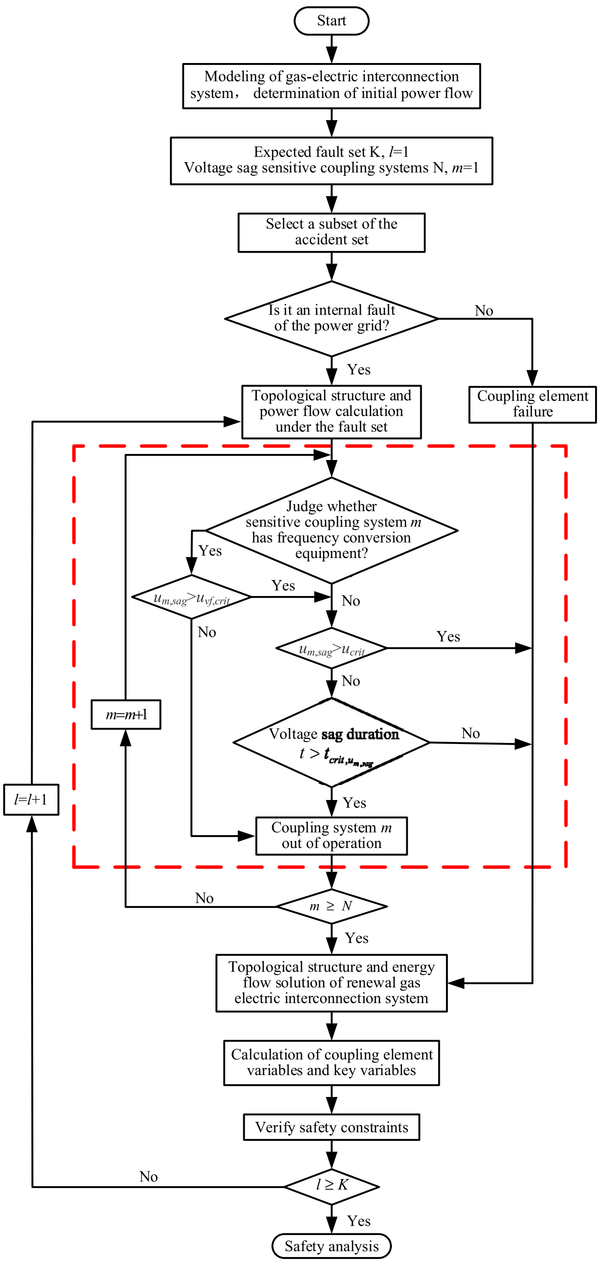

FIGURE 6. Flow chart of static safety analysis considering voltage sag.

capability are shown in Fig. 6, in which the red frame is the characteristics of the low-voltage crossing capability of the key voltage sag sensitive coupling node.

VI. CASE STUDY

Taking the traditional gas-electric interconnection system and the offshore multi-platform power system as examples, the safety analysis considering the low-voltage crossing capability of the key coupling nodes will be carried out.

A. AN EXAMPLE OF TRADITIONAL GAS ELECTRIC INTERCONNECTION SYSTEM

The gas-electric interconnection test system is composed of IEEE14 node [21], NGS 25 node system [22] and coupling

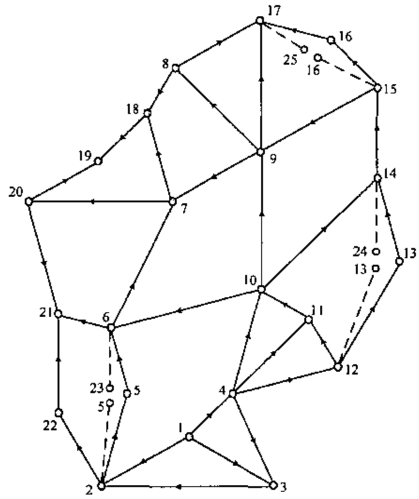

FIGURE 7. The topological structure of gas network in traditional calculation example.

TABLE 1. Safety critical voltage of electric compressor.

Model of induction motor	*Safety critical voltage (p.u)*
I（YKK56034）	0.65
II（Y4005-4）	0.75
III（250M4A）	0.58

elements. The gas network topology is shown in Fig. 7. The E1 node of the power system is coal-fired power unit, E2 is gas turbine unit, which is supplied by the N2 node of the gas network; In the natural gas system, N1 node is the gas source, G5, G13 and G16 are the compressor inlet nodes, G23, G24 and G25 are the compressor outlet nodes. Assuming that all three compressors are driven by electricity, they are respectively represented as E3-G13-II (grid node-gas network node- corresponding motor type), E5-G16-III and E7-G5-I; P2G equipment is the load of E14 node and the gas source of N2 node.

The energy flow results of the normal test system are shown in Fig. 8. From the curve of node pressure value of the natural gas system, it can be seen that the pressure of nodes 5, 13 and 16 are relatively low, and the load demand of the system can be satisfied only when the pressure is raised by the compressor. The operation conditions of the test gas electric interconnection system are as follows (all are unit values): the voltage amplitude range of the load node of the power system is 0.80-1.05, the power flow of the generator branch of the power system shall not exceed 4, and the power flow of the other branches shall not exceed 2; the node operation pressure of the natural gas system shall not exceed 0.8 (based on 5MPa), the flow of the natural gas pipeline branch shall not exceed 5, and the compression ratio range of the compressor 1.2-1.8.

The mechanical torque of constant torque load is T_L(pu)=1, and TABLE 1 and TABLE 2 are the safety critical voltage and CCT under different residual voltage of the motor driving the electric compressor.

TABLE 2. Voltage Sag CCT of electric compressor.

Residual voltage (.p.u)	CCT(s) I	II	III
0	0.6012	0.721	1.028
0.1	0.8028	0.731	1.048
0.2	0.9982	0.765	1.112
0.3	1.091	0.828	1.241
0.4	1.274	0.938	1.503
0.5	1.651	1.135	2.177
0.6	2.896	1.548	-
0.7	-	3.028	-

TABLE 3. Node pressure during failure.

Type of event	E3	E5	E7
a	0.6588	0.5568	0.4483
b	0.6787	0.5934	0.4018
c	0.6705	0.5926	0.2646
d	0.2660	0.0753	0.0432
e	0.815	0.925	0.903

TABLE 4. Node pressure after protection action.

Compressor node	Protection action a	b	c	d
E3	0.9884	1.001	0.9868	0.9794
E5	0.9857	0.999	0.9760	0.9983
E7	0.9520	1.026	0.9377	0.9583

According to the constant value of low-voltage protection, when the voltage of compressor II is less than 0.85, the protection is required to act immediately, and the compressor will stop running; according to the regulation of relay protection action time, when three-phase fault occurs, the protection action time is 0.5s-1s, that is to say, the sag time is greater than 0.5s.

Considering the low voltage crossing capability, several typical accidents in the accident concentration are selected to describe the safety analysis of the interconnected system. TABLE 3 shows the influence of the node voltage of the corresponding compressor in the power system when the accident occurs. After the protection action, the corresponding node voltage of the compressor is shown in TABLE 4, and each node voltage is within the safe operation restriction range.

Among them, event 'a' represents E6-E13, and nearly node E13 is short circuited; 'b' represents E9-E14, and nearly node E14 is short circuited; 'c' represents E7-E8, and nearly node E8 is short circuited; 'd' represents E4-E5, and nearly node E4 is short circuited; 'e' represents branch E2-E3 off, out of service.

The analysis process of corresponding events is as follows:

a. As the residual pressure of E3 node corresponding to compressor II is 0.6588<0.85, compressor II is out of operation; the residual pressure of E5 node corresponding to compressor III is 0.5568<0.58, so compressor III is out of operation; Since the residual pressure of E7 node corresponding to compressor I is 0.4483<0.65, but the protection action time is 1.274s less than the CCT, when the protection action cuts off line E6-E13, the voltage of E7 node is 0.952>0.65, so compressor I operates.

b. As the residual pressure of E3 node corresponding to compressor II is 0.6787<0.85, compressor II is out of operation; the residual pressure of E5 node corresponding to compressor III is 0.5934>0.58, so compressor III is in operation; Since the residual voltage of E7 node corresponding to compressor I is 0.4018<0.65, but the protection action time is less than the CCT of 1.274s, when the protection action cuts off line E9-E14, the voltages of E5 and E7 nodes are 0.999 and 1.026 respectively, which are greater than the safety critical voltage, so compressor I and III operate.

c. As the residual pressure of E3 node corresponding to compressor II is 0.6705<0.85, compressor II is out of operation; as the residual pressure of E5 node corresponding to compressor III is 0.5926>0.58, compressor III is in operation; as the residual pressure of E7 node corresponding to compressor I is 0.2646<0.65, but the protection action time is > the CCT 0.9982s, compressor I is out of operation.

d. As the residual pressure of E3 node corresponding to compressor II is 0.2660<0.85, compressor II is out of operation; as the residual pressure of E5 node corresponding to compressor III is 0.0753<0.58, compressor III is out of operation; as the residual pressure of E7 node corresponding to compressor I is 0.0432<0.5, but the protection action time > the CCT is 0.8028s, compressor I is out of operation.

e. When E2-E3 branch is out of operation, the voltage of each node is within the operating range, which can be regarded as a safe state; however, when considering the low-voltage crossing capacity of the corresponding induction motor of the compressor, since compressor II is a variable-frequency compressor, the voltage of E3 node is 0.815<0.85, so compressor II is out of operation, and I and III operate normally.

To sum up, the fault states of compressors in the gas network are classified as follows:

(1) Compressor I and III operate, compressor II is out of operation. —'b' and 'e'.

(2) Compressor I operates, compressor II and III are out of operation. —'a'.

(3) Compressor III operates, compressor I and II are out of operation. —'c'.

(4) Compressor I, II and III are out of operation. —'d'.

After the compressor is out of operation, it has the same function as the common pipeline branch, and the safety analysis results that can ensure the gas transmission are listed in TABLE 5; after the compressor is out of operation, it cannot pass the gas flow, and the safety analysis results that the bypass pipeline connected with the compressor is also disconnected are listed in TABLE 6. Only for the safety problems of node pressure and branch flow of the gas network, in which the brackets are the over limit of components. ('+' represents

TABLE 5. Consider safety checks a for voltage sag.

Number	Types of disturbances	Compressor status	Safety performance of gas network
1	'e'	Compressor I and III operate, compressor II is out of operation.	Unsafe: Node G16(+0.27) Pipeline G15-16(+0.06), G16-17(0.06) Compression ratio of III(-0.23) Running in reverse: 10 pipes
2	'a'	Compressor I operates, compressor II and III are out of operation.	Unsafe: Compression ratio of I(-0.01) Running in reverse: 5 pipes
3	'c'	Compressor III operates, compressor I and II are out of operation	Unsafe: Node G16(+0.25) Compression ratio of III(-0.22) Running in reverse: 10 pipes
4	'd'	Compressor I, II and III are out of operation.	Unsafe: Node G14(+0.18) Pipeline G1-4(+0.7) Running in reverse: 7 pipes
5	'b'	Compressor I and III operate, compressor II is out of operation.	Unsafe: The system is unstable

TABLE 6. Consider safety checks B for voltage sag.

Number	Types of disturbances	Pipeline status	Safety performance of gas network
1	'e'	Pipeline disconnect: G12-G13, G13-G14	Unsafe: Compression ratio of I (-0.09), III (-0.13) Running in reverse: 14 pipes
2	'a'	Pipeline disconnect G12-G13, G13-G14、G15-16, G16-17	Unsafe: Running in reverse: 4pipes
3	'c'	Pipeline disconnect G2-G5, G5-G6, G12-G13, G13-G14	Unsafe: Compression ratio of III (-0.13) Running in reverse: 8 pipes
4	'd'	Pipeline disconnect G2-G5, G5-G6, G12-G13, G13-G14, G12-G13, G13-G14	Unsafe: Running in reverse: 5 pipes
5	'b'	Pipeline disconnect G12-G13, G13-G14	Unsafe: The system is unstable.

the upper limit is exceeded; '-'represents the lower limit is exceeded)

From the above analysis, it can be seen that the power grid fault causes compressor shutdown, which has a great impact on the interconnected system, so compressor shutdown should be regarded as an unsafe event. When the compressor is out of operation, the pipeline connected with the compressor is disconnected. In order to meet the node load demand, some pipelines that originally flow to the compressor inlet will run in reverse direction, and some pipelines that originally flow out of the compressor outlet will increase, and the safety margin will decrease. If the compressor shutdown is considered as an unsafe event, it is assumed that the function of the compressor is the same as that of the common branch after the compressor exits operation, so that the original compressor inlet and outlet nodes are equivalent to a load node. According to the inlet pressure of the compressor during normal operation before the safety analysis in Fig. 8, if there is no pressure boosting function of the compressor, the natural gas will not continue to flow under the premise of meeting the load demand, which has a greater impact on system security.

It can be seen from the above data analysis that the safety analysis of the system is more comprehensive considering the low-voltage crossing capacity of coupling nodes. For example, E2-E3 is disconnected, in the traditional N-1 safety analysis of gas-electric interconnection system, it does not cause the over limit of voltage, branch power, gas network node pressure and branch flow, so it can be concluded that the fault does not cause safety problems. However, when the low-voltage crossing capability of nodes is considered in this paper, this fault causes the compressor to exit from operation and causes a series of safety problems such as over limit. Corresponding measures should be taken to ensure the key nodes to achieve low-voltage crossing during occurring faults. It also proves the necessity of gas-electric interconnection system safety analysis considering low voltage crossing capability.

B. CALCULATION EXAMPLE OF POWER SYSTEM OF OFFSHORE PLATFORM

Taking an offshore multi-platform as an example, the network topology of offshore platform power system considering the gas network is shown in Fig. 9. Without the supply of the onshore power grid, the whole offshore platform operates in isolated islands. Among them, each wellhead platform is regarded as a load node, and the calculation example is actually the interconnection of a 4-node power grid and a 4-node gas network.

During the normal operation of the interconnected system, the natural gas flow of the three platforms is $7.7551\times10^4 m^3/h$, $1.4981\times10^4 m^3/h$ and $0.4537\times10^4 m^3/h$ respectively. The total external gas supply of the gas network is $7.7083\times10^4 m^3/h$; the total active power range of platform A gas turbine is 0-46 MW, the total active power range of platform B gas turbine is 0-23 MW, and the power generation of the two platforms are 40.06MW and 8.86 MW respectively. As the total power consumption of the gas network accounts for about 33% of the whole grid loads, and the "power to gas" system is the gas source of the gas network, the operation mode of the electric compressor system and the "power to gas" system plays an important role in the safety of the interconnected system.

The equipment of platform A, B and C "power to gas" system is frequency conversion equipment. After all frequency

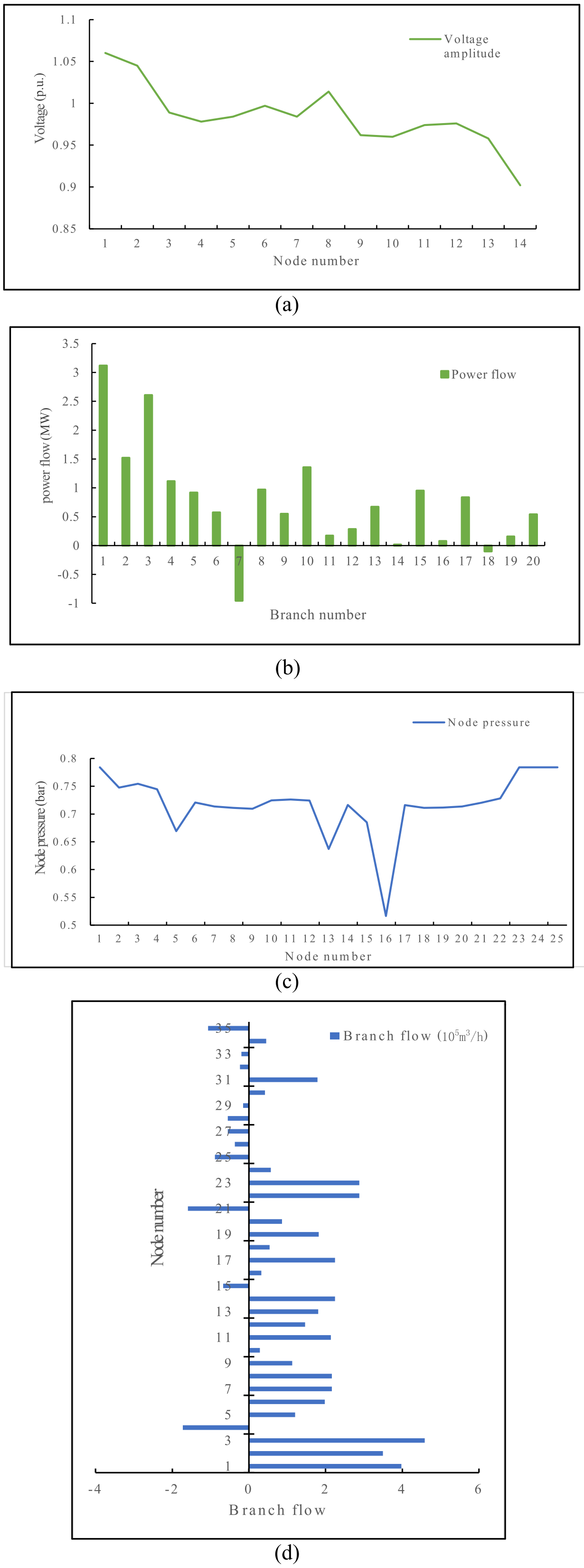

FIGURE 8. Energy flow calculation results of traditional examples: (a) node voltage of power system, (b) branch power flow of power system, (c) node pressure of natural gas system, (d) branch flow of natural gas system.

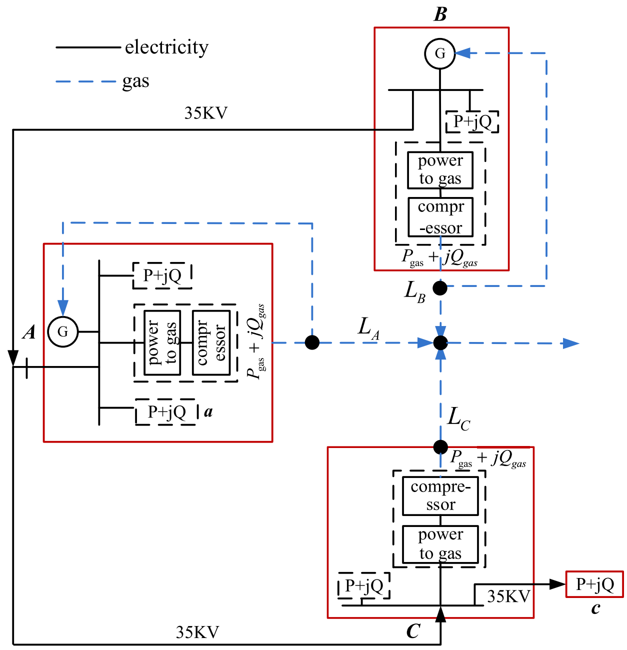

FIGURE 9. Network topology of an actual offshore platform.

TABLE 7. Voltage sag CCT of electric compressor system.

Residual voltage (.p.u)	CCT(s)
0	0.6012
0.1	0.731
0.2	0.765
0.3	0.828
0.4	0.938
0.5	1.135

conversion equipment are integrated, it is set that when the node voltage is less than 0.80, the "power to gas" system will stop running; The types of induction motors corresponding to the low pressure, medium pressure and high pressure compressors of the compressor systems are I (YKK56034), II (Y4005-4) and III (250M4A) in TABLE 1, respectively. Therefore, the low voltage crossing capacity of the electric compressor system is 0.58 and the CCT is shown in TABLE 7.

The safety analysis is based on the line fault in the power grid.

a. Branch A-B, and nearly node A is short circuited.

The voltages of nodes A, B, C and c are 0.8748, 0.9392, 0.8448 and 0.8448 respectively. The node voltage of the MPs is greater than the safety critical value of the "power to gas" system and the compressors, it will not stop; when the protection action cuts off line A-B (equivalent to line A-B disconnection), the "power to gas" systems and the compressors also work normally. If it is necessary to meet the demand of land natural gas loads, the gas turbine of platform A needs to generate 43MW, close to the full capacity (46 MW), and the safety margin is very small; gas turbine of

TABLE 8. Consider safety checks for voltage sags.

Number	Types of disturbances	State of coupled system	Safety performance
1	'a'	normal operation	Gas turbine of platform A is close to full capacity, with minimal safety margin
2	'b' and 'c'	Platform C and c coupling system shutdown	The power of the "power to gas" systems exceeds the rated operation power and cannot meet the load demand of the gas network

platform B only needs to generate 5.86mw, because the line of platform A and platform B is cut off, unable to transmit power, which will lead to the decrease of the system safety margin.

b. Branch C-c, and nearly node c is short circuited.

The line C-c is short circuited, the platform c loses power, the voltage is 0, the voltage of other nodes A, B and C are 0.9609, 0.9996 and 0.0882, respectively. It can be seen that, in "power to gas" system, the voltage of platform C is less than the low voltage crossing safe critical value of frequency conversion equipment, and less than the safe critical voltage of voltage compressor system. So platform C and c exit from operation. If the interconnected system after the protection action wants to meet the demand of natural gas load on land, the power generation capacity of gas turbines of platform A and platform B is within the safe range with certain safety margin. However, in the "power to gas" system, it is calculated that electric submersible pumps of platform A needs to work at a power of 3310.2 kW, which is far beyond the normal working range of electric submersible pumps in the platform (75 KW×40). Therefore, the interconnected system cannot fully meet the load demand of the gas network, resulting in certain economic losses.

c. Branch A-C, and nearly node C is short circuited.

When the line A-C is short circuited, both platform C and platform c lose power and their voltage are 0, so platform C and platform c exit; the voltage of other platforms A and B are 0.8794 and 0.9983. It can be seen that the voltage of two platforms are higher than the low-voltage crossing critical value of frequency conversion equipment and the safety critical voltage of induction motors corresponding to electric compressors. After the protection action, the voltage is still within the safety restriction range, so platform A and platform B operate. At this time, the system is consistent with the system after the short-circuit protection of C-c near c node, so the analysis will not be repeated here.

The results of above safety analysis are listed in TABLE 8. The results of the safety analysis are the system operation status under the premise of meeting the load demand of the gas network.

It can be seen from above analysis that when the offshore platform power system fails, based on the gas-electricity coupling relationship between the gas turbine and the "power to gas" system, its economic loss should not be underestimated. so it is more necessary to comprehensively consider the system safety issues, so that relevant measures can be taken as early as possible to prevent serious safety accidents of the system.

VII. CONCLUSION

Based on the consideration of gas network, this paper analyzes the safety of offshore platform power system considering low voltage crossing capability. As the power system of offshore platform serves for natural gas and closely coupled, the operation state of natural gas network should be considered in the safety analysis of the power system of offshore platform rather than split. Because the power system of offshore platform contains a large number of frequency conversion equipment, which is very sensitive to voltage disturbance, the low voltage crossing capability of coupling equipment (system) should be considered in the safety analysis of offshore platform. In the safety protection measures of offshore platform power system, the measures of low-voltage crossing capability of key voltage sensitive coupling parts should be considered.

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