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A method for analysing and evaluating the comprehensive conversion efficiency of Pumped Storage Power Station

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Abstract. The comprehensive conversion efficiency of Pumped Storage Power Station reflects the operation benefit of power station in power system. Analysing and studying the influencing factors of comprehensive conversion efficiency is very important to the overall design of power plant and efficiency improvement. This paper presents a method for analysis and evaluation of conversion efficiency of Pumped Storage Power Station based on a large number of daily operation data calculation, combined with model test, performance test and field efficiency measurement results. Through this method, the annual comprehensive conversion efficiency level of the power station is calculated. It is clear that the efficiency of the pump-turbine is the main factor, and the low efficiency level of the unit itself and the unreasonable generation operation mode lead to the low comprehensive conversion efficiency level. The measures and suggestions for improving the comprehensive conversion efficiency of the power station are put forward.

1. Introduction

The comprehensive conversion efficiency of pumped storage power station is one of the important parameters in power plant design, which directly reflects the operation benefit in power system. With the continuous improvement of design and manufacturing level of energy storage units, the integrated conversion efficiency has been continuously improved, from 65% to 75% in the early period, and gradually generally increased to 75%. In recent years, the integrated conversion efficiency has exceeded 80%. Therefore, for the storage power station which has been put into operation for many years and the level of comprehensive conversion efficiency is not high, a scientific and reasonable analysis method is adopted to analyze the level of comprehensive conversion efficiency and its influencing factors, to clarify the reasons for the low efficiency and put forward proposals for improving the comprehensive conversion efficiency.

2. Definition of integrated conversion efficiency

Generally, the comprehensive conversion efficiency of a storage power station is defined as the ratio of the power on the grid to the power off the grid. Power on the grid is the actual power generation after deducting the line loss and power consumption for the annual total power generation of all pump-turbine-generator units. Correspondingly, power off the grid is supplied by the power grid after



deducting line losses and auxiliary power consumption. Therefore, comprehensive conversion efficiency can be written:

$$\eta_{\text{intergrated}} = \frac{\text{Power on the grid}}{\text{Power off the grid}} = \frac{\text{Total generating capacity} - \text{loss}}{\text{Total power consumption} + \text{loss}} \quad (1)$$

It can be seen that the ratio of power loss to power generation or power consumption can be obtained by analyzing and counting the line consumption and auxiliary power consumption under the annual power generation and pumping operation of the storage power station. It is more convenient for analysis and study to introduce the power utilization efficiency to convert the online and offline power to the unit terminal. The electricity utilization efficiency is divided into two parts: power generation and pumping.

$$\eta_{\text{Power generation utilization}} = \frac{\text{Loss for generation}}{\text{Total generating capacity}} \quad (2)$$

$$\eta_{\text{Pumping capacity utilization}} = \frac{\text{Loss for pumping}}{\text{Total power consumption}} \quad (3)$$

Comprehensive conversion efficiency can be written:

$$\eta_{\text{integrated}} = \frac{\text{Total generating capacity} \times (1 - \eta_{\text{power generation utilization}})}{\text{Total power consumption} \times (1 + \eta_{\text{pumping capacity utilization}})} \quad (4)$$

Therefore, through the definition and analysis of the integrated conversion efficiency of the storage power station, it is clear that the integrated conversion efficiency is directly related to the generating capacity, electricity consumption and utilization efficiency of the unit.

3. Analysis of factors affecting comprehensive conversion efficiency

3.1 Factors affecting the comprehensive conversion efficiency

According to the definition of comprehensive conversion efficiency, the ratio of total generating capacity to total generating capacity is the unit efficiency. Therefore, formula (4) can be written:

$$\eta_{\text{integrated}} = \eta_{\text{unit}} \times \frac{(1 - \eta_{\text{power generation utilization}})}{(1 + \eta_{\text{pumping capacity utilization}})} \quad (5)$$

From the whole working process of pumped-storage power plant units, it can be seen that the electric energy provided by the power grid is supplied to the unit for pumping after line loss, auxiliary power loss and main transformer loss, and the electric energy is finally converted into potential energy through the motor, pump and water pipeline, and the water flow is pumped from the lower reservoir to the upper reservoir. Under the power generation condition, the potential energy of upper reservoir water can be converted into generating electricity by water pipeline, turbine and generator etc. Unit efficiency can be written:

$$\eta_{\text{unit}} = \eta_{\text{generation}} \times \eta_{\text{pumping}} \quad (6)$$

$$\eta_{\text{generation}} = \eta_{\text{waterway}} \times \eta_{\text{turbine}} \times \eta_{\text{generator}} \quad (7)$$

$$\eta_{\text{pumping}} = \eta_{\text{motor}} \times \eta_{\text{pump}} \times \eta_{\text{waterway}} \quad (8)$$

In addition, considering the characteristics of different power stations, such as evaporation and leakage of reservoirs, the correction factor is considered. The formula (5) can be amended to:

$$\eta_{integrated} = \eta_{unit} \times \frac{(1 - \eta_{power\ generation\ utilization})}{(1 + \eta_{pumping\ capacity\ utilization})} \times e_{correction} \quad (9)$$

The efficiency of the unit is calculated by formula (6), (7) and (8).

Therefore, the factors affecting the comprehensive conversion efficiency of power plants mainly include: turbine efficiency, pump efficiency, generator motor efficiency, waterway efficiency under power generation and pumping conditions, energy utilization efficiency under power generation and pumping conditions, and correction coefficient.

3.2 Efficiency analysis of hydraulic turbines

The formula for calculating the efficiency of hydraulic turbines is as follows:

$$\eta_t = \frac{N_t}{\rho gQH} \times 100\% \quad (10)$$

In the form: η_t —efficiency of turbine, %; N_t —turbine output, kW; ρ —water density, kg/m³; g —acceleration of gravity, m/s²; Q —discharge, m³/s; H —head, m.

Through the above formula, the turbine efficiency value under each operating condition can be calculated, and its operating law and operating time can be obtained. Through the analysis of the operation law, it is known that the relationship between turbine efficiency, head and load can be clearly defined. Through the statistics of the running time of each working condition, it can reflect the law of generating set operation. The ratio of the running time to the total power generation time is the proportion of the influence of the working condition on the power generation efficiency. The total power generation efficiency can be calculated by calculating the efficiency under each working condition and the corresponding influence proportion.

$$\eta_{t,i} = \frac{N_{t,i}}{\rho gQ_i H_i} \times 100\% \times \frac{T_i}{T_t} \quad (11)$$

$$\eta_t = \sum_{i=1}^{n_t} \eta_{t,i} \quad (12)$$

In the form: $\eta_{t,i}$ —efficiency of turbine on point, %; $N_{t,i}$ —turbine output on point, kW; ρ —water density, kg/m³; g —acceleration of gravity, m/s²; Q_i —discharge on point, m³/s; H_i —head on point, m; T_i —operation time on point, h; T_t —total operation time, h; η_t —total turbine efficiency, %; n_t —total number of working conditions.

3.3 Efficiency analysis of pumps

The formula for calculating the efficiency of the pump is as follows:

$$\eta_p = \frac{\rho gQH}{N_p} \times 100\% \quad (13)$$

In the form: η_p —efficiency of pump, %; N_p —pump input, kW; ρ —water density, kg/m³; g —acceleration of gravity, m/s²; Q —discharge, m³/s; H —head, m.

Similarly, the pump efficiency under each pumping condition can be calculated by the above formula, and then the total pumping efficiency can be obtained.

$$\eta_{p,i} = \frac{\rho g Q_i H_i}{N_{p,i}} \times 100\% \times \frac{T_i}{T_p} \quad (14)$$

$$\eta_p = \sum_{i=1}^{n_p} \eta_{p,i} \quad (15)$$

In the form: $\eta_{p,i}$ —efficiency of pump on point, %; $N_{p,i}$ —pump input on point, kW; ρ —water density, kg/m³; g —acceleration of gravity, m/s²; Q_i —discharge on point, m³/s; H_i —head on point, m; T_i —operation time on point, h; T_p —total operation time, h; η_p —total pump efficiency, %; n_p —total number of working conditions.

4. Analysis and evaluation method

Based on the calculation of a large number of daily operation data, this method obtains the annual comprehensive conversion efficiency of the storage power station in a fixed year and in many years and the influence of various factors. At the same time, combined with model test, performance test and field efficiency test data, the unit efficiency and comprehensive conversion efficiency are evaluated. According to the evaluation results, it puts forward feasible proposals for improving the comprehensive conversion efficiency of power stations.

4.1 Data collection

First, according to the different conditions and characteristics of each power station, the composition of influencing factors is clearly defined. The influencing factors are usually composed of the above-mentioned analysis, but the conditions of each power station are different. Besides reservoir evaporation and seepage, there may be other factors affecting power generation and pumping capacity, which can be considered in the correction factor. Therefore, it is necessary to collect the data of pump-turbine model test, performance acceptance test, field efficiency test, generator motor test report and annual operation data for the analysis and evaluation of the integrated conversion efficiency. Annual operation data mainly include line loss, auxiliary power loss, data related to correction coefficient and operation data of each unit. Operating data of the unit include water level, guide vane opening, turbine output power, pump input power, flow rate, volute inlet pressure, and draft tube outlet pressure.

4.2 Data analysis and review

According to the unit model test data, performance test data and field efficiency measurement data, the unit efficiency design level and efficiency characteristics can be clearly defined. When analysing and reviewing a large number of daily running data, the flow rate of each working condition is emphasized. The accuracy of flow directly affects the efficiency of pump and turbine. According to the actual situation of power plant, the flow value obtained by collecting data of flow meter or spiral case pressure difference method is compared and corrected with prototype predicted value, performance acceptance test value and field measured value, and the flow value of this evaluation method is determined.

4.3 Data calculation

On the basis of defining the unit flow rate, a calculation program is developed. According to the efficiency calculation formula, the operation data of the unit are input, including the upper and lower water level, the inlet pressure, the outlet pressure, the guide vane opening and the flow rate. The efficiency of the turbine and the pump and the corresponding loss of the waterway are calculated. According to the running time of each working condition, the annual total efficiency and waterway efficiency are calculated. According to the data collected, statistics and calculation, the one-year

comprehensive conversion efficiency of the power station is calculated by applying the relevant formula in 3.1.

4.4 Evaluation of integrated conversion efficiency

According to the calculation results, the comprehensive conversion efficiency level of the power station is comprehensively analyzed and evaluated. Firstly, the annual comprehensive conversion efficiency is compared with the ratio of power on the grid and off grids to judge the rationality of the analysis method. According to the initial design value of the power station, the comprehensive conversion efficiency level of the power station is evaluated. Secondly, it analyses the degree of influence of various factors on the comprehensive conversion efficiency, and clarifies the reasons for the low overall efficiency. Finally, it puts forward effective measures and suggestions to improve the level of comprehensive conversion efficiency.

5. Method application example

The comprehensive conversion efficiency of a pumped storage power station in 2017 is analysed and evaluated by this method.

According to the actual operation conditions and characteristics of the power station, the influencing factors of the comprehensive conversion efficiency of the power station mainly include power loss, unit efficiency and correction factor. Among them, the correction coefficient mainly considers the influence of reservoir evaporation and leakage on power generation. The unit model test, performance acceptance test at initial stage of commissioning and field efficiency test data are sorted and analysed. The initial efficiency of the unit meets the contract requirements and the turbine efficiency is superior to the predicted value of the model. Deviation exists in pump flow measurement. The field efficiency test results after many years operation show that the measured value of turbine flow is consistent with the original predicted value and performance acceptance value, and the turbine efficiency is better than the prototype predicted value. The results of the pump flow measurement agree with the performance acceptance test.

The initial design value of turbine weighted efficiency is 90.346%, the pump weighted efficiency is 92.40%, the field measured efficiency of the generator motor is 98.6%, and the correction coefficient is 98%. The calculated energy utilization efficiency is 98.91%.

For the analysis and review of a large number of daily operation data, we need to specify the value of the flow. The power station is equipped with ultrasonic flow meter. The analysis of flow collection data shows that data is unstable in the process of frequent load regulation due to the automatic regulation system (AGC) put into the power station. After checking and comparing, the flow record value of hydraulic turbine does not reflect the real flow rate under working conditions. For long-term stable load operation conditions, the flow data are more accurate and less volatile. During the operation process with obvious load variation, the fluctuation range is large, and some recorded data are wrong. Therefore, ultrasonic flow cannot be used directly. According to the analysis results of model test, performance test and field efficiency test, the actual operation efficiency of the turbine is consistent with the predicted performance of the prototype, and the flow value of the turbine is also consistent with the predicted value of the prototype in stable test conditions. Therefore, the prototype prediction flow corresponding to the actual operation condition is used for subsequent calculation. Under pump condition, the installation condition of ultrasonic flow meter is limited by the factory building, which leads to the deviation of pump flow measurement. According to the field measured data and performance acceptance test results, the pump flow is corrected by the measurement deviation determined by the manufacturer.

After defining the value of flow rate, the efficiency of each operating condition is calculated. The results show that the total efficiency of turbine, pump, power generation channel and pumping channel is 89.69%, 91.16%, 98.29%, 97.86% and 74.10% respectively in 2017. The ratio of power on grid and off grid is 74.09%, which is basically consistent with the two values, indicating that the analysis and evaluation method is reasonable.

From the calculation results, the efficiency of pump and turbine is the main factor, while the efficiency of pump and turbine is mainly affected by the unit's own efficiency level and turbine operation mode. The unit capacity is 200MW. The turbine efficiency values in each load area are calculated according to the operation data of the power station in 2017 as shown in Table 1. It can be seen that the turbine runs for a long time under partial load, especially at 50% rated load. The operating efficiency value is only 85.39%, and the influence on the total efficiency of the turbine is 17.08%, which leads to the low overall efficiency of the turbine throughout the year. The efficiency of each pump in 2017 is shown in Table 2. The design value of pump efficiency is not high compared with the current level of storage power plant units, and the distribution of pump operating weight in each head is also changed compared with the original design, resulting in the total efficiency of the pump is lower than the initial design level.

Table 1. Summary of generating units operation at various loads in 2017

Output(MW)	190~210	180~190	170~180	160~170	150~160	140~150	130~140	120~130	110~120	90~110
Operation time(h)	2564.975	528.58	442.09	364.13	310.74	293.66	284.05	273.37	318.22	1108.43
Efficiency(%)	91.10	91.60	91.63	91.17	90.56	89.79	88.90	87.90	86.84	85.39
Weight(%)	39.53	8.15	6.81	5.61	4.79	4.53	4.38	4.21	4.90	17.08

Table 2. Pump efficiency of each unit in 2017

Unit	1#	2#	3#	4#
Operation time(h)	1894.6	1938.8	1403.8	1752.8
Efficiency(%)	90.58	90.79	91.57	91.87

Based on this method, the comprehensive conversion efficiency of a storage power station in 2017 is calculated, and combined with the model test results, performance test results and field test results, it is concluded that the pump turbine is the main factor. And the efficiency level of pump turbine is not high, long-term operation of the turbine under partial load, especially under 50% of the load operating time is too long, resulting in low efficiency of pump turbine, and then affect the level of comprehensive conversion efficiency. It is suggested that the power station should rationally arrange the power generation operation mode so as to make the unit run in the area above 80% rated load. At the same time, the operation area should be optimized combined with the unit stability. For the units that have been in operation for many years, it is suggested that the technical transformation of production be carried out, the runners be replaced, and the efficiency of the units themselves be improved. The comprehensive conversion efficiency of the power station will be obviously improved.

6. Conclusion

This paper presents a method to analyze the comprehensive conversion efficiency of Pumped Storage Power Station based on a large number of daily operation data and combined with the results of unit model test, performance test and field efficiency test.

- (1) Through this method, the annual comprehensive conversion efficiency level and its influencing factors can be obtained, the main factors can be identified, and the reasons for the low efficiency level of the power plant can be further found. Through in-depth analysis of the various factors, it can be more scientific and reasonable to evaluate the comprehensive conversion level of the power plant, not only through the ratio of power on the grid to power off the grid, to measure and judge by a unified standard.
- (2) Through the analysis and evaluation of the comprehensive conversion efficiency of a typical pumped storage power station which has been in operation for many years, it is clear that the low efficiency level of the unit itself and the unreasonable operation mode of the generator are the reasons for the low comprehensive conversion efficiency level.

- (3) It is suggested that the generating units of this power station should be rationally arranged to operate in the area above 80% rated load. At the same time, for units that have been in operation for many years, the replacement of runners can be considered to improve the efficiency level of the unit itself, and the comprehensive conversion efficiency level of the power station will be significantly improved.

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