Feasibility Study on Frequency Conversion Transformation of Electric Feedwater Pump in Nuclear Power Plant

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Abstract: In order to study the feasibility of frequency conversion of electric feedwater pump in nuclear power plant, and to provide reference for the improvement of electric feedwater pump in nuclear power plant and new nuclear power plant, this paper discusses the technical and economic aspects, and analyzes the feasibility of frequency conversion transformation of electric feed pump in nuclear power plant. The results show that there is no technical difficulty for the electric feedwater pump of nuclear power plant from the technical point of view, and the economic analysis shows that it will take about 4 years to recover the cost for the frequency conversion of the electric feedwater pump of nuclear power plant. Therefore, the frequent participation in the peak load of the power grid units can be considered for transformation. For the nuclear power units that serve as the base load of the power grid, the cost can be recovered in about 6 years by eliminating the loss of capacity, and they can be retrofitted according to the needs of the plants themselves.

Key words: Electric feedwater pump, Frequency conversion, Transformation

1. Introduction

As an important equipment in the secondary circuit of nuclear power plant, the main feed water pump is responsible for sending the deaerated water from the deaerator to the Steam generator, taking away the core heat, generating steam to push the turbo-generator to rotate and generate electric energy. The main feed water pump has electric and steam-driven type. Because the CPR1000 steam turbine adopts half-speed machine, the steam-driven feed water pump does not need to share the pressure of the low-pressure cylinder of the steam turbine, and all the main feed water pumps adopt electric type. Electric feed water pump consumes a lot of power, accounting for about 30% of auxiliary power and 1.6% of unit power generation. In addition, it is a trend for nuclear to participate in peak shaving of power grid. Nuclear power plants often operate at low power, and electric feed water pump with hydraulic coupler cannot work at the highest efficiency point, resulting in huge waste of power. Reducing the power consumption rate of electric feed water pump is one of the important contents of reducing costs and increasing efficiency in plant. At present, there are many researches on frequency conversion transformation of electric feed water pump in thermal power plants. Li Zhengkun analyzed the transformation of motor frequency conversion device by using hydraulic coupler variable speed Regulating Fan, and proved that the energy saving effect of frequency conversion drive is more obvious than that of Regulating mode using hydraulic coupler, and the failure rate is less than that of Regulating device using hydraulic coupler [1]. Combined with the frequency conversion reconstruction project of Wustai plant water supply system, Li Junhong expounded the control system reconstruction scheme in frequency conversion reconstruction under the condition of retaining its hydraulic coupler. The research shows that after the water supply system reconstruction, not only the power consumption is reduced, but also the unit operation safety is improved [2]. After analyzing the frequency conversion transformation of several plant in China, Nye adopted the “one-to-one” mode to transform the original water supply system with hydraulic coupler speed regulation, which made the power saving rate of the water supply system about 24% [3]. At present, Qinshan Nuclear Power Plant and Zhangzhou Nuclear Power Circulating Water Pump have carried out frequency conversion transformation, but there is no research on frequency conversion transformation of electric feed water pump in nuclear power plant. According to the characteristics of CPR1000 units in nuclear power plant, this paper analyzes the possibility of electric feed water pump transformation from two aspects of technology and economy.

2. Electric feed water pump unit in nuclear power plant

The main feed water pump of nuclear power plant adopts 3*50% configuration scheme, with two normal operation and one standby. The feed water pump consists of front pump, motor, hydraulic coupler and pressure class feed
The feed water enters the pressure stage feed water pump after being pressurized by the front pump, and then enters the steam generator through the high-pressure heater. The electric feed water pump of CPR1000 unit is driven by power frequency motor. When the power of the unit changes, the rotating speed of the feed water pump and the opening of the main feed water valve are changed by hydraulic coupler, so as to adjust the steam generator feed water quantity. In the whole electric feed water pump unit, the efficiency of front pump, motor and feed water pump is generally stable, but the efficiency of hydraulic coupler has great loss under off-design conditions. Fig. 1 shows the basic configuration of electric feed water pump. Among them, the front pump, motor and hydraulic coupler pump wheel are coaxial. The related parameters of the electric feed water pump motor are shown in Table 1.

![Fig. 1 Basic configuration of electric feed water pump](image)

Table 1 Main parameters of motor

<table>
<thead>
<tr>
<th>Serial number</th>
<th>Name</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Type</td>
<td>Squirrel cage induction motor</td>
</tr>
<tr>
<td>2</td>
<td>Rated power</td>
<td>10000KW</td>
</tr>
<tr>
<td>3</td>
<td>Rotational speed</td>
<td>1493rpm</td>
</tr>
<tr>
<td>4</td>
<td>Voltage</td>
<td>6.6KV</td>
</tr>
<tr>
<td>5</td>
<td>Full load efficiency</td>
<td>97.6%</td>
</tr>
<tr>
<td>6</td>
<td>Full power factor</td>
<td>0.89</td>
</tr>
<tr>
<td>7</td>
<td>Full load Current</td>
<td>1006A</td>
</tr>
</tbody>
</table>

3. Analysis of hydraulic coupler

The hydraulic coupler can transfer the motor torque to the pressure stage pump, and regulating the speed of the pressure stage pump according to the steam-water pressure difference signal. The hydraulic coupler is composed of driving shaft, pump wheel, turbine, driven shaft and rotating shell. When working, the coupler is filled with working oil. When the driving shaft drives the pump wheel to rotate, the working oil is driven by the blade and flows from the inner side of the pump wheel to the outer edge due to centrifugal force, forming a high-pressure and high-speed liquid flow to impact the turbine blade. Working oil in the turbine from the outer edge to the inner flow process of decompression and deceleration, so as to obtain torque from the driven shaft, so that the turbine with the pump wheel in the same direction of rotation. Working oil also depends on the pressure drop between pump wheel and turbine. In this circulating flow process, the pump wheel converts the input mechanical energy into the kinetic energy and potential energy of the working oil, while the turbine converts the kinetic energy and potential energy of the working oil into the output mechanical energy, thus realizing the power transmission. As far as the power transmission process of hydraulic coupler is concerned, if the external torque acting on it by resistance torque such as bearing is ignored:

$$\Sigma M = 0$$

i.e. $M_B + M_i = 0$

In the formula $MB, MT$ is the torque acting on the coupler pump wheel and turbine, the ratio of input power to output power is the efficiency of hydraulic coupler, that is:

$$\eta = \frac{P_T}{P_B} = \frac{M_T n_T}{M_B n_B} = \frac{n_T}{n_B} = i$$

$$S = \frac{n_B - n_T}{n_B} = 1 - \frac{n_T}{n_B} = 1 - i$$

In the formula:

$S$——Slip difference of hydraulic coupler

$n_B$——Speed of pump wheel

$n_T$——Turbine speed

$i$——Ratio of rotational speed

The above formula indicates that the efficiency of the hydraulic coupler is directly proportional to the speed ratio, and the slip ratio is negatively correlated with the speed ratio. The parameters of the hydraulic coupler are shown in Table 2.

Table 2 Main parameters of hydraulic coupler

<table>
<thead>
<tr>
<th>Serial number</th>
<th>Name</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Input speed</td>
<td>1493rpm</td>
</tr>
<tr>
<td>2</td>
<td>Output speed</td>
<td>4775rpm</td>
</tr>
<tr>
<td>3</td>
<td>Slip difference</td>
<td>2.8%</td>
</tr>
<tr>
<td>4</td>
<td>Slip loss</td>
<td>366.1KW</td>
</tr>
<tr>
<td>5</td>
<td>Mechanical loss</td>
<td>184.9KW</td>
</tr>
<tr>
<td>6</td>
<td>Input power</td>
<td>5994±32.6KW</td>
</tr>
<tr>
<td>7</td>
<td>Output power (rated power)</td>
<td>5443KW</td>
</tr>
</tbody>
</table>

The rated output speed of hydraulic coupler is generally matched with the maximum output of feed water pump. According to the design of Annual Average and System Design Manual in Main and Startup Feedwater System, normal water supply can be completed at 49.5 Hz, and normal water supply can be completed by adjusting the rotating speed of hydraulic coupler at normal power frequency. The maximum output of the two electric feed pumps is 110% of the normal water supply at full power. If the whole fuel cycle of the unit keeps running at full power, the Annual Average efficiency of the main feed pump is about 80 Annual Average. If the nuclear power unit participates in the peak shaving of the power grid and cannot maintain full power, the efficiency of the electric main feed water pump will be lower. According to the yearbook of a nuclear power company in 2019 [4], the operating hours of a nuclear power unit at 77% rated power are 1410h, the operating hours at 50% rated power are 42h, and the disconnection hours are 288h. It is roughly calculated that the loss caused by the decrease of peak shaving efficiency of electric feed water pump in
power grid is about 3.74 million (the electricity price above power grid is calculated by 0.4 yuan, two electric feed water pumps with 77% rated power are operated, and a single pump is separated), and the loss caused by the decrease of efficiency of electric feed water pump due to design reasons in the whole year is about 5.05 million. According to the calculation results, it can be seen that the existing operation mode of electric feed water pump is very uneconomical and needs to be improved.

4. Improved analysis

According to the relationship between speed and frequency of asynchronous motor:

\[ n = \frac{60f}{p} (1 - S) = (1 - S) n_1 \]

In the formula, \( n_1 \) is synchronous speed, \( S \) is slip ratio, \( p \) is polar logarithm, \( f \) is power supply frequency of asynchronous motor. The variable frequency transformation of electric feed water pump is to use the variable frequency device as the variable frequency Power supply. By changing the power supply frequency \( f \) of the electric feed water pump motor Stator, the synchronous speed \( n_1 \) is changed, thus changing the asynchronous motor speed \( n \), realizing the purpose of speed regulation. The induction electromotive force of each phase winding of asynchronous motor Stator validity is:

\[ E_1 = 4.44f_1N_1\phi_m \]  

(1)

In the above formula: \( E_1 \) is the induced electromotive force generated by air gap magnetic flux in each phase winding of Stator, \( f_1 \) is the power supply frequency of Stator Stator, \( N_1 \) is the number of turns of Stator phase of Stator winding, and \( \phi_m \) is the air gap magnetic flux. If the structural parameters of the motor are constant, it can be obtained according to Equation 1:

\[ \phi_m \propto \frac{E_1}{f_1} \]  

(2)

The electromagnetic torque of the motor is:

\[ T_e = K_f\phi_m I_2 \cos \varphi_2 \]  

(3)

In the above formula: \( K_f \) is a constant, \( \varphi_m \) is the flux per pole, \( I_2 \) is the rotor Current, \( \cos \varphi_2 \) is the power factor per phase circuit of the rotor. It can be seen from Equations 2 and 3 that the Guaranty needs to be \( \phi_m \) unchanged while converting frequency, otherwise it will cause \( T_e \) reduction or flux saturation, which will eventually lead to the temperature rise of the motor. In severe cases, it may lead to overheating of the winding and damage to the motor, so it is necessary to control the voltage and keep \( \phi_m \) unchanged while converting frequency.

If the power of the nuclear power plant is reduced to 77% of the rated power, the Steam generator feed water flow demand will also be reduced to about 77%. According to the similarity law of pumps, the power of the electric feed water pump will be reduced to 45.6% of the rated power, thus achieving the effect of reducing energy consumption.

4.1 Electrical part

The electrical part of frequency conversion transformation is mainly to install high-voltage frequency converter in the power supply part of feed water pump motor. According to the characteristic that the configuration of electric feed water pump in nuclear power plant is 2 operation and 1 standby, the frequency conversion design should adopt one drag and one mode, which makes the operation more flexible. After frequency conversion transformation, during normal operation, K2 and K4 circuit breakers are closed, and the feed water pump motor runs with frequency conversion; When the inverter fails, K3 is closed, K2 and K4 are disconnected, and the feed water pump can be put into power frequency standby.

4.2 Mechanical part

The mechanical part of the improvement of electric feed water pump mainly involves the improvement of hydraulic coupler, among which there are two schemes. The first scheme adopts a more efficient speed-increasing gearbox to replace the hydraulic coupler, and the second scheme retains the hydraulic coupler, improves the lubricating oil and cooling water system of the main feed water pump, and increases the frequency conversion device. Scheme 1 may involve the change of thermodynamic system and interface parameters, which has a long transformation cycle and a large demand for transformation funds, and has a great impact on the overhaul period of nuclear power plants. For the economy and feasibility of Guaranty transformation, Scheme 2 is adopted, which only increases the frequency converter and retains the original hydraulic coupler.
This scheme retains the function of the hydraulic coupler, through structural improvement or setting, the position of the spoon tube is 100% when running at low power, eliminates the speed regulation function of the hydraulic coupler, and uses the frequency converter to regulate the speed, so as to keep the maximum efficiency of the hydraulic coupler. In addition, the original feed water pump has not been changed, only a set of frequency conversion device is added, and the lubricating oil and cooling system are simply improved, which is simple, safe and low in cost.

When the frequency converter fails, the speed regulation function of the spoon tube is restored. However, the efficiency of this improvement is slightly lower than that of replacing the hydraulic coupler with the gearbox, and the frequency conversion Regulating is added on the basis of the original speed regulation, which makes the Regulating of the electric feed water pump more complicated. In addition, when the hydraulic coupler is under the rated output power for a long time, the Regulating efficiency is improved, while the cooling capacity of the working oil system is relatively increased, the deterioration period of the working oil is shortened, and the consumption and maintenance are correspondingly increased.

Because the front pump and motor of the electric feed water pump are coaxial, when the motor is driven by frequency conversion, the front pump will also slow down. At this time, the necessary cavitation allowance and head of the pressure stage pump must be analyzed. According to the manual of electric feed water system, the NPSH (3%) of the pressure stage pump is 74m water column, then the outlet pressure of the front booster pump must be greater than 7.4 bar. According to the flow head relationship curve of the front pump, the lowest frequency of frequency conversion operation is set. The advantages of the treatment scheme for the front pump are that there is no need to improve the existing equipment, infrastructure and factory buildings, and there is no need to add new driving motors.

However, the disadvantage is that in the low load area, there may be cavitation risk of pressure stage pump, and the frequency conversion frequency cannot be too low, which restricts some energy-saving effects.

5. Analysis of the influence of improvement on the operation control of electric feed water pump

According to the speed control schematic diagram of the electric feed water pump, as shown in Figure 3, the setting value of steam-water pressure difference is generated according to the steam flow of the Steam generator, and the setting value of speed is generated by function operation with the measured value of steam-water pressure difference, and then compared with the measured value of speed of the electric feed water pump, the position signal of the spoon tube is generated, and the opening of the spoon pipe is generated, so as to achieve the purpose of speed regulation.

Automatic control: The improved electric feed water pump is in frequency conversion condition, the hydraulic coupler runs at 100% opening, and there is no speed regulation capacity. The speed setting value and the speed measured value generate speed deviation, thus generating frequency deviation, which is used as the input signal of the frequency modulator for frequency modulation, thus achieving the purpose of speed regulation. Its schematic diagram is shown in Figure 4.

Manually operated control: At present, there are three ways to run manually operated: 1. Adjust the demand value of steam-water pressure difference, which is slow to respond to the speed Regulating of electric feed water pump; 2. Manually operated adjusts the speed demand value; 3. Directly manually operated Regulating spoon tube position, this method has the fastest adjustment speed.

In the frequency conversion condition, a new manually operated Regulating mode is added, which can directly adjust the rotating speed by adjusting the motor frequency, and can add a frequency modulation button in the DCS screen, and the frequency conversion amplitude is consistent with the adjustment spoon tube amplitude.

Abnormal working condition: When the safety injection and P14 (Steam generator liquid level high 2) abnormal working condition occur, the electric feed water pump accepts trip signal. This improvement adds frequency conversion in Regulating, Regulating. Regulating has no change in logic and does not affect the electric feed water pump to accept trip signal. In addition, it has no influence on the trip signal of the electric pump itself, such as low lubricating oil pressure and high thrust bush of the front pump.

![Fig. 3 Schematic diagram of speed regulation of electric feed water pump](image-url)
6. Economic analysis

According to a typical hydraulic coupler and inverter efficiency Figure 5, the hydraulic coupler efficiency is lower at low loads, but the inverter can maintain higher efficiency. According to the operation of the nuclear power plant in 2019, the operating hours of 77% rated power are 1410h, the operating hours of 50% rated power are 42h, and the disconnection hours are 288h. After the improvement of frequency conversion, 7.5 million KW.h can be saved every year. In addition, after the improvement of frequency conversion, the hydraulic coupler keeps 100% opening, and the loss caused by 110% capacity of electric feed water pump is saved by frequency conversion. According to Qinshan Nuclear Power Plant, the cost of single frequency conversion transformation in Circulating Water Pump is about 2.5 million [5], and its Circulating Water Pump in is 1600kW. According to Huolinhe Kengkou Power Plant, the frequency conversion transformation of three electric feed pumps is about 20 million, and the electric power rate of the electric feed pumps is 8500kW [6]. According to the application prospect of frequency conversion energy saving in BOP of nuclear power plant [7], the imported frequency converter is about 1000 yuan/kW, and the electric feed pump studied in this paper is 10000kW. It is preliminarily estimated that the transformation cost of three electric feed pumps is about 30 million, and the recovery cost is about 4 years.

7. Summarize

According to the actual operation of a nuclear power unit, this paper analyzes the frequency conversion of electric feed water pump from the technical and economic aspects, and draws the following conclusions:

(1) The low efficiency of electric feed water pump in nuclear power plant at low power is mainly due to the adoption of hydraulic coupler structure, and the lower the power, the lower the efficiency of hydraulic coupler;
(2) The capacity loss of electric feed water pump is relatively large, and the nuclear power unit bearing the base load can also consider frequency conversion improvement to eliminate the capacity loss;
(3) Frequency conversion transformation of electric feed water pump in nuclear power plant is technically feasible, attention should be paid to low frequency control to prevent cavitation of pressure stage pump;
(4) The frequency conversion of electric feed water pump in nuclear power plant has a high economic income, and it can be repaid in about 4 years;
(5) The Steam generator feed water system of nuclear power plant is not a safety-related system, and the frequency conversion transformation of electric feed water pump has no impact on the safety of reactor and the reception of various trip signals of electric pump.

References


