# OPTIMAL DESIGN OF A NUCLEAR POWER PLANT CONDENSER CONTROL SYSTEM BASED ON MULTI-OBJECTIVE OPTIMIZATION ALGORITHM

by

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Scientific paper
https://doi.org/10.2298/NTRP2002095Z

**A condenser control system of a nuclear power plant consists of a pressure control system, a condensate water sub-cooling degree control system and a water level control system. The existing control optimization methods can hardly take into account all the performance indices of the three control systems at the same time. To solve this problem, this paper presents a control optimization method based on a multi-objective optimization algorithm. This method takes control parameters as optimization objects, and takes the performance of step response as optimization objectives. The multi-objective particle swarm optimization algorithm based on Pareto dominance concept is used to solve the optimization problem. This enables obtaining of high-quality control parameters. Simulation results confirm the feasibility and effectiveness of this control optimization method.**

*Key words: nuclear power plant, condenser control system, control parameter optimization, multi-objective optimization algorithm, particle swarm optimization algorithm*

## INTRODUCTION

As the most important cooling source in a secondary circuit, a condenser plays an irreplaceable role in the process of energy conversion and mass circulation in a nuclear power plant. The quality of the condenser control system directly affects the response speed and stability of the device [1], so it needs to meet higher control requirements. The condenser itself has complex characteristics such as strong coupling, drastic phase change, multi-input, and multi-output. These characteristics cause difficulties in the control process of a condenser. At present, most condenser control systems of nuclear power plants adopt the proportional integral (PI) control method. In order to improve the quality of a condenser control system, it is necessary to optimize the parameters of PI controller.

The condenser control system of a nuclear power plant is composed of the following three subsystems: a pressure control system, a condensate water sub-cooling degree control system, and a water level control system. There are complex coupling relations among controlled objects of the above three control systems. The traditional optimization method is to optimize a single control system one by one after decoupling. But the optimization of one control system may affect the quality of other control systems. In order to simultaneously take into account the performance indices of the three control systems, the optimization problem of the coupled control systems can be regarded as a multi-objective optimization problem. A multi-objective optimization algorithm can then be used to solve the multi-objective optimization problem and the limitations of separate optimizations after decoupling can in this way be avoided.

Considering the rapidity and stability of the three control systems, in this paper the time-domain performance index, ISTE, based on error integral is taken as the optimization objective. The optimization design methods of a nuclear power system include Monte Carlo method [2], neural network method [3], and intelligent optimization algorithm [4]. An intelligent optimization algorithm named multi-objective particle swarm optimization (MOPSO) [5] based on Pareto dominance concept is adopted to optimize the control parameters, thus a good control quality of the control system can be obtained.

## MODELING OF A NUCLEAR POWER PLANT CONDENSER

The RELAP5 program is a transient simulation program commonly used in nuclear power plant mod-

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eling [6, 7]. The nuclear power plant condenser model established by RELAP5 program can be reliable [8]. The modeling of a condenser by RELAP5 program consists of three steps: model nodes partition, boundaries setting, and input cards compiling.

### Model nodes partition

The nodes partition method of control simulation model needs to consider the following three important factors:

- First, the nodes partition of the model should correctly reflect the basic structure.
- Second, the relevant parts of control quantities (such as parts of measuring points) should be divided into separate nodes to ensure the accuracy of control simulation.
- Third, for a two-phase flow model, the parts where the phase changes should be divided into relatively detailed nodes to ensure accuracy.

According to those three factors, the condenser model is divided into shell side and tube side, and the shell side is divided into steam zone and water zone. Condensate flow of the tube side runs through the steam zone to condense steam. The bubble deaerator is connected to the bottom of the water zone. The water supply tank and drain tank connect to the water zone. The circulating water pump is installed at the front of the tube side.

### Setting boundaries

To separate the condenser from the secondary loop system, it is necessary to set boundaries for the condenser model. The shell side and the tube side of the condenser are two non-circulating parts, so we need to set boundaries separately for each part.

For the shell side, the exhaust nozzle connecting the condenser to the steam turbine is set as the upper boundary, and the back end of the condensate pipe is set at the bottom of shell side as the lower boundary. For the tube side, the inlet and outlet of the tube side connecting to sea water is set as the left boundary and the right boundary. Temperature, pressure and phase state are kept constant in each boundary. Exhaust flow from the upper boundary to the condenser is used to be the load of the secondary circuit system.

### Compiling input cards

Model nodes partition and boundaries setting is shown in fig. 1. Based on the analysis and design parameters of the condenser, we complete the RELAP5 input cards of the condenser. After that, a controlled object model of a nuclear power plant is established.

## CONDENSER CONTROL SYSTEM SCHEME

### Condenser pressure control system

When a nuclear power plant is in normal working conditions, the pressure of the condenser needs to be maintained at a low and stable level. In this way the condenser can provide low and stable back pressure for the steam turbine to ensure the efficiency and stability of the plant [9, 10]. The existing pressure control system of the condenser generally adopts PI control method. The controller keeps pressure at a set point by changing the flow of the circulating cooling water by adjusting the speed of the circulating water pump. The scheme of the condenser pressure control system is shown in fig. 2.

The system adopts cascade and feed-forward control scheme. The exhaust flow signal is used as feed-forward signal to rapidly adjust the circulating cooling water flow. The circulating cooling water flow signal is used as the feedback signal to overcome the speed disturbance of the circulating pump. The pressure measurement value signal is used to calculate pres-

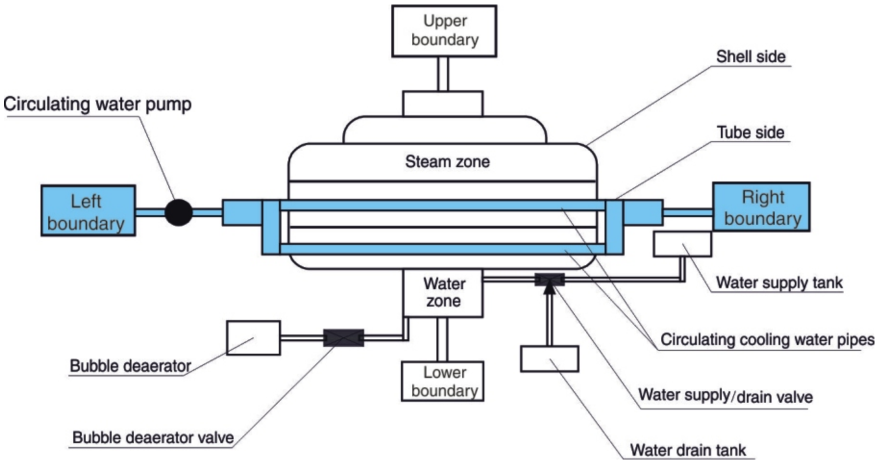

**Figure 1. Schematic diagram of a nuclear power plant condenser model structure**

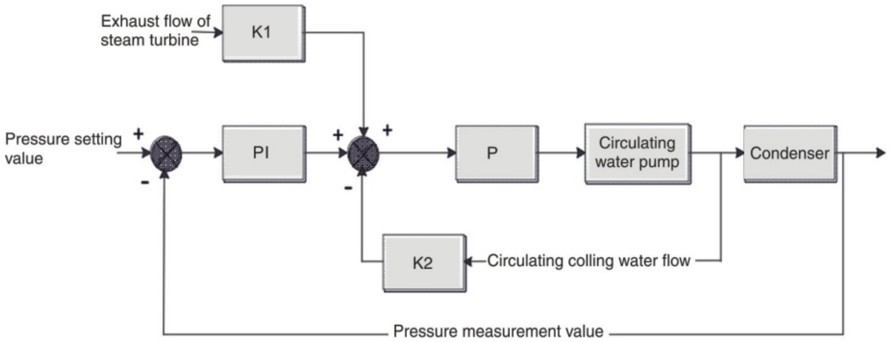

**Figure 2. Schematic diagram of a condenser pressure control system:** *K1 – the feed forward gain of exhaust flow signal, K2 – the feedback gain of circulating cooling water flow rate signal, PI – the proportional integral controller, and P – the proportional controller*

sure deviation. The main controller is a PI controller, and the secondary controller is a proportional controller.

### Condensate water sub-cooling degree control system

Condensate water sub-cooling degree is the difference between saturation temperature that corresponds to condenser pressure and condensate water temperature. The reasons why the sub-cooling degree appears are the uneven distribution of condensate film temperature and gas resistance on the shell side [11]. High sub-cooling degree will lead to high oxygen content in condensate water, and high oxygen content will threaten the safety of the devices and systems. Low sub-cooling degree may cause condensate water gasification which will damage the condensate pump. Therefore, the sub-cooling degree of condensate water is required to be controlled at a set point. The scheme of condensate water sub-cooling degree control system is shown in fig. 3. By regulating the opening of the bubble deaerator valve, the rate of exhaust steam flow for heating condensate is adjusted, and then the condensate sub-cooling degree can be controlled at a set point.

### Water level control system

High water level in the condenser may cause the cooling water pipes to be submerged, and this situation will affect steam condensation and cause condensate water sub-cooling. Low water level may cause cavitation in the condensate pump and damage the pump [12]. Therefore, the water level is required to be controlled within a proper range. The PI controller is adopted in the control system, and the water level is controlled by regulating the opening of the supply/drain valve. The scheme of water level control system is shown in fig. 4.

### Coupling relation of control systems

The condenser of a nuclear power plant is a multivariable coupled device. In normal working conditions, the three control systems work simultaneously, and the controlled objects of the system have the following complex coupling relations:

– First, the change of pressure causes the change of saturation temperature, which leads to the change of condensate water sub-cooling degree.

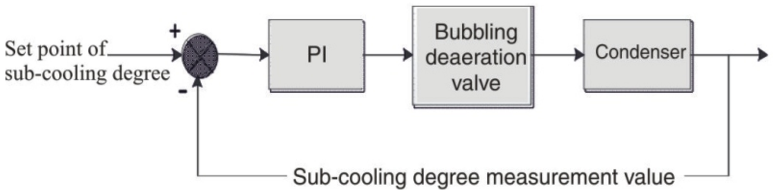

**Figure 3. Schematic diagram of condensate water sub-cooling degree control system**

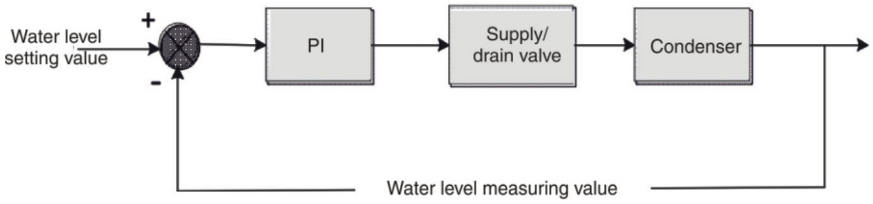

**Figure 4. Schematic diagram of water level control system**

– Second, the change of circulating cooling flow rate will cause the change of steam condensation amount, which leads to the change of water level.
– Third, supply/drain flow rate causes the change of condensate temperature, which leads to the change of condensate water sub-cooling degree.
– And last, the rate of bubbling exhaust steam flow may cause condensate water to flash and the pressure to change.

According to those analysis, it can be concluded that although the controllers and actuators of the three control systems are independent, the controlled objects are coupled with each other. In this way, the three control systems of a condenser have an indirect coupling relationship. This coupling relationship results in difficulties in the optimization of the control systems. Traditional optimization methods can only optimize control systems one by one in the optimization process. During the optimization for one control system, the other control systems are treated as boundaries. This situation makes it difficult to ensure that the performance of other control systems is not affected. In contrast, the multi-objective optimization method for multiple control systems is obviously more suitable for the performance optimization of coupled control systems.

## MULTI-OBJECTIVE OPTIMIZATION ALGORITHM BASED ON PARETO DOMINANCE CONCEPT

### Multi-objective optimization problem and pareto dominance relation

In the field of optimization, the general definition of multi-objective optimization problem (MOP) is as follows [13].

There exists a MOP

$$\begin{aligned} \min\ f(x) \quad & [f_1(x), f_2(x), \ldots f_n(x)]^T \\ s.t.\ g_i(x) \quad 0 \quad i \quad & 1,2,\ldots,j \\ h_i(x) \quad 0 \quad i \quad j \quad & 1,\ldots,p \end{aligned} \tag{1}$$

where $s.t.$ is the abbreviation of the subject, $x = (x_1, x_2, ..., x_n)^T$ – the $n$-dimensional solution of the optimization problem, and $f_i(x)$ ($i = 1, 2, ...., n$) – the sub-objective function of the problem. The space where the $n$-dimensional vector $f(x) \quad [f_1(x), f_2(x), \ldots f_n(x)]^T$ is located is called the objective space. Here, $g_i(x) \quad \underline{i} \quad j$ stands for inequality constraints and $h_i(x) = 0$ ($i = = j + 1, ..., p$) are equality constraints.

Unlike solving single-objective optimization problems, solving MOP requires comparison of the multiple sub-objective functions of different solutions according to Pareto dominance relations. The Pareto dominance relation is defined as follows [13]

Solution $x^0$ dominates $x^1$ denoted by $x^0 \succ x^1$, if and only if

$$\begin{aligned} f_i(x^0) \quad f_i(x^1), i \quad & 1,2,\ldots,M \\ f_i(x^0) \quad f_i(x^1), \ i \quad & \{1,2,\ldots,M\} \end{aligned}$$

There are three kinds of relations among the solutions of MOP: dominating, dominated, and non-dominated. The solution which is not dominated by any other solution is called the Pareto optimal solution of the MOP. In general, the Pareto optimal solution is not unique. The set of all Pareto optimal solutions is called the Pareto optimal solution set. For practical problems, we need to select some of the Pareto optimal solutions according to relevant requirements.

### Multi-objective particle swarm optimization algorithm based on pareto dominance concept

Particle swarm optimization (PSO) [14] is an evolutionary computing technology based on swarm intelligence.

The MOPSO algorithm adds an external elite set based on PSO. In addition to updating particle velocity and position, each iteration process also needs to update the external elite set according to Pareto dominance. After the completion of the final iteration, the external elite set is the optimal solution set of the MOP. The key steps of MOP algorithm include updating of Particlebest (the best position of itself, or *pbest* for short) and Globalbest (the best position of the whole space, or *gbest* for short), updating the particle swarm speed and position, and updating the external elite set.

### Particlebest and globalbest update

After one step of iteration, if the previous *pbest* of a particle dominates the current particle position, its *pbest* remains unchanged, if the current particle position dominates its previous *pbest*, update its *pbest* to the current particle position, if the previous *pbest* of a particle and its current position are not dominated by each other, randomly select one of the two positions as its *pbest*.

Select a set of solutions randomly from the current elite group as the *gbest*.

### Particle swarm velocity and location update

The standard particle swarm algorithm updating formulas are used to update the speed and position of the particle swarm. The updating formulas are

$$\begin{aligned} v(i)_{k \quad 1} \quad w_k v(i)_k \quad & c_1 rand[pbest(i)_k \quad x(i)_k] \\ & c^2 rand[gbest(i)_k \quad x(i)_k] \end{aligned} \tag{2}$$

$$x(i)_{k+1} = x(i)_k + v(i)_{k+1} \tag{3}$$

where $v(i)_k$ is the current particle velocity, $v(i)_{k+1}$ – the updated particle velocity, $w_k$ – the inertia weight of the $k$-generation particle, $c_1$ and $c_2$ are individual learning factor and global learning factor, separately, $pbest(i)_k$ – the Particlebest $gbest(i)_k$ – the Globalbest, and $x(i)_k$ and $x(i)_{k+1}$ are the current particle position and the updated particle position separately.

### External elite set update

The external elite set is used to reserve the Pareto optimal solutions obtained in the iteration process. After an iteration, if the current particle is dominated by any member of the elite set, then it is rejected and not included in the elite set; if the current particle dominates one or more members of the elite set, the dominated member is removed and the current particle is added to the elite set; if the current particle and all elite members do not dominate each other, the current particle is added to the elite set.

### Basic algorithm steps

According to the basic principle of the multi-objective algorithm, the implementation steps of the multi-objective algorithm proposed in this paper are as follows:

- *Step 1*. The maximum number of iterations, inertia weight and learning factor variation are set. The number of iterations, inertia weights and learning factors are initialized. Initialize the velocity and position of particle swarm are randomly initialized in the search range. The values of objective functions are obtained according to the initial positions and the initial elite set is obtained by using Pareto dominance relation. The initial position is set as the *pbest* of each particle.
- *Step 2.* The *gbest* is randomly selected from the elite set.
- *Step 3.* The speed and position of particles are updated by using updating formulas of standard particle swarm algorithm.
- *Step 4.* Pbest of each particle is updated.
- *Step 5.* External elite sets are updated;
- *Step 6.* It is verified whether the maximum number of iterations is reached, if so, searching is interrupted, and the external elite set is output as the Pareto optimal solution for the MOP, otherwise, it is necessary to turn to *Step 2*.

## APPLICATION OF MULTI-OBJECTIVE OPTIMIZATION ALGORITHM IN CONDENSER CONTROL OPTIMIZATION

### Modeling of condenser control system and controlled object

According to the condenser control system scheme, the condenser control system model is established in MATLAB/SIMULINK program. The condenser controlled object model is established in the RELAP5 program. The control system model and the condenser controlled object model are combined to form a closed control loop by using the control simulation platform called Server Manager.

### Multi-objective optimization model of control parameters

In order to make the condenser control performance meet the requirements concerning rapidity and stability, the integral of time multiplied with squared error (ITSE) indices of pressure and condensate water sub-cooling degree control systems are taken as the optimization objectives. The ITSE index can be expressed as follows

$$ITSE = \int t e^2 \mathrm{d}t \tag{4}$$

where $t$ is the simulation time and $e$ – the error between the measured value and the set value. The smaller ITSE is, the faster the system tends to be stable, and the smaller the average error is.

In order to keep water level in the prescriptive range during the transient process, the prescriptive range is taken as the inequality constraint. The control parameters of the three control systems are taken as optimization objects. This optimization model can be expressed as

$$\begin{gathered} \min f(kp_1, kp_1, ki_1, kp_2, ki_2, kp_3, ki_3) \\ = [ITSE1, ITSE2]^T \\ s.t.\ kp_{\min} \le kp \le kp_{\max} \\ ki_{\min} \le ki \le ki_{\max} \\ lw_{\min} \le lw \le lw_{\max} \end{gathered} \tag{5}$$

where $kp_1$, $ki_1$, $kp_2$, $ki_2$, $kp_3$, and $ki_3$ are the PI controller parameters of the three control systems, and $kp_1$ is P controller parameter of the condenser pressure control system. The $ITSE1$ is the $ITSE$ index of the condenser pressure control system. The IT is the $ITSE$ index of condensate water sub-cooling degree control system. $[kp_{\min}, kp_{\max}]$ and $[ki_{\min}, ki_{\max}]$ are the search ranges for all the parameters. The search ranges are obtained by extending the tuning results of the critical proportional method [15]. The search ranges are some rough ranges with low precision requirement.

### Application of multi-objective optimization algorithm

For general optimization problems, the feasible solution is usually entered into the objective function to calculate the objective value. For the optimization problem of condenser control parameters, we take the feasible solutions as the control parameters and enter them into the control simulation model to get the ITSE indices as optimization objectives through a transient process simulation. The application process of multi-objective optimization algorithm in condenser control optimization is shown in fig. 5.

The aforementioned process is written in MATLAB program to realize the algorithm. The maximum number of iterations is set to 100 and set the number of particle swarm to 30. The initial inertia weight is 0.9, and the range of variation is [0.4, 0.9]. The range of individual learning factor and global learning factor is [1.25, 2.75] and [0.5, 2.25]. Working condition of step load from 90 % FP (full power) to 100 % FP is used as the transient process to be optimized.

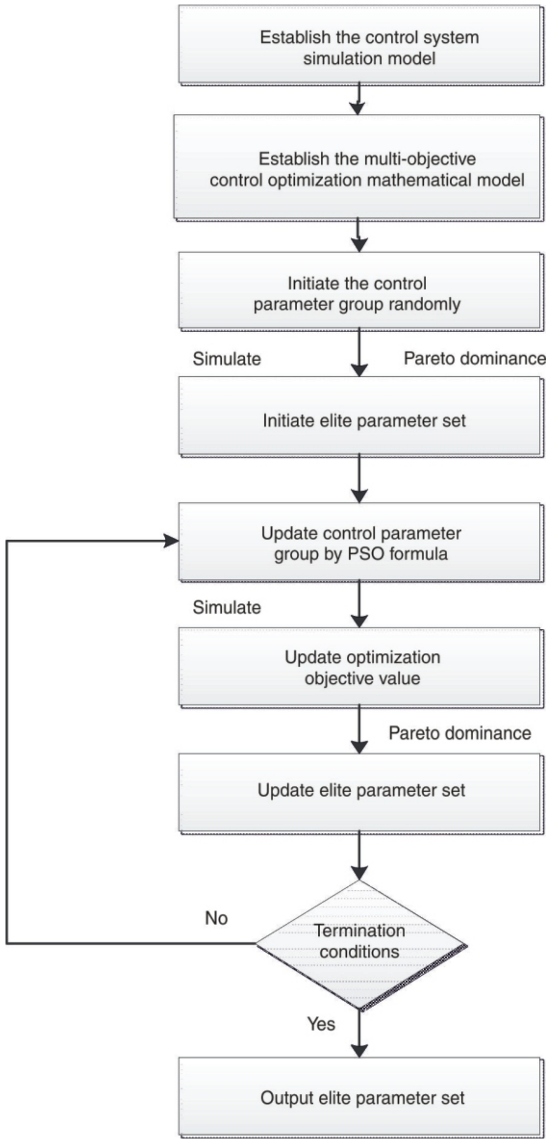

**Figure 5. Application process of multi-objective optimization algorithm in optimization of control system parameters**

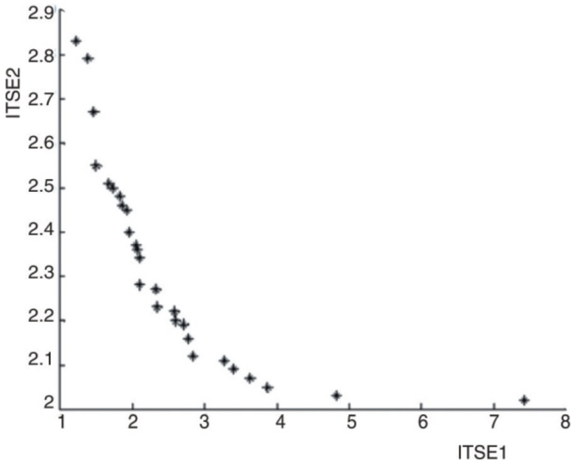

**Figure 6. The distribution of Pareto optimal solutions in the objective plane**

**Table 1. Optimal control parameters and optimal objective values**

| No. | $kp_1$ | $kp_1'$ | $ki_1$ | $kp_2$ | $ki_2$ | $kp_3$ | $ki_3$ | ITSE1 | ITSE2 |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 16.91 | 2.26 | 2.50 | 23.09 | 1.55 | 13.81 | 0.41 | 1.24 | 2.83 |
| 2 | 18.25 | 2.93 | 1.31 | 29.02 | 2.00 | 14.04 | 0.80 | 1.74 | 2.50 |
| 3 | 11.65 | 2.45 | 0.73 | 27.39 | 2.14 | 13.26 | 0.58 | 2.33 | 2.27 |
| 4 | 18.57 | 2.63 | 1.13 | 24.37 | 1.72 | 18.17 | 0.41 | 3.64 | 2.07 |
| 5 | 17.98 | 2.97 | 1.72 | 11.10 | 1.44 | 11.03 | 0.57 | 7.43 | 2.02 |

After all the iterations, 27 sets of Pareto optimal solutions are obtained, that is 27 sets of optimal control parameters. The optimization objectives corresponding to all control parameter sets are shown in the objective plane, as shown in fig. 6.

Five representative sets of optimal control parameters were selected, as shown and numbered in tab. 1.

According to fig. 6 and tab. 1, it can be seen that the optimal objective values of the obtained optimal control parameters do not dominate each other. The optimization degree of the condenser pressure control system performance (ITSE1) and the condensate water sub-cooling degree control system performance (ITSE2) are different. If the optimization of ITSE1 is emphasized, the optimization of ITSE2 is relatively weak, and vice versa. Decision makers can choose one or more sets of solutions according to their preference.

## SIMULATION AND VERIFICATION OF OPTIMIZATION RESULTS

Set of optimal control parameters No. 3 with more balances optimization degrees in tab. 1 is selected as the final parameters of condenser control systems. The simulation result is compared with the

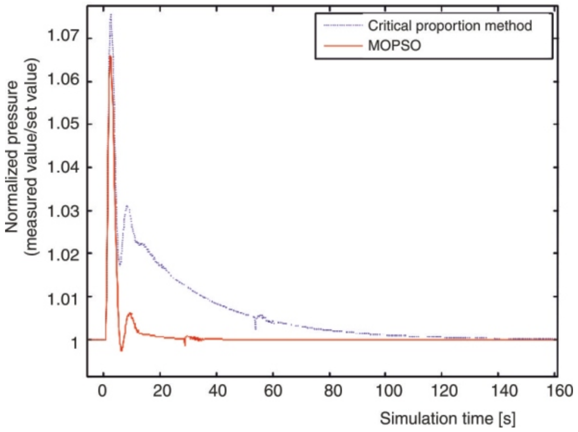

**Figure 7. Comparison of the control performance of condenser pressure**

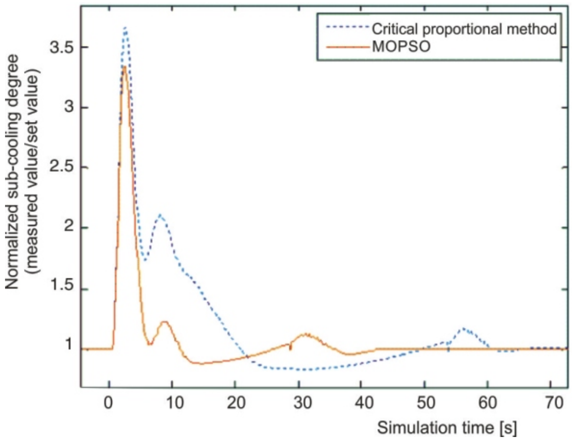

**Figure 8. Comparison of the control performance of condensate sub-cooling degree**

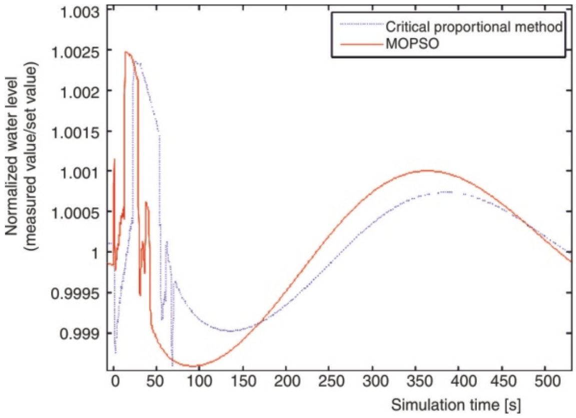

**Figure 9. Comparison of the control performance of hot well water level**

optimization result of the critical proportional method. The transient simulation working condition is step load change from 90 % FP to 100 % FP. The comparison results are shown in figs. 7-9.

In the comparison of control performance of condenser pressure, and condensate water sub-cooling degree, the average oscillation amplitude of transient curve obtained by MOPSO algorithm is smaller, the adjustment time is shorter, and the transient curve can be stabilized faster after load step. At the same time, the transient curves of the water level obtained by the two methods are kept within the set range, which meets the control requirement. The result of the control optimization by MOPSO algorithm is better than the critical proportional method in general.

## CONCLUSION

In this paper, a multi-objective optimization algorithm based on Pareto dominance concept is used to optimize the control parameters of nuclear power plant condenser control system. The optimization and simulation result shows that the multi-objective optimization algorithm can achieve control optimization that takes into account multiple indices. Compared with the critical proportional method, the multi-objective optimization algorithm has a better optimization effect. On the other hand, the Pareto optimal solution sets obtained by the multi-objective optimization algorithm has the diversity which can bring better flexibility in solving specific engineering problems. Clearly, this multi-objective optimization algorithm offers strong generality in optimization of coupling control system.

## AUTHORS CONTRIBUTIONS

All the authors made valuable contributions to this research. L. Yiliang did a lot of work about control systems modeling and algorithmic coding; H. Ke helped with simulation data processing; X. Kai provided important help in thermal and hydraulic modeling.

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Received on April 16, 2020
Accepted on July 21, 2020

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# ОПТИМАЛНИ ДИЗАЈН КОНТРОЛНОГ СИСТЕМА ХЛАДИОЦА НУКЛЕАРНЕ ЕЛЕКТРАНЕ ЗАСНОВАН НА МУЛТИ-ОБЈЕКТИВНОМ АЛГОРИТМУ ОПТИМИЗАЦИЈЕ

Систем за контролу хладиоца нуклеарне електране састоји се од система за контролу притиска, систем за контролу степена подхлађења кондензоване воде и система за контролу нивоа воде. Постојеће методе за оптимизацију контроле система тешко да могу да узму у обзир све индексе перформанси сва три система за контролу истовремено. Како би се овај проблем решио, овај рад представља методу за оптимизацију контроле система засновану на мулти-објективном оптимизационом алгоритму. Метода узима параметре контроле за објекте оптимизације и сматра извођење степ одзива циљевима оптимизације. Мулти-објективни оптимизациони алгоритам мноштва честица заснован на Парето концепту доминације примењен је за решавање проблема оптимизације. Ово омогућава добијање контролних параметара високог квалитета. Резултати симулација потврђују практичност и ефективности ове методе за оптимизацију контроле система.

*Кључне речи: нуклеарна електрана, контролни систем хладиоца, оптимизација контролних параметара, мулти-објективни алгоритам оптимизације, оптимизациони алгоритам мноштва честица*