Analysis based on the Phase Entry Test of Pumped Storage Power Station Units

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Abstract: The phase entry operation of synchronous generator is an economical and efficient measure to solve the excess reactive power and high voltage during the off-peak operation of power grid. A Pumped Storage Unit has a series of phase entry test before it's commercial operation. In this way, it can examine the low excitation limit ability of the excitation regulator under different working conditions, and also verify the regulation ability of the phase entry operation on the power grid voltage of 500kV system. Through the four Pumped Storage Units' advanced test, it summarizes the actual leading capacity, limiting factors of generation/motor, and the regulation effect, influence on 500kV voltage of power grid, analyzes the excitation regulator's effect on improving generation/motor phase entry capacity and static/dynamic stability. Finally, it determines the safe operating range of the generation/motor phase entry, and determines the rationality of the main transformer and high plant transformer connection position. It guarantees for the safe and stable operation of the power grid by the phase advancement capability analysis.

Keywords: Generation/Motor; Phase Entry; Excitation; Low Excitation Limit

1. Introduction

At present, the national power grid system is growing larger. As a special power source in the grid, pumped storage power stations undertake tasks such as peak shaving, valley filling, frequency regulation, phase regulation, and emergency backup [1]. The vigorous development of pumped storage power stations is in line with the country's green development concept of "carbon peak and carbon neutrality" [2]. The grid connection of pumped storage units enhances the safe and stable operation capacity of the power grid and contributes to the development goal of building a strong power grid.

When there is an excess of reactive power and the system voltage is too high during the off-peak operation of the power grid, in order to improve the power quality of the power grid, it is an economical, effective and feasible method to adopt the phase-advancing operation method of the unit to consume the excess reactive power of the system and keep the system voltage within the allowable range. For the power generation/electric units of pumped storage power stations, there are two reversible operation modes: power generation and water pumping [3]. When operating in different directions, the amount of reactive power absorbed by the unit in the system depends on the phase advancement capacity under that condition. To improve the power quality of the power grid as much as possible while ensuring the safe operation of the units themselves, the phase advance limit of the units is determined through phase advance tests, and the low-excitation limit of the excitation system is utilized to protect the safe operation of the units [4]. Based on the operational characteristics of a certain pumped storage unit, phase advance tests were conducted respectively under the conditions of power generation, pumped phase regulation and pumped pumping, and the actual phase advance capabilities of the four units under different working conditions were analyzed. Analyze the limiting factors of its influence; Verify the low-excitation limiting capability of the excitation regulator, its role in enhancing the phase advancement capacity of power generation/motors, and its static/dynamic stability. The regulation effect of the units on the 500kV voltage of the power grid was investigated, and the phase advancement characteristics of each of the four units were obtained.

2. Test Purpose

When the reactive power of the power grid system is excessive and the system voltage is too high, the voltage regulation ability of the unit is used to make the unit enter phase operation to adjust the system voltage [5]. The phase entry test is used to protect the unit runs within its safety and stability when entering the phase.

3. Test Principle

The normal operating state of the generator is to provide active and reactive power to the system, which is called the generator in the hysteresis phase operation state. The incoming operation of the generator is to provide active power and absorb reactive power from the system [6]. The process of the generator from hysteresis operation to phase operation is manifested in the process of reactive power from generation to absorption [7]. This feature is used to absorb the local reactive power excess of the system and solve the problem of high voltage. There are a variety of limiting factors in the phase operation of the generator, and only by meeting these constraints can we ensure the safe and stable operation of the generator set [8].

4. Test Methods and Restrictions

4.1 Test Methods

The test is carried out after the normal operation of the power generation motor with the load connected to the grid. The test process is divided into two stages: power generation working condition and electric working condition. The power generation working condition includes phase entry test under 100% active load, 75% active load, 50% active load and 0% active load [9].

During the phase incoming test, the test unit operates under automatic excitation mode, and the active power of the test unit remains unchanged, and the cooling system of the power generation motor is not adjusted.

1) Connect the measuring instrument to the device. The voltage at the end of the unit is connected to the test instrument from the on-site control cabinet, and the speed signal of the unit is connected to the tester from the electrical cabinet of the governor to analyze the power angle of the generator.

2) Protection Check. Check that the protection device of the power generation motor is normal, there is no alarm signal, and the demagnetization protection signal is put into service; Check that the excitation regulator is running normally, there is no alarm signal, and temporarily modify the low excitation limit value.

3) Test process. Select the power generation condition to start, select the corresponding active load under the power generation condition and electric working condition, adjust the reactive power by manually adjusting the "increase/decrease" knob of the excitation regulator, observe the generator end voltage, 500kV bus voltage, generator stator current, factory power 10kV and 400V voltage, stator core temperature and stator winding temperature at each reactive load point, and pay attention to whether there are other alarm signals in the monitoring system [10].

4.2 Restrictions

When the generator enters into phase, the stator voltage of the generator decreases, the stator current increases, the static stability limit decreases, the dynamic stability weakens, the temperature rise of the core at the end of the stator increases, the power voltage of the plant decreases. These are all constraints that restrict the phase operation of the generator. The demagnetization should be stopped when the unit parameters reach the following parameters. (The following parameters are determined according to the rated parameters of a power station).

1) The stator voltage of the unit shall not be less than 90% of the rated voltage (16.2kV);

2) The stator current of the unit shall not be greater than the rated current of 10691.67A;

3) the stator core temperature is less than 120°C, the temperature of the stator coil is less than 105°C, the hot air temperature of the air cooler is less than 70°C, and the cold air temperature of the air cooler is less than 40°C;

4) The power bus voltage of the high-voltage plant shall not be less than 90% of the rated load voltage (9.45kV);

5) The power voltage of the 400V plant shall not be less than 360V;

6) The system bus voltage shall not be lower than the allowable range of the dispatching department;

7) The power angle doesn’t exceed the theoretical calculation when entering the phase;

8) Minimum excitation current limit.

5. Test Results and Data Analysis

The power station has 4 vertical shaft

single-stage mixed-flow pump turbine-power generation motor units with a single capacity of 300MW.Each unit is equipped with a three-phase double-winding forced oil circulation water cooling, 360MVA, 500kV power transformer. The four units were tested under two working conditions, and the motor used two active loads of -300MW and 0MW. The generator uses four active loads, 300MW, 225MW, 150MW, and 0MW.

5.1 Test Data Analysis

Record the electrical parameters such as unit power angle, stator voltage, stator current, 10kV factory bus voltage, 400V low-voltage factory bus voltage, main transformer high-voltage side voltage and the highest temperature of each part of the generator during the test process. After comprehensive measurement, the phase advance depth is determined, and the low excitation limit setting value of the excitation regulator is obtained.

5.1.1 Electrical data

Comparing the test data of the four units, the corresponding constraints are the same. Taking Unit 3 as an example, the pumping phase modulation working conditions, pumping full load conditions, power generation 100% load conditions, power generation 75% load conditions, power generation 50% load working conditions, and power generation phase modulation conditions are recorded respectively, as shown in Table 1.

Table 1. Electrical Data of Unit 3

Working conditions	serial number	active power(MW)	Reactive power(Mvar)	power angle(°)	Stator voltage(kV)	Stator current(kA)	10kV factory bus voltage(kV)	400V factory bus voltage(V)
motor	1	-5.88	-175.36	0.72	16.20	6267.00	10.39	392.00
	2	-300.90	-83.68	37.80	17.05	10691.7	10.38	393.00
generator	3	299.97	-94.52	42.84	16.95	10691.7	10.35	394.00
	4	225.19	-165.10	45.00	16.20	9677.00	10.38	395.00
	5	148.50	-171.94	36.00	16.20	8050.00	10.40	493.0
	6	-5.81	-175.36	1.80	16.20	6248.00	10.40	389.00

Under the phase modulation condition of pumping water (-5.88 MW), the phase advance depth reaches -175.36Mvar. The main limitation is that the voltage at the generator end reaches the lower limit of 16.20kV. Under the pumping condition (-300.90MW), the phase advance depth reaches -83.68Mvar, and the main limiting condition is that the current at the machine end increases to the limit value of 16091.70A. Under the 100% load condition (299.97MW) of power generation, the phase advance depth reaches -94. 52Mvar, and its main limiting condition is that the current at the machine end increases to the limit value of 16091.70A; Under the load condition of 75% of the power generation (225. 19MW), the phase depth reaches -165.l0Mvar, and the main limitation is that the generator end voltage reaches 16.20kV;Under the 50% load condition (148.50MW), the phase advance depth reaches -171.94Mvar, and the main limiting condition is that the generator terminal voltage reaches the lower limit of 16.20kV, and under the power generation phase modulation condition (-5.81MW), the phase advance depth reaches -175.36Mvar, and the main limitation generator terminal voltage reaches the lower limit of 16.20kV.

5.1.2 Effect of phase depth on 500kV system voltage

Take the voltage at CT on the high voltage side of the main transformer as the 500kV system voltage, and also take the data of Unit 3 as an example to measure 6 test load points under two working conditions. The voltage change of the main transformer high voltage with side from zero to the maximum phase depth of reactive power is shown in Figure 1.

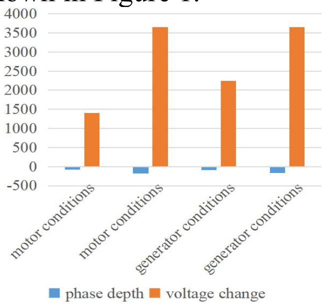

Figure 1. Phase Intake Depth and Voltage Change Meter on the High Voltage Side of the Main Transformer

As can be seen from Figure 1, under pumping conditions, the system voltage decreases by 1.4kV; the system voltage decreases by 4.6kV under pumping phase modulation conditions. The phase operation of Unit 3 under different loads can reduce the system voltage by 500kV and have a significant voltage regulation effect. This process also verifies the proper position of the main transformer and the high plant transformer.

By comparing the other three units, they all have the same effect as Unit 3.

5.1.3 The depth of phase and the temperature rise of each part of the unit

During the test, monitor the temperature change of the unit by installing temperature measuring points. As shown in Table 2.

Table 2. The Depth of Phase and the Temperature Rise of Each Part of the Unit

the temperature rise of each part of the unit(°C) load(MW)	stator core(°C)	pressure finger temperature(°C)	stator coil temperature(°C)	hot air temperature of air cooler(°C)	cold air part temperature of air cooler (°C)
-5.68(Pumping water condition)	47.20	50.20	45.90	41.80	26.40
-307.80(Motor working condition)	49.60	62.30	63.80	46.10	26.90
299.80(Generator condition)	51.70	69.20	70.90	48.10	26.80
223.00(Generator condition)	48.70	58.90	58.10	46.50	26.00
146.90(Generator condition)	47.30	52.00	52.30	44.00	25.70
-5.20(Generator condition)	51.20	56.40	52.00	44.50	26.60

As can be seen from Table 2, under any working conditions, the stator core temperature, pressure finger temperature, stator coil temperature, hot air temperature of air cooler, and cold air part temperature of air cooler of Unit 3 are all within the limit values.

5.1.4 The low excitation limit setting value of excitation regulator

Through the comprehensive analysis of the electrical and non-electrical data during the phase intake test, the reactive power corresponding to the active power measured in Table 1 under different working conditions is determined to be the maximum phase advance capacity of the unit. The same setting value is taken as the low excitation limit setting value of the excitation regulator, as shown in Table 3 below.

Table 3. Low Excitation Limit Set Value

	Pumping working conditions		Power generation working conditions			
active power (MW)	-300	-0	300	225	150	0
reactive power (Mvar)	-75	-160	-90	-155	-165	-170

5.2 Checking the Function of the Static Limit

For hydro turbine power generation/motor, when different active power is emitted, its ultimate power angle decreases with the decrease of active power. During the test, the work angle is set with a safety margin of 10°relative to the ultimate work angle, as shown in Table 4.the test records that when different active power is emitted, the power angle of units 1~4 is shown in Table 5.

Table 4. The Ultimate Power Angle at Different Active Powers

Working conditions	motor	generator			
	-300MW	300MW	225MW	150MW	0MW
power angle(°)	-52.9	52.9	50.5	45.3	0

Table 5. Comparison of the Power Angle of the Four Units under Different Active Power

number	unit	active power(MW)	reactive power(MW)
1 (-300MW)	1#	-300	-41.4
	2#	-307.8	-37.08
	3#	-300.9	-37.08
	4#	-301.49	-36.4
2(0MW)	1#	-5.6	1.8
	2#	-5.68	0.9
	3#	-5.88	0.72
	4#	-5.84	1.08
3(300MW)	1#	303.2	41.67
	2#	299.8	40.32
	3#	299.97	42.84
	4#	307.25	44.64
4(225MW)	1#	225.67	46.1
	2#	223	43.2
	3#	225.19	45
	4#	224.41	48
5(150MW)	1#	150.3	43.74
	2#	146.9	39.96
	3#	148.5	36
	4#	147.03	38.88

Through the data analysis in Table 5, it can be found that the active power of Units 1#~4# is 300MW and the unit is running under pumping conditions, the work angle after entering the phase is within the range of -52.9°;When the active power of unit is 0MW and running under the condition of pumping water phase modulation, the maximum work angle after entering the phase is 1.8°, which is very small; When the 1#~4# unit is running under power generation conditions, under 100% active load, 75% active load, and 50% active load, the work angle after entering the phase is within the corresponding range of Table 4； When the active load is 0%, the unit is operated under the phase modulation condition of power generation, and the minimum active power of the unit is set to -5MW, and the phase intake depth is not greater than 2°.

In comprehensive comparison, under different working conditions, when the corresponding phase intake depth is reached, the phase intake power angle is within the safe range, which meets the requirements of the static stability limit of the unit.

5.3 Check the Accuracy of the Excitation Regulator with Low Excitation Limiting Action

The static and dynamic characteristics of the low excitation limit of the excitation regulator are checked by the phase incoming test, and the low excitation limit is tested by slowly reducing the excitation current in the static characteristic check test. The dynamic characteristic verification test is realized by the step test under a given voltage.

5.3.1 Static characteristic verification

Through data analysis, it is found that when the active power of the four units is 300MW, 225MW, 150MW and 0MW respectively, the minimum deviation value of the actual operation value is 0, the maximum deviation value is ±2, and the actual operating value is within the limit setting value ±2. The test proves that the low excitation limit can operate reliably under the power generation condition and pumping condition.

5.3.2 Dynamic Characteristic Verification

The low excitation limit value of the excitation regulator under 300MW load is set to -90Mvar, and a quick reduction (step amount of 2%) is applied to a given voltage. When the reactive power reaches the low excitation limit setting value, the low excitation limit action. The reactive power of the 1# unit is maintained around the value of 92 Mvar, and the reactive power of the 2#, 3#, and 4# units are maintained around the value of 90Mvar.The excitation regulator can play a role in limiting the low excitation limit of the unit. The dynamic verification diagram of low excitation limit is shown in Figure 2 .

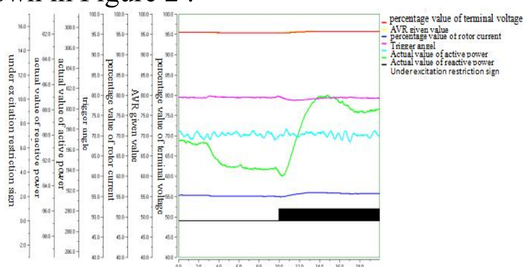

Figure 2. Dynamic Check Diagram with Low Excitation Limit

6. Conclusion

By using the same test method and test conditions for the four units of pumped storage power station, the test data are uniformly compared and analyzed. The test shows that the phase intake depth of the four units under the corresponding working conditions is similar, and the same low excitation limit setting value and the same unit P-Q curve. Through this test, it ensures the safe and stable operation of the unit, the consumption of new energy in the power grid, and the safety and economy of the power grid.

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