Study on Optimization of Control Strategy for Pump Shutdown in Pumped-Storage Unit

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Abstract. In view of the formulation of power failure control strategy of pumped-storage unit at pump operation condition caused by hydraulic, mechanical and electrical factors, taking Heimifeng pumped-storage power station as an example, downtime control strategy at the pump working condition were analyzed under different heads. The transition characteristics at the pump condition of power outage for different guide vane opening were discussed. The stability parameter variation characteristics for the key points of vibration/sway and pressure pulsation at the process of shutdown were analyzed. Combination the GCB characteristics of unit, the optimal load and the guide vane opening in the power outage process of shutdown at pump working condition were determined, and the electric life. The optimized shutdown strategy can ensure the safe operation of the unit, and the shutdown load can meet the requirements of the industry standard.

Keywords: Pumped-storage unit, Pump operation condition, Transient process, Stability, Shutdown strategy

1. Introduction
As the only pumped-storage power station in Hunan Province, Heimifeng Power Station undertakes the functions of system backup and main peak-modulation. After the UHV power grid is put into Hunan, the unit starts and stops more frequently, which puts forward higher requirements for the reliability of equipment. Heimifeng power station unit pump working condition of power outage strategy is given on the basis of the turbine manufacturer of conductance leaves opening, namely when the guide vane opening exports to 18% open circuit power motor circuit breaker (GCB), the actual power unit when the input power doesn’t meet the industry standards [1] of less than 33% of the rated input power.

The formulation of the power off control strategy for pump shutdown in pumped-storage unit is influenced by water, machine, electricity and other factors. When the pump is shut down in working condition, the large opening of the conduction vane and the large on-off current directly affect the service life of GCB. Secondly, when the power is cut off at high load, the electromagnetic force will suddenly disappear and the torque will suddenly change, which will have a great impact on the...
generator set and affect the structural safety. In addition, the characteristics of reducing the opening of the broken conductance vane, the flow passage pressure of the unit, pressure pulsation, vibration/swing and other indicators are not fully mastered. A number of scholars have carried out a lot of studies on the calculation of the transition process [2-5] of full-feature surface treatment and full-load power failure of the pump, but few studies on the transition process of power failure with different guide vane opening when the pump is down at working conditions. In the formulation of power failure strategy [6-8], only a few parameters, such as GCB electrical life and vaneless pressure pulsation, are usually taken into account. According to the characteristics of Heimifeng power station, the paper studied the transition process characteristics and stability characteristics of the unit pump under different guide vane opening cut-off conditions, optimized the shutdown strategy of the pump under different operating conditions, and realized the optimal transition process, stability and GCB electrical life indexes.

2. Research Methods
In the calculation of transition process, the characteristic line method, Suter curve method and full-characteristic space surface method can be used to simulate the changes of characteristic parameters such as unit speed and water pressure in the condition of pump power off [2-4], and the hydraulic changes in different conditions of pump power off can be simulated by changing the boundary conditions of the runner [5]. In this paper, through the way of combination of numerical simulation and field test, according to the Suter transform theory, introducing the correction coefficient, based on the simulink and s-Function, establish for Heimifeng power outage of unit pump condition of transient mathematical model [9], stop process simulation to carry out the working condition of the pump, to guide the real machine test, the working condition of the pump on the comprehensive analysis of the measured data of different guide vane opening power outage transition process of features, analysis of the vibration stability, degree of sway and pressure pulsation features with the features of GCB electrical life At the same time, the difference in stability parameters between the pump shutdown process and the pump shutdown process (CP-P) is compared and analyzed to determine the optimal load and guide vane opening during the pump shutdown process and optimize the pump shutdown strategy under the pump shutdown condition. Among them, the stability of CP-P operating condition during the start-up process is based on the fact that the pump of Heimifeng power station will continuously puddle the water for more than 20 seconds after the backwater pressure is built up, and then the guide vane is opened. The oscillations and pressure pulsation of the unit are maintained at a certain level, so as to evaluate the acceptability of the stability changes of the unit during the shutdown process of the pump operating condition.

During the true machine test of the unit, the guide vane opening is taken as the stop control target, and the absorbed power is taken as the standby signal. The test conditions are shown in table 1. Among them, conditions 1, 6 and 8 are the original strategy shutdown test results of the pump condition, and condition 10 is the test result of the pump CP-P condition.

| Working conditions | 1   | 2   | 3   | 4   | 5   |
|--------------------|-----|-----|-----|-----|-----|
| Upstream water level (m) | 397.6 | 398.2 | 399.4 | 396.1 | 398.2 |
| Downstream water level (m) | 74.2 | 71.6 | 69.9 | 77.3 | 71.8 |
| Head (m) | 323.4 | 326.6 | 329.6 | 318.8 | 326.4 |
| Power outage load (MW) | -140.4 | -82.2 | -58.3 | -56.4 | -55.5 |
| Turn off the current (kA) | 4.5 | 2.6 | 1.9 | 1.8 | 1.8 |
| Power outage opening (%) | 11.1 | 3.9 | 1.7 | 0.2 | 0 |
| Working conditions | 6 | 7 | 8 | 9 | 10 |
| Upstream water level (m) | 391.4 | 390.0 | 380.7 | 384.0 | 378.8 |
| Downstream water level (m) | 87.3 | 89.5 | 100.7 | 96.5 | 102.0 |
By statistics, at Heimifeng power station, pump shutdowns are often carried out under high heads. So the test mainly test and analyzed the 326 m or so of the guide vane opening under different head power outage of unit parameters variation characteristics, power outage strategy optimization of unit pump working conditions, and under the low head is about 300 m and 285 m head analysis put forward under high head pump working condition of the applicability of the downtime strategy.

3. Analysis of Pump Shutdown Characteristics under Working Condition

3.1. Analysis of Transition Process Characteristics

According to the flow passage, turbine operation characteristics and guide vane closing characteristics of Heimifeng power station. The guide vane closing rule of Heimifeng power plant is a period of closing, and the closing time is designed to be 18s. The closing rate of guide vane is 6%/s when the pump is normally shutdown. The closing rate of guide vane at each head is consistent.

In this paper, the shutdown transition process of pumps under 326m, 300m and 285m heads was analyzed according to the actual closing law. Among them, the simulation results of the shutdown of the original strategy pump under 326m head are shown in figure 1, the simulation results under each head are shown in table 2, and the measured results are shown in table 3.

| Head (m) | Power outage opening (%) | Maximum pressure of vaneless (kPa) | Maximum inlet pressure of spiral case (kPa) | Maximum inlet pressure of draft pipe (kPa) |
|----------|--------------------------|-----------------------------------|-------------------------------------------|------------------------------------------|
| 325      | 11                       | 3745                              | 3815                                      | 844                                      |
| 325      | 4                        | 3839                              | 3804                                      | 810                                      |
| 325      | 2                        | 3814                              | 3825                                      | 793                                      |
| 325      | 0                        | 3847                              | 3806                                      | 803                                      |
| 300      | 9                        | 3939                              | 3748                                      | 974                                      |
| 300      | 5                        | 3985                              | 3757                                      | 975                                      |
| 300      | 0                        | 4013                              | 3735                                      | 995                                      |
| 285      | 10.5                     | 4018                              | 3569                                      | 1118                                     |
| 285      | 5                        | 4032                              | 3573                                      | 1061                                     |
| 285      | 0                        | 4069                              | 3592                                      | 1053                                     |

Figure 1. Simulation results of original strategy under 326m head.
The simulation results show that, at 326m head, with the interruption of the conduction vane opening during the shutdown of the pump working condition, the maximum vaneless pressure increases slightly, the maximum spiral case inlet pressure does not change greatly, and the maximum draft pipe inlet pressure decreases gradually. Under 300m head, the maximum vaneless pressure increased slightly with the decrease of the guide vane disconnection degree during the shutdown of the pump under working conditions, while the maximum spiral case inlet pressure and the maximum draft pipe inlet pressure did not change greatly. Under the head of 285m, with the decrease of the disconnection degree between guide vanes during the shutdown of the pump under working condition, the maximum vaneless pressure increases slightly, the maximum spiral case inlet pressure increases slightly, and the maximum draft pipe inlet pressure decreases slightly.

Table 3. Test results of transition process of pump shutdown.

| Working condition | 1    | 2    | 3    | 4    | 5    |
|-------------------|------|------|------|------|------|
| Vaneless pressure (kPa) | 3888 | 3970 | 3919 | 4042 | 3993 |
| Draft pipe inlet pressure (kPa) | 982  | 941  | 957  | 1013 | 923  |
| Back pressure of rotary valve (kPa) | 3841 | 3885 | 3913 | 3852 | 3858 |
| Pressure under headcover (kPa) | 1172 | 1044 | 1148 | 1167 | 1115 |

Table 4. Test results of Pressure pulsation characteristic.

| Working condition | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   |
|-------------------|------|------|------|------|------|------|------|------|------|------|
| RMS for vaneless pressure (kPa) | 30.0 | 27.2 | 28.0 | 26.1 | 31.9 | 26.0 | 28.0 | 21.9 | 27.4 | 41.8 |
| RMS for inlet pressure of draft tube (kPa) | 18.0 | 15.3 | 19.4 | 18.5 | 16.3 | 17.9 | 19.4 | 17.1 | 15.9 | 16.7 |

Compared with the measured data, the simulation results of the pump shutdown transition process are reliable, and the trend of the two is consistent. The deviation of the value is mainly due to the pressure pulsation in the measured data.

Simulation and experimental results show that the maximum vaneless pressure and spiral case inlet pressure of the unit are all less than 500 mH₂O during the shutdown of the pump under various operating conditions, which meet the requirements of adjustment guarantee calculation.

3.2. Analysis of Unit Stability Characteristics

According to the measured results, the guide vane turns off from full load for about 10s during the shutdown of the pump under each head of the unit. Accordingly, in order to ensure the comparability of test data, 10s test data before and after the guide vane was closed were selected for analysis in this paper. Among them, the effective values of each measuring point are calculated by using empirical mode decomposition method after stationary random processing of test data. The peak-peak value of pressure pulsation is calculated with 95% confidence. The P-P algorithm of vibration and sway measurement points adopts 97% confidence fusion mean time period method, and each calculation interval includes 8 periods of data.

3.2.1. Analysis of Variation Characteristics of Pressure Pulsation. The pressure pulsation of the unit is mainly measured in vaneless area, under the headcover, inlet of the draft tube and several measuring points in front/back of the rotary valve. The test results during pump shutdown in various working conditions are shown in table 4.
RMS for pressure in front of rotary valve (kPa) | 10.4 | 8.9 | 8.8 | 9.5 | 9.0 | 12.2 | 8.8 | 15.8 | 14.8 | 9.6
---|---|---|---|---|---|---|---|---|---|---
RMS for pressure behind rotary valve (kPa) | 10.4 | 14.0 | 8.8 | 9.5 | 12.2 | 12.2 | 8.8 | 15.8 | 19.2 | 9.6
RMS for pressure under headcover (kPa) | 39.7 | 41.2 | 41.0 | 47.2 | 41.4 | 45.0 | 41.0 | 66.6 | 52.3 | 47.8
P-P Pressure in vaneless region (kPa) | 124.9 | 122.6 | 121.4 | 120.2 | 131.0 | 115.9 | 110.5 | 89.8 | 110.1 | 183.8
P-P for inlet pressure of draft tube (kPa) | 91.8 | 80.1 | 88.8 | 81.6 | 70.7 | 86.6 | 96.8 | 91.5 | 74.7 | 83.8
P-P pressure in front of rotary valve (kPa) | 65.2 | 54.3 | 51.9 | 55.9 | 50.3 | 86.6 | 76.8 | 106.4 | 93.6 | 62.9
P-P pressure after rotary valve (kPa) | 65.0 | 86.9 | 51.8 | 56.0 | 70.0 | 86.6 | 76.9 | 106.7 | 125.5 | 95.4
P-P pressure under headcover (kPa) | 192.2 | 196.5 | 200.4 | 231.2 | 196.7 | 273.2 | 398.9 | 376.5 | 238.6 | 267.1

The test results show that:

1. At a high head (about 326m), there is no obvious change trend in the effective value and P-P value of pressure pulsation in various working conditions with the decrease in the opening of the conduction vane; When the guide vane opening is 1.7% and the GCB is fully closed, the overall pulsation level is reduced, the pressure pulsation under the headcover is slightly increased, the effective value of the pressure pulsation behind the rotary valve is increased, and the pulsation level of each measuring point is basically lower than that of the CP-P condition during the startup process.

2. Compared with the original strategy, the pressure pulsation in the vaneless area increases slightly during the shutdown of the GCB with full shut-off of guide vanes under medium and low head; the pressure pulsation of other measuring points has little change and some measuring points have been improved. The pressure pulsation level of vaneless region is better than that of CP-P condition during startup, and the pulsation P-P values of other measurement points are better than that of CP-P condition.

3.2.2. Analysis of Vibration and Sway Variation Characteristics: The test results during the shutdown of the pump in various working conditions are shown in table 5.

| Working condition | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|------------------|---|---|---|---|---|---|---|---|---|---|
| P-P for upper bearing sway (μm) | 128.7 | 134.5 | 144.2 | 2139.2 | 141.5 | 151.5 | 1456.8 | 139.1 | 1140.1 | 1168.3 |
| P-P for lower bearing sway (μm) | 125.1 | 1123.3 | 1315.9 | 135.2 | 2133.6 | 6209.2 | 2221.8 | 1810.1 | 1163.8 | 2697.9 |
| P-P for turbine bearing sway (μm) | 296.2 | 321.5 | 364.5 | 350.3 | 3345.4 | 3432.1 | 3370.0 | 3232.5 | 5363.2 | 2489.4 |
| RMS for upper bearing sway (μm) | 36.8 | 37.8 | 40.4 | 39.1 | 39.7 | 37.3 | 35.4 | 37.8 | 38.3 | 45.6 |
| RMS for lower bearing sway (μm) | 30.8 | 31.6 | 32.9 | 33.2 | 32.1 | 55.1 | 53.5 | 45.0 | 37.7 | 68.6 |
| RMS for turbine bearing sway (μm) | 92.2 | 88.6 | 95.3 | 94.3 | 90.7 | 98.0 | 90.3 | 86.9 | 88.2 | 117.9 |
| P-P for horizontal vibration of upper frame (μm) | 34.3 | 29.3 | 27.2 | 26.1 | 29.1 | 39.5 | 23.4 | 57.1 | 37.3 | 20.7 |
| P-P for horizontal vibration of lower frame (μm) | 24.3 | 29.4 | 23.4 | 21.4 | 24.5 | 19.0 | 21.6 | 26.9 | 30.8 | 21.1 |
| P-P for vertical vibration of lower frame (μm) | 38.5 | 49.9 | 88.7 | 45.1 | 67.0 | 94.3 | 74.8 | 104.7 | 61.3 | 38.5 |
| P-P for horizontal vibration of headcover (μm) | 110.3 | 143.2 | 274.6 | 91.0 | 94.8 | 71.4 | 78.3 | 106.3 | 132.6 | 260.8 |
| P-P for vertical vibration of headcover (μm) | 69.1 | 80.5 | 87.8 | 94.5 | 97.4 | 97.2 | 79.5 | 103.4 | 78.2 | 83.6 |
| RMS for horizontal vibration of upper frame (μm) | 9.7 | 7.6 | 6.9 | 6.4 | 7.1 | 9.2 | 5.1 | 14.4 | 9.6 | 6.2 |
| RMS for horizontal vibration of lower frame (μm) | 6.5 | 8.7 | 6.1 | 5.4 | 6.0 | 4.3 | 5.1 | 6.3 | 8.3 | 5.9 |
RMS for vertical vibration of lower frame (μm)  

|     |     |     |     |     |     |     |
|-----|-----|-----|-----|-----|-----|-----|
| 10.8 | 13.3 | 26.7 | 11.9 | 17.5 | 28.6 | 16.7 | 28.3 | 16.4 | 11.4 |

RMS for horizontal vibration of headcover (μm)  

|     |     |     |     |     |     |     |
|-----|-----|-----|-----|-----|-----|-----|
| 28.8 | 35.4 | 20.1 | 22.2 | 24.3 | 17.3 | 13.4 | 28.6 | 32.6 | 29.7 |

RMS for vertical vibration of headcover (μm)  

|     |     |     |     |     |     |     |
|-----|-----|-----|-----|-----|-----|-----|
| 18.3 | 20.3 | 21.6 | 23.7 | 23.5 | 22.6 | 15.4 | 25.9 | 20.8 | 27.3 |

The test results show that:

(1) At high head, with the decrease of the guide vane opening when GCB is broken, the measured values of each sway degree increase slightly, the horizontal vibration of the unit decreases gradually, and the vertical vibration increases gradually. According to the sway degree, the optimal guide vane opening is about 3.89% when the pump is shut down. According to the vibration analysis of the top cover, the optimal guide vane opening is about 1.7% when GCB is broken. According to the vibration analysis of the frame, when the pump of the unit is shut down under GCB, the optimal guide vane opening is fully closed. The effective value of horizontal/vertical vibration of the top cover is reduced compared with the CP-P condition when the guide vane is fully closed off.

(2) Compared with the shutdown process of the pump under the original strategy, the overall vibration and swing degree of the unit are reduced, and the vertical vibration of the unit is more favorable; At a low head of about 285m, when the guide vanes are completely shut off, the unit's downward guide sways decrease to some extent, while other measuring points of sways increase slightly, with a small range of variation.

(3) Under different heads, the sway level of each measuring point is better than the vibration level of CP-P condition when the pump is shut down in different guide vane opening conditions.

4. Optimization of Control Strategy for Pump Shutdown and Verification of Effect

4.1. Optimization of Pump Shutdown Control Strategy

According to the simulation and measured results of the transition process of pump shutdown in working condition, the cut-off vane opening of pump shutdown can be arbitrarily selected below the current opening. According to the analysis results of pressure pulsation characteristics, the optimal guide vane opening of the pump when the power is shut down is less than 1.7%. According to the analysis results of the stability characteristics, the optimal guide vane opening is below 3.89% when the pump is shut down under working conditions. According to the electrical life characteristics of the UNIT GCB, the breaking current is the main factor affecting the electrical life of GCB. Reducing the breaking current can improve the electrical life of GCB [8]. As shown in table 1, the breaking current decreases significantly with the decrease of the opening degree of the breaking conductance vane when the unit is shut down. To sum up, the optimal guide vane opening of Heimifeng power station is completely closed when the pump stops at working condition.

Referring to the pump shutdown control strategy of domestic pumped-storage power station, the absorbing power/current of the unit or the opening of the guide vane during the shutdown process are generally used as the judgment conditions. The GCB breaking strategy of Heimifeng Power Station is modified as follows:

Main signal: guide vane is closed completely; Standby signal: absorption power ≤65MW, delay 0.5s. Among them, 65MW is the fixed value of splash power protection during the startup of the unit's pump in the working condition. The measured absorbed power fluctuation range within 20s after pressure building in the CP-P condition of the unit is -36.70~64.39MW, and the average value is -52.34MW. Therefore, the standby signal is determined as ≤65MW according to the fixed value of splash power protection to ensure the normal shutdown of the unit.

4.2. Verification of the Control Strategy of Pump Shutdown

The optimized shutdown strategy of unit 3 of Heimifeng power station was put into operation. During
the shutdown of the pump of No. 3 machine, the parameters of No. 4 machine in normal pumping operation still fluctuated for a short time, the guide vane opening increased by about 3.5%, the unit's absorption power increased by about -0.5MW, the stability changed little, and it returned to the normal state about 10s. The stability test results of no. 3 pump during shutdown under working condition are shown in table 6. The results show that there is no significant change in the stability of the unit after shutdown under optimized pump condition. The measured value of horizontal vibration measuring point decreases slightly while that of vertical vibration measuring point increases slightly. The sway point has rise and fall, and the overall change is not big. After the optimization, the average absorbed power of the unit is -55.99MW, the average switching current is 1.80ka, and the electrical life of GCB is increased by more than one time.

| Pressure pulsation point       | Value | Vibration point                                      | Value | Sway point                                      | Value |
|-------------------------------|-------|-----------------------------------------------------|-------|------------------------------------------------|-------|
| RMS for vaneless pressure     | 28.9  | P-P for horizontal vibration of upper frame (μm)     | 27.5  | P-P for upper bearing sway (μm)                 | 140.4 |
| RMS for inlet pressure of draft tube | 17.3  | P-P for horizontal vibration of lower frame (μm)     | 22.9  | P-P for lower bearing sway (μm)                 | 134.4 |
| RMS behind rotary valve (kPa)  | 9.2   | P-P for vertical vibration of lower frame (μm)       | 56.0  | P-P for turbine bearing sway (μm)               | 347.4 |
| RMS for pressure under headcover (kPa) | 44.2  | P-P for horizontal vibration of headcover (μm)       | 92.8  | RMS for upper bearing sway (μm)                 | 39.3  |
| P-P Pressure in vaneless region (kPa) | 125.5 | P-P for vertical vibration of headcover (μm)         | 95.9  | RMS for lower bearing sway (μm)                 | 32.6  |
| P-P for inlet pressure of draft tube (kPa) | 76.1  | RMS for horizontal vibration of upper frame (μm)     | 6.7   | RMS for turbine bearing sway (μm)               | 92.4  |
| P-P pressure after rotary valve (kPa) | 62.9  | RMS for horizontal vibration of lower frame (μm)     | 5.6   |                                                 |       |
| P-P pressure under headcover (kPa) | 213.9 | RMS for vertical vibration of lower frame (μm)       | 14.6  |                                                 |       |
|                               |       | RMS for horizontal vibration of headcover (μm)       | 23.2  |                                                 |       |
|                               |       | RMS for vertical vibration of headcover (μm)         | 23.5  |                                                 |       |

5. Conclusion
By means of pumped-storage power station unit 3 Heimifeng CP-P condition and different head, pump under different working condition of the guide vane opening process as well as the vibration of the working condition of CP-P system downtime, degrees, pressure and pressure pulsation signal monitoring analysis, combined with the life of electric GCB features, will be Heimifeng power station pump operating mode of the strategy for power outage vanes fitted breaking GCB; After the shutdown strategy is optimized, the operating state of the unit is stable, and the electrical life of GCB is greatly improved.

References
[1] China Electric Power Press 2011 Code of Operation for Pump-Turbine of Pumped-Storage (DL/T 293-2011).
[2] Chen Y L, Ju X M 2001 Calculation method of hydraulic transient process after power outage of pump Sichuan Hydropower Generation 20(S1): 91-92, 96.

[3] Cai L, Liu C Y, Shi T L, etc. 2017 Mathematical simulation of characteristic parameters for pump failure of unit 1 in Hongping pumped storage power station Water Resources and Power 35(2): 170-173, 90.

[4] Yang X 2012 Description of Full-Characteristic Space Surface of Pump Turbine and Research on Hydraulic Transition Process Regulation and Control Huazhong University of Science & Technology.

[5] Li R N, Huang Q, Li Q F, etc. 2013 Research on pump turbine's conditions when out of electricity supply during pump working Journal of Xihua University(Natural Science Edition) 32(2): 33-36.

[6] Deng L, Shan Q G, Zhou D Y, etc. 2016 Pumping characteristics research of first unit in Hongping pumped-storage power station Water Power 42(8): 80-82.

[7] He R F. 2015, Analysis on the electrical Life of the Circuit breaker at the end of pumped storage unit Guangdong Electric Power 28(07): 24-27.

[8] Bi Z W, Liu P, Wei J F, etc. 2019 Electrical life analysis of circuit breakers in Heimifeng pumped-storage power station Hunan Electric Power 39(06): 38-41.

[9] Liu P, Li B, Wei J F, etc. 2019 Simulation study on hydraulic transition process of unit in Heimifeng pumped-storage power station Water Resources and Engineering 50(S2): 111-115.