IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received February 29, 2020, accepted March 14, 2020, date of publication March 18, 2020, date of current version March 26, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2981614

Transient Frequency Stability Emergency Control for the Power System Interconnected With Offshore Wind Power Through VSC-HVDC

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This work was supported in part by the National Key Research and Development Program of China under Grant 2017YFB0902000, in part by the National Natural Science Foundation of China under Grant 51477050, Grant 51627811, and Grant 51725702, and in part by the Fundamental Research Funds for the Central Universities under Grant 2018ZD01.

ABSTRACT For the power system interconnected with the large-scale offshore wind power through VSC-HVDC, such as SZ power grid, it may be engaged with transient frequency stability and lack of related control due to the randomness, fluctuation and intermittence of the wind. This paper proposes a transient frequency control strategy for the power system interconnected with offshore wind power through VSC-HVDC based on sensitivity. Firstly, the structure of SZ power grid and the calculation method of transient frequency stability index are introduced, and the transient frequency problems existing in SZ power grid are explored. Secondly, the mathematical formulation for the transient frequency control is described, including the objective function and the constraints. Furthermore, a transient frequency emergency control strategy based on special sequence and the sensitivities is proposed, which includes thermal units regulation, wind power regulation, DC modulation and load shedding. Finally, the effectiveness of the proposed control strategy is verified by simulation in SZ power grid.

INDEX TERMS Wind power, VSC-HVDC, transient frequency stability, emergency control strategy.

I. INTRODUCTION

With the pressure of fossil energy shortage, climate change and environment needs, the wind power, which is a popular green and low-carbon energy, develops rapidly in China. In general, the wind power can be divided into onshore and offshore wind power.

Currently, China's offshore wind power has accumulated 4.4 million kilowatts of grid-connected installed capacity, ranking 3rd in the world second only to the UK and Germany. Furthermore, China aims at reaching 75 GW offshore wind power in 2030, which will be mainly distributed in the offshore areas along Jiangsu, Fujian, Guangdong, Zhejiang and other coastal cities. Therefore, the offshore wind power generation has attracted a lot of attention.

On the other hand, with the development of VSC-HVDC, some of the wind farms transmit power through VSC-HVDC, such as Gotland project in Sweden [1], Tjaereborg project in Denmark [2], five terminal VSC-HVDC project in Zhejiang, China [3], etc. However, the wind power is stochastic, fluctuating and intermittent due to the wind. Therefore, with flexible interconnection of large-scale wind power and the power grid through power electronic devices, the frequency, which determined by the balance of the power generation and consumer, may deteriorate due to power imbalance and other factors such as the disturbance, the failure of wind turbines, the failure of DC line and so on. It may even threaten the safe and stable operation of the power grid [4], [5]. As so, it is necessary to study the frequency control strategy for the power system interconnected with the offshore wind power through VSC-HVDC.

In addition, with regard to stability control of the power system interconnected with the offshore wind power, most studies concentrate on the rotor-angle stability control [6], the voltage stability control [7], the damping control [8] and the steady state frequency control [9], while few of the

The associate editor coordinating the review of this manuscript and approving it for publication was Tariq Masood.

work concentrate on the transient frequency stability control. For example, ref. [6] presents a coordinated control strategy for the DC grid and offshore wind farms to improve rotor-angle stability of the onshore synchronous power system; ref. [7] presents an impedance-based system model to analyze and control voltage stability of offshore wind farms; ref. [8] presents a coordinated damping control through offshore wind farms and onshore VSC-HVDC converters to restrain power oscillation; ref. [9] develops the frequency regulation strategies for offshore wind farms at the device level.

Furthermore, with the viewpoint of the stability control measures, the control measures for the power system interconnected with large-scale wind power can be divided into following two categories. One is the special control embedded in the VSC-HVDC, such as DC voltage control in [10], [11] and active and reactive power control in [12], [13]. The other is the wind farm curtailment and generation tripping. For example, ref. [14], [15] analyze the difference between the curtailment of conventional thermal power units and wind turbines and propose an optimal curtailment scheme for serious faults. References [16], [17] design and develop the large cluster wind power intelligent control system which can realize the coordinated control of wind power and thermal power. The above control measures are control for the specific system, and not only lack of comprehensive control strategies including thermal units, wind power, DC and load shedding, but also lack of the consideration for the transient frequency stability.

In virtue of recognizing the above problems and facing the transient frequency stability problem engaged with SZ power grid, which is a power system interconnected with the offshore wind power through VSC-HVDC, this paper proposes an emergency control strategy for transient frequency stability of the offshore wind power system integrated through VSC-HVDC and verifies it with the above system. The contributions of this work are briefly summarized as follows:

(1) A mathematical model for the transient frequency stability control of the power system interconnected with the offshore wind power through VSC-HVDC is proposed. In this model, the minimum of the transient frequency stability index [18] and the curtailment of the wind power is taken as the objective, which comprehensively considers the transient frequency stability and incentive policy for the renewable energy power generation.

(2) The comprehensive control strategy for the transient frequency stability control is proposed. On the one hand, the sequence of emergency control measures is determined, which is first to adjust the output of thermal units and wind farms. Then, adjust the power transferred by the DC modulation, and the last step is load shedding. On the other hand, the amount of the control is determined with the principle of the assignment priority to the control with high sensitivity to the objective function, so this control scheme can restore transient frequency stability more quickly than the traditional one.

(3) For SZ power grid, the transient frequency stability is analyzed and the proposed method is verified.

The remainders of the paper are organized as follows. Section II introduces the SZ power grid and the transient frequency stability index, together with the transient frequency stability problem of SZ power grid. Section III presents the mathematical formulation for the transient frequency control, including the objective function and the constraints. Section IV proposes the control strategy based on special sequence and sensitivity. Section V presents the simulation results which verify the effectiveness of the proposed control strategy. And Section VI presents the conclusions.

II. SZ POWER GRID AND TRANSIENT FREQUENCY PROBLEMS

This section introduces the SZ power grid and the transient frequency stability index, together with the transient frequency stability problem of SZ power grid.

A. BRIEF INTRODUCTION OF SZ POWER GRID

This subsection gives a brief introduction of SZ power grid.

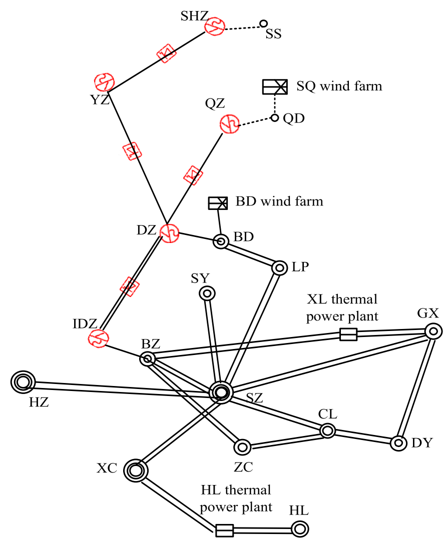

FIGURE 1. The backbone of SZ power grid.

SZ power grid is a typical power system interconnected with offshore wind power through VSC-HVDC, whose main topological structure is shown in Fig.1. It includes five terminal VSC-HVDC and two wind farms. The five DC converter stations are IDZ, DZ, QZ, YZ and SHZ, which all adopt the MMC technology [19]. SZ power grid is connected to the external large power grid through three double circuit lines, i.e., the SZ-HZ double-circuit line, the XC-SZ double-circuit line and the HL-XC double-circuit line.

B. TRANSIENT FREQUENCY STABILITY INDEX

This subsection introduces transient frequency stability index, and proposes the calculation formula suitable for SZ power grid.

The transient frequency stability index [18] of a power system can be the sum of the different frequency band integration with different weight, which can be expressed mathematically as follows:

$$F = \sum_{i=0}^{n} \sum_{j=1}^{m} K_j g\left(f\left[t_i\right]\right) \left|f\left[t_i\right] - f_N\right| \Delta t_i \tag{1}$$

where:

$$g\left(f\left[t_i\right]\right) = \begin{cases} 1 & \left(f_{j-1} \leq f\left[t_i\right] \leq f_j\right) \\ 0 & \left(f\left[t_i\right] < f_{j-1} \; or \; f\left[t_i\right] > f_j\right) \end{cases} \tag{2}$$

And K_j is the weight coefficient of the frequency band; $f[t_i]$ is the frequency at time t_i; f_N is the rated frequency of the power grid; Δt_i is the step length of frequency response calculation; and f_j is the upper/lower limit frequency of the frequency band (when the frequency is lower/higher than the rated frequency).

The calculation of the transient frequency index can be divided into following steps. First, dividing the range that the frequency response curve can reach into multiple frequency bands, and then, assigning different weights to different frequency bands. Finally, the transient frequency stability index can be obtained by weighted integration.

Furthermore, as stated in Ref [18], if $F \geq 1$, the transient frequency of the system will be unstable, and then, corresponding control measures should be taken; if $F < 1$, the transient frequency of the system will be stable.

For SZ power grid, the frequency of the first round of under frequency load shedding is 49.0 Hz. The frequency deviation of the small system cannot exceed ±0.5 Hz, and the range of normal frequency deviation is ±0.2 Hz. Therefore, the transient frequency response curve is divided into three frequency bands from low to high, which are lower than or equal to 49.0 Hz, 49.0-49.5 Hz and 49.5-49.8 Hz respectively. Consider that the duration of the frequency lower than 49.0 Hz shall not exceed 0.3 s; the duration of the frequency lower than 49.5 Hz shall not exceed 10 s; the duration of the frequency lower than 49.8 Hz shall not exceed 10 min, i.e., the weight coefficient corresponding to different frequency bands shall meet the formula as shown in (3):

$$\begin{cases} F = K_1 \times (50 - 49.0) \times 0.3 = 1 \\ F = K_2 \times (50 - 49.5) \times 10 = 1 \\ F = K_3 \times (50 - 49.8) \times 600 = 1 \end{cases} \tag{3}$$

The weight coefficient can be calculated from (3), and the transient frequency stability index suitable for SZ power grid can be further obtained as shown in (4):

$$\begin{aligned} F = &(3.3333 \times \sum_{i=0}^{n_i} \left|f[t_i] - f_N\right| \\ &+ 0.2 \times \sum_{l=0}^{n_l} \left|f[t_l] - f_N\right| \\ &+ 0.0083 \times \sum_{p=0}^{n_p} \left|f[t_p] - f_N\right|) \times \Delta t \end{aligned} \tag{4}$$

TABLE 1. The transient frequency stability index in different conditions.

Condition	Short circuit	Maintenance	F
Case 1：Normal	/	/	0
Case 2：N-2	XC-SZ	/	0.0019
Case 3：N-4	XC-SZ	HZ-SZ	79.5922
Case 4：N-6	HZ-SZ	XC-SZ; BZ-SZ	80.8321

Note: according to the actual situation, the frequency band division points of SZ power grid in this paper are 49.0 Hz, 49.5 Hz and 49.8 Hz while the frequency band division points in [18] are 48.8 Hz, 49.0 Hz and 49.5 Hz.

C. THE TRANSIENT FREQUENCY PROBLEMS OF SZ POWER GRID

In this subsection, the transient frequency stability of SZ power grid under different disturbances is quantitatively analyzed.

Consider the following four cases which are engaged with different disturbances and operation conditions.

Case 1: wind power suddenly drops

Wind turbines of BD and SQ both have a sudden power drop of 300MW.

Case 2: N-2 + wind power suddenly drops

(a) On the SZ side of XC-SZ line, one circuit has a three-phase short circuit, and the other circuit also has a three-phase trip;

(b) Wind turbines of BD and SQ both have a sudden power drop of 300MW.

Case 3: N-4 + wind power suddenly drops

(a) HZ-SZ line is under maintenance;

(b) On the SZ side of XC-SZ line, one circuit has three-phase short circuit, and the other circuit also has three-phase trip;

(c) Wind turbines of BD and SQ both have a sudden power drop of 300MW.

Case 4: N-6 + wind power suddenly drops

(a) BZ-SZ line and XC-SZ line are under maintenance;

(b) On the SZ side of HZ-SZ line, one circuit has a three-phase short circuit, and the other circuit also has a three-phase trip;

(c) Wind turbines of BD and SQ both have a sudden power drop of 300MW.

After the disturbances occur, the transient frequency stability index calculated by (4) is shown in Table 1, and the frequency response curve of SZ bus is shown in Fig. 2 and Fig. 3.

Fig. 2 shows that when wind power suddenly drops in the normal condition and N-2 condition, the frequency of SZ power grid fluctuates slightly. As is calculated that the transient frequency stability index $F < 1$, it can be inferred that the transient frequency of SZ power grid can remain stable in both cases.

Fig. 3 shows that when the wind power suddenly drops in the N-4 and N-6 condition, the frequency of SZ power

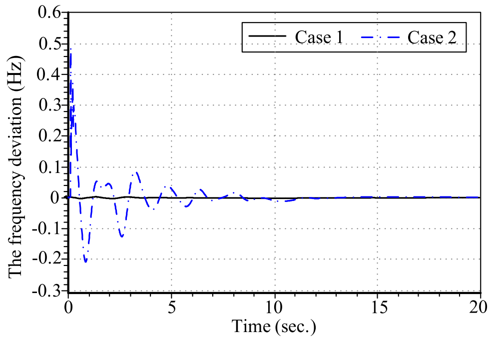

FIGURE 2. Frequency deviation of SZ system in Case 1 and Case 2.

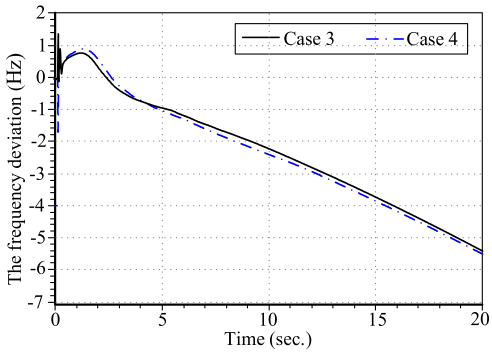

FIGURE 3. Frequency deviation of SZ system in Case 3 and Case 4.

grid will drop. As is calculated that the transient frequency stability index $F > 1$, it can be inferred that the transient frequency of the system is unstable in both cases, and the transient frequency control strategy is needed.

III. MATHEMATICAL FORMULATION FOR THE TRANSIENT FREQUENCY CONTROL

This section presents the mathematical formulation for the transient frequency control, including the objective function and the constraints.

A. OBJECTIVE FUNCTION

For the transient frequency control, the first objective is to ensure the transient frequency of the power system. Once the system is not transiently stable, various control measures (such as thermal units regulation, wind power regulation, DC modulation, load shedding, etc.) can be taken to restore the stability of the system. However, considering the incentive policy for maximum production of the renewable energy power generation, the curtailment of renewable energy should be avoided as much as possible. Therefore, the minimum of the transient frequency stability index and the curtailment of wind power can be served as the objective function of the transient frequency control. Mathematically, the objective of the emergency control strategy for the transient frequency stability of the power system with renewable energy can be described as follows:

$$\min J = \alpha F + \beta \sum_{j=1}^{n_2} C_j u_{2,j} \tag{5}$$

where n_2 is the number of adjustable wind turbines; u_{2j} is the adjustment values of wind turbines at node j; C_j is the weight coefficient of corresponding wind turbines; α and β are weight coefficients of the transient frequency stability index and the adjustment value of the wind turbine respectively.

B. CONSTRAINTS

In the actual power grid, the implementation of control measures is constrained by many conditions, including equality constraints and inequality constraints.

For the electric power system with renewable energy, the equality constraints include power flow constraints, dynamic constraints and network constraints; inequality constraints include operation inequality constraints, stability inequality constraints and constraints for the control measures. The specific constraints are as follows.

(a) Power flow constraints

In the electric power system, the power flow constraint is used to represent power balance. The active power and reactive power of each node satisfy the following equality constraints.

$$\begin{cases} P_{Gi} - P_{Li} - P_i(V,\theta) = 0 \\ Q_{Gi} - Q_{Li} - Q_i(V,\theta) = 0 \end{cases} \tag{6}$$

where,

$$\begin{cases} P_i(V,\theta) = \sum_{j=1}^{n} \left(V_i V_j B_{ij} \sin\theta_{ij} + V_i V_j G_{ij} \cos\theta_{ij}\right) \\ Q_i(V,\theta) = \sum_{j=1}^{n} \left(V_i V_j G_{ij} \sin\theta_{ij} - V_i V_j B_{ij} \cos\theta_{ij}\right) \end{cases} \tag{7}$$

where P_{Gi} and Q_{Gi} are the active power and reactive power of the generator at the node i; P_{Li} and Q_{Li} are the active power and reactive power consumed by the load at the node i; V_i and V_j are the voltage amplitude of the node i and the node j respectively; θ_{ij} is the voltage phase angle difference between the node i and the node j; $Y_{ij} = G_{ij} + jB_{ij}$ is the admittance matrix; n is the total number of nodes.

(b) Dynamic equality constraints

The dynamic equality constraints reflect the dynamic process of the system, mainly including the dynamic equation of the generator and the load, as shown in (8) and (9) respectively.

$$\begin{cases} \dot{\delta}_i = \omega_i \\ M_i(u,t)\dot{\omega}_i = P_{mi}(x,y,u,t) - D_i(u,t)\omega_i - P_{ei}(x,y,u,t) \end{cases} \tag{8}$$

$$\begin{cases} P_{Li}(u,t) = P_{0i}\left(p_1 V_i^2 + p_2 V_{0i} + p_3\right)\left(1 + K_{fp}\Delta f\right) \\ Q_{Li}(u,t) = Q_{0i}\left(q_1 V_i^2 + q_2 V_{0i} + q_3\right)\left(1 + K_{fq}\Delta f\right) \end{cases} \tag{9}$$

where δ is the power angle; Ω is the electric angular speed; x is the state variable; y is the algebraic variable; u is the control variable of the emergency control measures, which represents the adjustment values of the thermal units, the wind turbine, the DC power and the load, etc.; t is the time. P_{Li} and Q_{Li} are the actual active power and reactive power of the load; P_{0i} and Q_{0i} are the active power and reactive power of the load during the steady-state operation at the reference point; p_1, p_2, p_3 are the percentages of the active power of the constant impedance, constant current and constant power load in the total active power; q_1, q_2, q_3 are the percentages of the reactive power of the constant impedance, constant current and constant power load in the total reactive power; K_{fp} and K_{fq} are active and reactive frequency characteristic indexes of the load; V is voltage; Δf is frequency variation.

(c) Network equality constraints

The power flow in an electric power network obeys the physical law, which can be stated as the network constrains, which are algebraic equations as shown in (10).

$$\begin{pmatrix} \begin{pmatrix} -B_{11} & G_{11} \\ G_{11} & B_{11} \end{pmatrix} & \cdots & \begin{pmatrix} -B_{1m} & G_{1m} \\ G_{1m} & B_{1m} \end{pmatrix} \\ \vdots & \cdots & \vdots \\ \begin{pmatrix} -B_{m1} & G_{m1} \\ G_{m1} & B_{m1} \end{pmatrix} & \cdots & \begin{pmatrix} -B_{mm} & G_{mm} \\ G_{mm} & B_{mm} \end{pmatrix} \end{pmatrix} \begin{pmatrix} \begin{pmatrix} V_{y1} \\ V_{x1} \end{pmatrix} \\ \begin{pmatrix} V_{ym} \\ V_{xm} \end{pmatrix} \end{pmatrix} = \begin{pmatrix} \begin{pmatrix} I_{x1} \\ I_{y1} \end{pmatrix} \\ \begin{pmatrix} I_{xm} \\ I_{ym} \end{pmatrix} \end{pmatrix} \tag{10}$$

where $G_{ij}+jB_{ij} = Y_{ij}$ is the element in the admittance matrix; $I_{x1}+jI_{y1} = \dot{I}_i$ and $V_{x1}+jV_{y1} = \dot{V}_i$ are the elements in $\dot{\boldsymbol{I}}$ and $\dot{\boldsymbol{V}}$ respectively.

(d) Operation inequality constraints

In the operation, the power system should operate in certain range, i.e., the active/reactive power of the generator (load), node voltage, frequency and line power flow have some limits. Mathematically, they can be stated as follows.

$$\begin{cases} P_{Gi}^{\min} < P_{Gi} < P_{Gi}^{\max} \\ Q_{Gi}^{\min} < Q_{Gi} < Q_{Gi}^{\max} \\ V_i^{\min} < V_i < V_i^{\max} \\ f_i^{\min} < f_i < f_i^{\max} \\ S_{ij}^{\min} < S_{ij} < S_{ij}^{\max} \end{cases} \tag{11}$$

(e) Stability inequality constraints

In the operation, the system should be stable. Furthermore, the system should leave some margin away from the critical stable state [20]. Thus, for the transient frequency, the index should be within the certain range. Mathematically, it can be stated as follows.

$$F \leq F_{up} \tag{12}$$

where $F_{up} < 1$.

Note: Other stability problems such as transient angle stability and voltage stability are not considered, as the frequency stability is focused on in this paper.

(f) Constraints for the control measures

The inequality constraints for the control measures (which can be the values of power adjustment, etc.) are as shown in (13).

$$u_i \leq u_{ip\max} \tag{13}$$

where $u_{ip\max}$ is the maximum control value that device i can provide; u_i is the actual control value.

IV. PROCESS OF EMERGENCY CONTROL STRATEGY

This section presents the method to determine the control strategies of (5) based on sensitivities.

For the optimization problem (5), the sensitivities of the control measures (such as thermal units regulation, wind power regulation, DC modulation, load shedding, etc.) with respect to the objective function under various operating conditions, can be obtained from the historical data and even form a sensitivity database with respect to different operation conditions. The sensitivity can be expressed as follows:

$$S_e = \Delta J/u \tag{14}$$

where ΔJ is the change of the objective function and u is the adjustment value of the active power (controllable variable).

Based on the above sensitivity database, the general process of the online transient frequency stability emergency control strategy can be stated as three steps, as shown in Fig. 4.

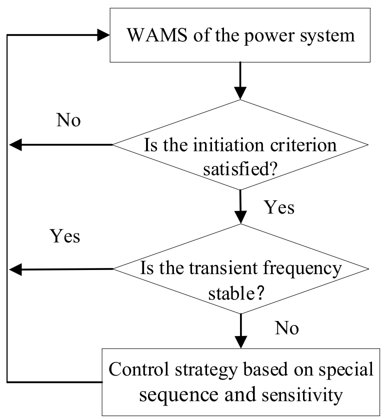

FIGURE 4. General process of transient frequency emergency control.

The details of three steps in Fig.4 are as follows.

Step 1: Detect the critical state of the power system. Monitor the system frequency with PMU/WAMS. When the frequency deviation exceeds ± 0.2 Hz, it indicates that the system suffers from large disturbance, and the transient frequency stability calculation will start.

Step 2: Determine the transient frequency stability of the power system fast according to the frequency data obtained from PMU/WAMS and the proposed transient frequency stability index.

Step 3: Determine the control scheme based on the sequence of emergency control measures and sensitivity.

Furthermore, the sequence of emergency control measures in Step 3 is shown in Fig. 5. That is to say, adjust the output of thermal units and wind farms first, and then, adjust the

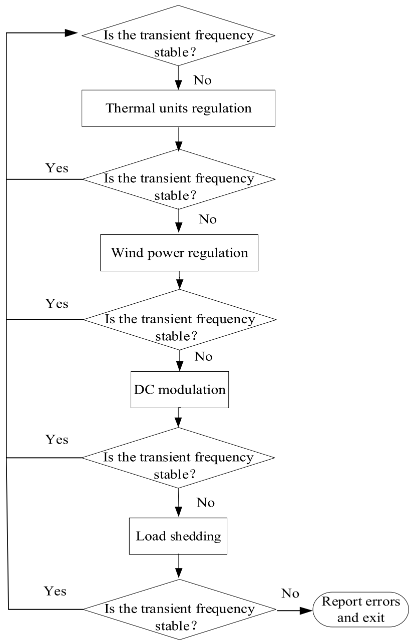

FIGURE 5. **The sequence of transient frequency emergency control.**

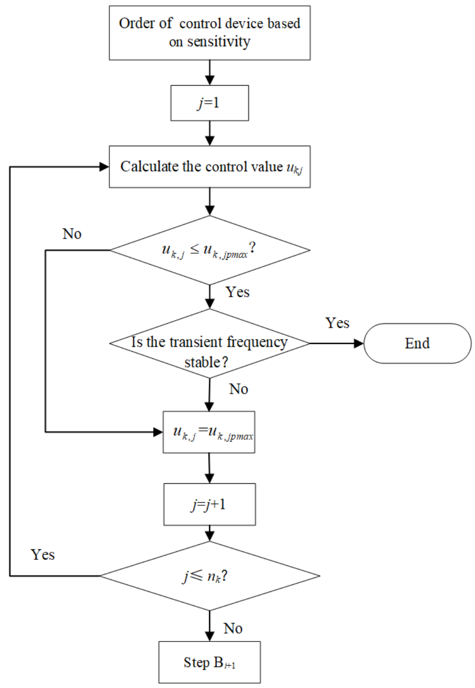

FIGURE 6. **The control scheme based on sensitivity.**

power transferred by the DC modulation. Finally, adjust the load (load shedding) in turn. In detail, it is as follows.

Step B_1: Adjust the output of thermal units. If the system is stable, then the work can be done. Otherwise, go to Step B_2.

Step B_2: Adjust the output of wind farms. If the system is stable, then the work can be done. Otherwise, go to Step B_3.

Step B_3: Adjust the output of the power transferred by the DC modulation. If the system is stable, then the work can be done. Otherwise, go to Step B_4.

Step B_4: Execute the load shedding until the system is stable.

Moreover, for each step B_k $(k = 1, 2, 3, 4)$, the amount of the control is determined with the principle of the assignment priority to the control based on sensitivity, as shown in Fig. 6. In details, it can be stated as follows.

Step D_{k1}: Calculate the sensitivity of each control device to the objective function in step B_k and rank it from large to small, which is $S_{a_{k,1}}, S_{a_{k,2}}, S_{a_{k,3}}, \ldots S_{a_{k,n_k}}$.

Step D_{k2}: Select the device $a_{k,j}$ $(j = 1, 2, 3, \ldots n_k)$ as the device to implement the control according to the sensitivity order of Step D_{k1}. Set $j = 1$.

Step D_{k3}: Calculate the control value which is needed to stabilize the system according to the sensitivity of the selected device $a_{k,j}$ and the objective function, i.e.,

$$u_{k,j} = J/S_{a_{k,j}} \tag{15}$$

If the required control value is no more than the value that the device $a_{k,j}$ can provide, i.e.,

$$u_{k,j} \le u_{k,jp\max} \tag{16}$$

Verify the stability of the system under this controller, and then, the control will be obtained.

Otherwise, set $u_{k,j} = u_{k,jp\max}, j = j + 1$.

Step D_{k4}: If $j \le n_k$, i.e., the device that has not been adjusted exits, return to step D_{k3}. If $j > n_k$, i.e., all devices have been adjusted, go to step B_{k+1}.

Note: in order to ensure the stability of the system, it is necessary to verify whether the transient frequency of the system is stable after the selected control devices implement the control scheme in this process.

V. SIMULATION RESULT

In this section, the effectiveness of the control strategy is verified by simulation of the unstability in Section II. Section II shows that when the wind power suddenly drops in the N-2, N-4 and N-6 condition, the frequency deviation exceeds ±0.2Hz, and the transient frequency stability calculation should start. As shown in Table 1, when the wind power suddenly drops in the N-4 and N-6 condition, the transient frequency of SZ power grid is unstable, so it is necessary to take control measures.

For the objective function in (5), we set $\alpha = 0.9$, $\beta = -0.1$, $C_1 = C_2 = 0.5$, so the objective function J is shown as (17).

$$J = 0.9F - 0.1\sum_{j=1}^{2} 0.5u_{2,j} \tag{17}$$

According to the emergency control strategy in Section IV and the sensitivity sequence shown in Table 2, the sequence

TABLE 2. The sensitivity of different control measures.

Control measures	S_e in Case 3	S_e in Case 4
Adjust the output of thermal units in XL	0.2588	0.2587
Adjust the output of thermal units in HL	0.1112	0.1110
Adjust the output of the wind farm in BD	0.1059	0.1054
Adjust the output of the wind farm in SQ	0.1055	0.1051
Adjust the power transmitted by the DC modulation	0.1037	0.1030
Shed the load	0.0988	0.0964

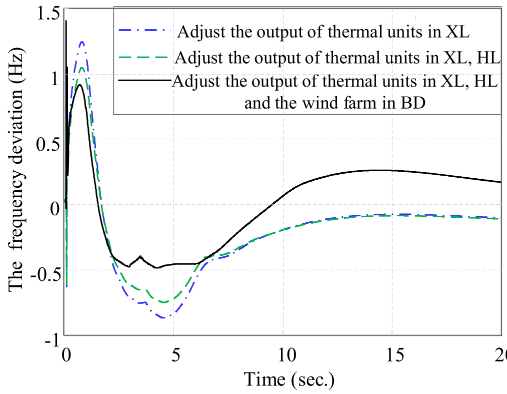

FIGURE 7. Frequency deviation of SZ power grid after taking emergency control measures in Case 3.

of transient frequency stability emergency control measures is as follows:

(1) Adjust the output of thermal units in XL;
(2) Adjust the output of thermal units in HL;
(3) Adjust the output of the wind farm in BD;
(4) Adjust the output of the wind farm in SQ;
(5) Adjust the power transmitted by the DC modulation;
(6) Shed the load.

For Case 3 in Section II, the simulation results of transient frequency stability emergency control are shown in Table 3 and Fig.7 respectively. They show that as the adjustment amount is gradually allocated according to the control strategy, F and J become smaller and smaller until the transient frequency is stable. It is worth noting that the transient frequency is still unstable even adjusting the output of thermal units in XL, HL to the maximum value, which means it needs to shed the load according to the traditional control scheme while according to the control strategy proposed in this paper, the output of the wind farm in BD can be adjusted to maintain transient frequency stability and avoid load shedding.

Similarly, for Case 4 in Section II, the simulation results of transient frequency stability emergency control are shown in Table 4 and Fig.8 respectively. They also show that after taking the control strategy, F and J become smaller and smaller until the transient frequency is stable. Compared with Case 3, F and J are larger and the changes of F and J are smaller when adjusting the same amount active power due to the more serious system fault. And the same measures as Case 3 can not keep the transient frequency stable, and the output of thermal units in XL, HL and the wind farm in BD, SQ need to be adjusted at the same time.

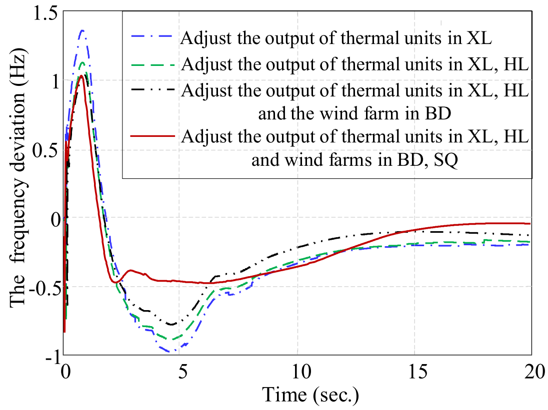

FIGURE 8. Frequency deviation of SZ power grid after taking emergency control measures in Case 4.

TABLE 3. The transient frequency stability index after taking emergency control measures in Case 3.

Faults and control measures	F	J
N-4+Wind power drops by 300MW	79.5922	71.6330
Adjust the output of thermal units in XL	7.7015	6.9314
Adjust the output of thermal units in XL, HL	1.5264	1.3738
Adjust the output of thermal units in XL, HL + Adjust the output of the wind farm in BD	0.9053	0.3148

TABLE 4. The transient frequency stability index after taking emergency control measures in Case 4.

Faults and control measures	F	J
N-6+Wind power drops by 300MW	80.8321	72.7489
Adjust the output of thermal units in XL	8.9714	8.0743
Adjust the output of thermal units in XL, HL	2.8063	2.5257
Adjust the output of thermal units in XL, HL + Adjust the output of the wind farm in BD	1.5742	0.4168
Adjust the output of thermal units in XL, HL + Adjust the output of wind farms in BD, SQ	0.9621	-0.6341

Note: The transient frequency stability margin is set to 0.02. That is, when $F \leq 0.98$, the transient frequency is considered stable.

Thus, the transient frequency of SZ power grid is stable after the control strategy is adopted, i.e., the control strategy is effective.

VI. CONCLUSION

Taking SZ power grid as an example, a transient frequency stability control model is established according to the characteristics of the power system interconnected with offshore wind power through VSC-HVDC, and a transient frequency stability emergency control strategy based on special sequence and sensitivity is proposed. It shows by simulation that the transient frequency of SZ power grid is unstable when the wind power suddenly drops in the N-4 and N-6 condition, and the transient frequency regains stability after the control strategy is adopted, which verifies the effectiveness of the control strategy.

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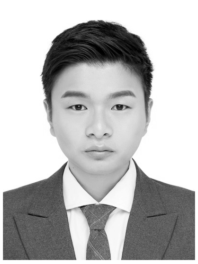

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