IOP Conference Series: Earth and Environmental Science

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To cite this article: Cheng Wang *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **300** 042070

The Parameter Optimization of Regenerative-reheat System in Pressurized Water Reactor Nuclear Power Plant

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Abstract. Regenerative-reheat system is the core of the thermal system of pressurized water reactor nuclear power plant (PWR NPP), which determines the economy of the unit directly. A mathematical model of regenerative-reheat system of a typical 900 MW nuclear power plant is established and validated. Given the bounding condition group, the regenerative-reheat system optimization is carried out by using the hybrid genetic algorithm to optimize the flow of extraction steam. The results show that the output power increases 7.84MW in the optimized scheme, which effectively reduces the nuclear fuel consumption and demonstrates the capability of the optimization method in improving the economy of the NPP.

1. Introduction

Pressurized water reactor nuclear power plant has more than three quarters markets of nuclear power in China. Compared with fossil fuel power plant, the PWR NPP is characterized by low thermal efficiency. Limited by the nuclear safety criterion and reactor core material, it is almost impossible to improve thermal efficiency of the PWR NPP by increasing the operation temperature of nuclear core at present stage. Thus, it is necessary to find an effective way from other aspects to realize the thermal efficiency improvement of the PWR NPP and to relieve the nuclear fuel supply pressure. In this work, the operation parameter optimization of PWR NPP thermal system using intelligence algorithm is studied.

In regenerative-reheat system of the PWR NPP, the live steam and the turbine extraction steam of different stages are extracted to reheat the exhaust steam of high-pressure turbine and to heat the feed-water of steam generator, which are conventional and effective means to increase the thermal efficiency of the NPP. However, the traditional design methods of regenerative-reheat system such as equal temperature rise distribution, equal specific enthalpy rise distribution, geometric progression distribution and cyclical function distribution etc. [1] are based on different degrees of simplified model of the thermal system, which cannot get an optimal thermal design of the system. Zhao et al. [2] and Zhou et al. [3] established mathematical models of regenerative system of given power plants, based on the models, the parametric optimization of the regenerative systems were conducted using intelligence algorithms. In their studies, the thermal efficiency the power plants increased by 0.31% and 0.51%, respectively. It should be pointed out that in the studies only the regenerative system, rather than the whole regenerative-reheat system was optimized, which limited the efficiency increment of the optimized thermal system. In this work, an accurate mathematical model of the regenerative-reheat system of a typical NPP is established, based on which, comprehensive parametric optimization of the regenerative-reheat system aiming at maximizing power output using a modified intelligence algorithm

IOP Conf. Series: Earth and Environmental Science **300** (2019) 042070 doi:10.1088/1755-1315/300/4/042070

is carried out. The comprehensive optimization is able to further improve the economy of the given power plant.

2. Mathematical model of the regenerative-reheat system

2.1. Configuration of the regenerative-reheat system

The Daya Bay nuclear power plant, a typical PWR NPP based on M310 technical scheme is selected for research [4]. The schematic diagram of the thermal system of Daya Bay NPP is given in Fig. 1.

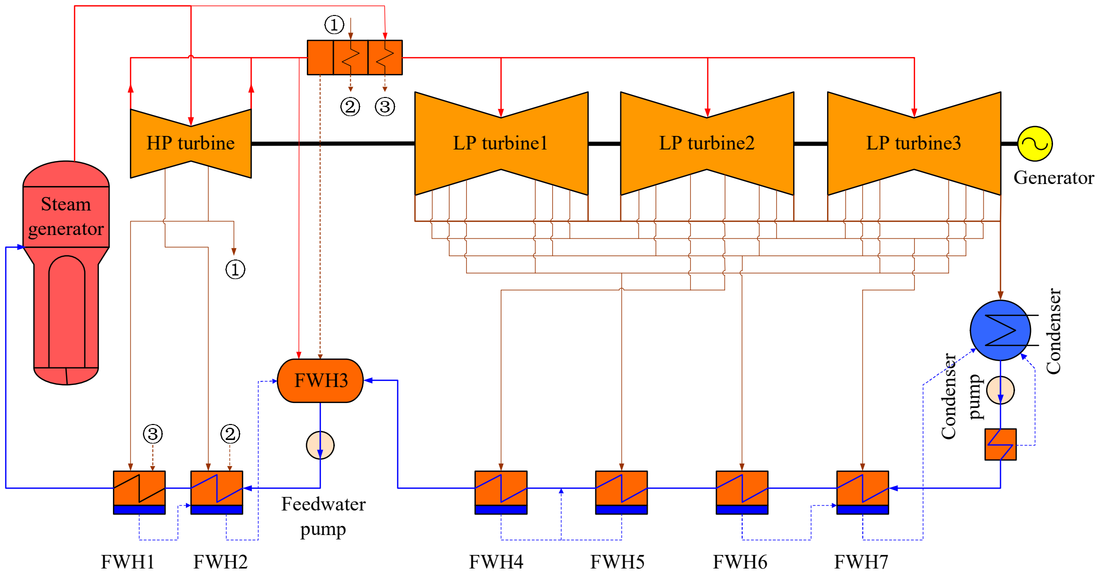

Figure 1. Diagram of the regenerative-reheat system of Daya Bay PWR NPP

It is a modified Rankine cycle with reheat and regenerative configuration. As is shown in the diagram, the reheat system includes two reheaters (RH1 and RH2) and one moisture separator (MS), and the regenerative system comprises two high pressure feedwater heaters (FWH1 and FWH2), one de-aerator also playing the role of feedwater heater (FWH3) and four low pressure feedwater heaters (FWH4, FWH5, FWH6 and FWH7). The heating steam of the RH1 is extracted from the 2th stage of high pressure turbine, and the drain water of the reheater is piped to the steam side of the FWH2. The heating steam of the RH2 is bypassed from the live steam line, and the drain water is piped to the steam side of the FWH1.The drain water of the MS is piped to the FHW3. The heating steam of the FWH1 and FWH2 is extracted from the 2th and 3th stage of high pressure turbine, and the drain water stepped flows to the FWH3. The heating steam of the FWH3 is bypassed from the exhaust steam line of the high pressure turbine. The heating steam of the FWH4 to FWH7 is extracted from the 1th to 4th stage of high pressure turbine, respectively. The drain water of FWH6 and FWH7 stepped flows to the condenser.

2.2. Mathematical model of the regenerative-reheat system

The state parameters and mass distribution of working fluid in the regenerative-reheat system are interrelated. Given the state of the system, the thermohydraulic performance including thermal efficiency can be determined. According to the configuration of the system, the power output and thermal efficiency of the system in a given state can be calculated by solving the set of mass conservation equation, heat balance equation and turbine power equation.

For all the device in the system (including heat exchanger, pump, turbine etc.), the mass balance equation can be given by a general formula:

$$\sum_{i=1}^{m} \dot{m}_{i,in} = \sum_{j=1}^{n} \dot{m}_{j,out}$$

Where $m_{i,in}$ is the mass flow rate of the i-th working fluid following into the device, $m_{j,out}$ is the mass flow rate of the j-th working fluid following out the device.

The reheater, feedwater heater, condenser and shaft-seal chiller are conventional heat exchanger, the heat balance equation is also given by a general formula:

$$\eta_{he}\left[\dot{m}_h(h_h - h_{out}^{dw}) + \sum_{i=1}^{n} \dot{m}_{in}^{dw,i}(h_{in}^{dw,i} - h_{out}^{dw})\right] = \dot{m}_c(h_{in}^{c} - h_{out}^{c})$$

Where η_{he} is the efficiency of the heat exchanger, and the value is 0.99 in this work, $\dot{m}_h$ and h_h are mass flow rate and specific enthalpy of the heating fluid, $\dot{m}_c$, h_{in}^{c} and h_{out}^{c} are mass flow rate and inlet/outlet specific enthalpy of the cooling fluid, $\dot{m}_{in}^{dw,i}$ and $h_{in}^{dw,i}$ are mass flow rate and specific enthalpy of the i-th drain water following into the heat exchanger, h_{out}^{dw} is the drain water specific enthalpy of the heat exchanger.

In order to accurately simulate the thermohydraulic state of the regenerative-reheat system, the pressurizing effect of the feedwater pump and condensate pump should be take into account though they occupy a small part of the total feedwater enthalpy rise. The feedwater enthalpy rise caused by the pumps can be estimated by:

$$\Delta h_p = \upsilon_{av}\left(p_{out} - p_{in}\right)/\eta_p$$

Where η_p is the efficiency of the pump (the value is 0.75), υ_{av} is the average specific volume of the inlet and outlet working fluid of the pump, p_{in} and p_{out} are inlet and outlet pressure of the pump.

The steam turbine generator unit comprises serial stages where the internal energy of the steam converted into kinetic energy, and further into electric energy. As the extraction points divide the turbine stages into different stage groups, the total power output of the turbine generator unit is the sum of all stage groups.

$$\dot{W}_e = \eta_m\eta_e\left[\sum_{i=1}^{m} \dot{m}_i^{hpt}(h_i^{hpt} - h_{i-1}^{hpt}) + \sum_{k=1}^{3}\sum_{j=1}^{n} \dot{m}_{k,j}^{lpt}(h_{k,j}^{lpt} - h_{k,j-1}^{lpt})\right]$$

Where η_m is the turbine mechanical efficiency (the value is 0.99), η_e is the generator efficiency (the value is 0.985), $\dot{m}_i^{hpt}$ and h_i^{hpt} are the mass flow rate and inlet specific enthalpy of i-th stage group of high pressure turbine, $\dot{m}_{k,j}^{lpt}$ and $h_{k,j}^{lpt}$ are the mass flow rate and inlet specific enthalpy of j-th stage group of k-th low pressure turbine.

Note that all the operation parameters in the regenerative-reheat system including turbine extraction parameters are interrelated. Hence, the Flugel formula [5] is an indispensable tool to calculate the turbine operation parameters at off-design condition:

$$\dot{m}_{st}'/m_{st} = \sqrt{(p_i'^2 - p_z'^2)/(p_i^2 - p_z^2)}\sqrt{T_i/T_i'}$$

Where m_{st}, T_i, p_i, $\dot{m}_{st}'$, T' and p_i' are the mass flow rate, temperature and pressure of inlet steam of i-th stage under design and off-design condition, p_z and p_z' are inlet steam pressure of last stage under design and off-design condition.

Based on the former formulas, the mathematical model of the regenerative-reheat system has been established. The input variables are the mass flow rates of the heat exchangers, and the outputs are operation parameters of the system including electric power. Figure 2 presents the flow of the mathematical model. It should be pointed out that the thermal load of the steam generator remains unchanged and the de-aerator keeps sliding-pressure operation mode.

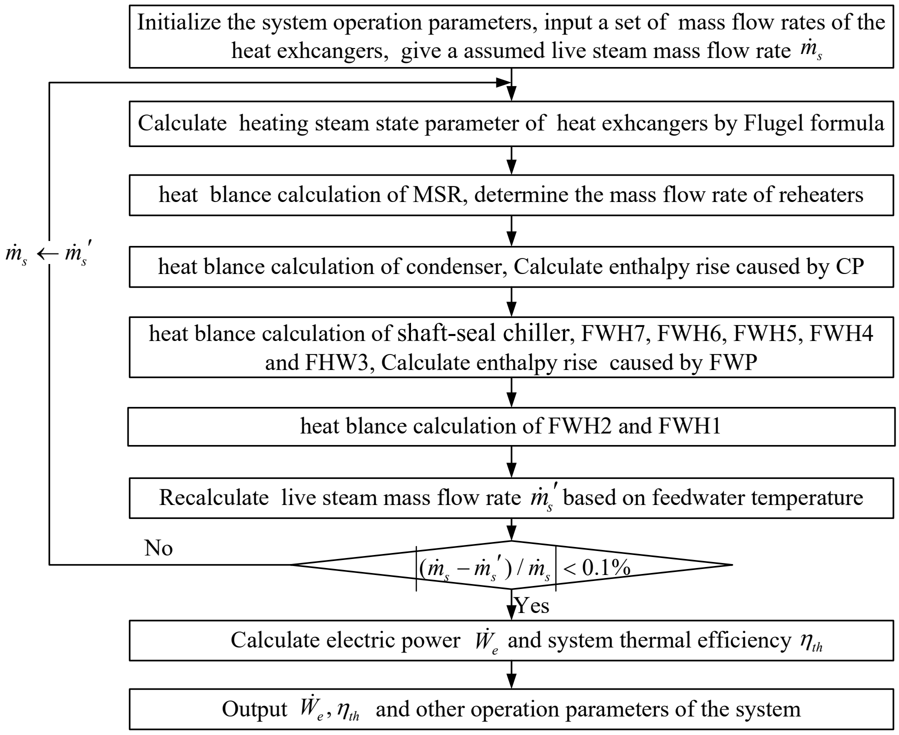

Figure 2. Flow of the mathematical model

2.3. Mathematical model validation

The validity of the mathematic model directly influences the accuracy of the parameter optimization results. Comparing the actual operation parameters with the simulation results of the Daya Bay PWR NPP at rated condition, the model accuracy has been validated. Table 1 presents the comparison results. The comparison indicates that the errors between the actual values and simulation values are within ±1%, which demonstrates that the model is suitable for the parameter optimization of the regenerative-reheat system.

Table 1. Comparison between actual values and simulation results

Parameters	Actual value	Simulation value	Error, %
Net electric power, MWe	983.8	981.6	-0.22
Live steam mass flow rate, kg/s	1613.4	1614.7	0.08
De-aerator pressure, MPa	0.7515	0.7493	-0.29
Condenser pressure, kPa	7.5	7.56	0.80
HP turbine outlet steam quality, %	85.80	85.95	0.17
LP turbine outlet steam quality, %	90.70	90.76	0.07
Feedwater temperature,℃	226.0	226.5	0.22

3. Parameter optimization of regenerative-reheat system

3.1. Design variables and objective function

The mass flow rate of heating steam of the heat exchangers directly influence the performance of the regenerative-reheat system. Thus the heating steam mass flow rates of the reheaters, de-aerator and feedwater heaters are taken as design variables simultaneously. The optimization objective is to maximize the power output of the NPP. The design variables and objective function is presented in the following form:

$$\begin{cases} \dot{W}_e = \max\limits_{\varphi_i(\mathbf{X})\le 0} f(\mathbf{X}) \\ \mathbf{X} = (m_{RH1}^{hs}, m_{RH2}^{hs}, m_{FWH1}^{hs}, m_{FWH2}^{hs}, m_{FWH3}^{hs}, m_{FWH4}^{hs}, m_{FWH5}^{hs}, m_{FWH6}^{hs}, m_{FWH7}^{hs})^T \end{cases}$$

3.2. Constraint conditions
Considering the thermohydraulic limitations and safe-operation demands, some reasonable constraints must be satisfied in the system parameter optimization. In this work, the constraint conditions are listed as follow:

1) The variations of the design variables are limited in ±20%, especially, the mass flow rate variations of heating steam of the first stage reheater is limited in ±10%;
2) The range of de-aerator operation pressure is 0.7MPa to 0.8 MPa;
3) The ratio of heating steam pressure and operation pressure of the de-aerator is larger than 1.05;
4) The range of feedwater temperature of the steam generator is 220℃ to 232℃;
5) The exhaust steam quality of the high pressure turbine is larger than 0.85;
6) The exhaust steam quality of the low pressure turbine is larger than 0.9;
7) The operation pressure of the condenser is larger than 7.0kPa.

All the constraint constraints form a feasible region of the design variables, which is expressed as $\varphi(\mathbf{X}) \le 0$.

3.3. Process of parameter optimization
Each **X** with concrete values represents an operation scheme of the regenerative-reheat system. The mathematical model can precisely estimate the power output and other performance parameters of every scheme. The intelligence algorithm is able to automatically search and compare different schemes within the feasible region, finally the optimal scheme is found. Because the parameter optimization of the regenerative-reheat system belongs to complex multi-variable non-liner constrained optimization problem, an algorithm with strong search ability is indispensable. In this work, a modified hybrid genetic algorithm is selected to implement the optimization. The excellent performance of the algorithm had been verified [6].

3.4. Parameter optimization results
The parameter optimization results are given in table 2 and table 3.
Seen from table 2, the electric power increases 7.84 MWe, and the corresponding thermal efficiency increases 0.79%. The power increment of the optimized scheme is owing to the increase of the feedwater temperature, which consequently increases the mass flow rate of live steam.

The operation parameter variations shown in table 3 indicate that the total mass flow rates must be increased to gain the feedwater temperature increment. Furthermore, a tendency can be seen that the mass flow rates of high quality heating steam decrease and meanwhile the mass flow rates of low quality heating steam increase.

Table 2. Optimization results of regenerative-reheat system

Parameters	original value	optimized value	Error, %
Net electric power, MWe	983.8	991.64	0.80
Thermal efficiency, %	33.95	34.22	0.79
Live steam mass flow rate, kg/s	1613.4	1638.8	1.57
De-aerator pressure, MPa	0.7515	0.7678	2.17
Condenser pressure, kPa	7.5	7.47	-0.4
HP turbine outlet steam quality, %	85.80	85.65	-0.17
LP turbine outlet steam quality, %	90.70	90.67	-0.33
Feedwater temperature,℃	226.0	232	2.65
Circulating water mass flow rate, t/s	43.94	43.71	-0.52

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Table 3. Variation of heating steam mass flow rate of the heat exchangers

Heat exchanger	original value	optimized value	Error, %
RH1	72.01	79.21	10.0
RH2	77.58	70.47	-9.2
FWH1	76.48	91.78	20.0
FWH2	120.68	111.02	8.7
FWH3	70.33	64.7	8.7
FWH4	33.14	41.42	-20.0
FWH5	30.19	40.24	-20.0
FWH6	53.95	48.36	11.6
FWH7	62.68	52.23	20.0

4. Conclusion

The comprehensive parameter optimization of regenerative-reheat system can effectively increase the power output of NPP and consequently reduce the nuclear fuel consumption without system configuration change or device replacement;

Decreasing the mass flow rates of high quality heating steam and meanwhile increasing the mass flow rates of low quality heating steam are effective tactics to maximize the power output and thermal efficiency of NPP.

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