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Modeling a high output marine steam generator feedwater control system which uses parallel turbine-driven feed pumps

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Abstract: Parallel turbine-driven feedwater pumps are needed when ships travel at high speed. In order to study marine steam generator feedwater control systems which use parallel turbine-driven feed pumps, a mathematical model of marine steam generator feedwater control system was developed which includes mathematical models of two steam generators and parallel turbine-driven feed pumps as well as mathematical models of feedwater pipes and feed regulating valves. The operating condition points of the parallel turbine-driven feed pumps were calculated by the Chebyshev curve fit method. A water level controller for the steam generator and a rotary speed controller for the turbine-driven feed pumps were also included in the model. The accuracy of the mathematical models and their controllers was verified by comparing their results with those from a simulator.

Keywords: feedwater control; steam generator; modeling; feed pump; turbine
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1 Introduction

Marine steam generator feedwater control system is important to ensure the safe running of steam generator. Two turbine-driven feed pumps in parallel are needed to increase feedwater when ship voyages at a high speed. Steam generator control system does not perform well at every turn due to the dissymmetry setting of feedwater pipes and the turbine-driven feed pumps. Many researchers have studied the feedwater control system of steam generator in recent years[1-4], but few of them have paid attention to the operating condition when turbine-driven feed pumps are in parallel[5]. The mathematical model of steam generator control system under the condition of turbine-driven feed pumps in parallel was established in this paper. The water level controller of steam generator and the rotary speed controller of feed pumps were designed. The model and controllers were verified by the simulation results.

2 Mathematical model of steam generator

2.1 Basic assumption and model division

The lumped parameter method is used to build the steam generator mathematical model[6]. The longitudinal heat conduction of the primary and secondary loop sides of the steam generator and the heat-transfer pipe are omitted. The heat transfer of steam generator, the ascending and descending segments are also omitted. The secondary loop side of steam generator is divided into an ascending segment, a descending segment, a steam space, and a primary loop side water room.

2.2 Mathematical model

The meanings of variables and subscripts of mathematical model in this paper are shown in Table 1 and Table 2. The international units are used.

2.2.1 The mathematical model of primary loop side steam generator

Energy balance equation:

$$(G_pC_p + G_mC_m)\mathrm{d}T_{pa}/\mathrm{d}\tau = W_pC_p(T_{po} - T_{pi}) - KHa(T_{pa} - T_{gs}). \quad (1)$$

2.2.2 The mathematical model of secondary loop side steam generator

1) Descending segment

Mass balance equation:

$$F_e\rho_d\mathrm{d}L/\mathrm{d}\tau = W_{fw} + (1-x_0)W_r - W_d; \quad (2)$$

Energy balance equation:

$$F_e\rho_d\mathrm{d}(Lh_d)/\mathrm{d}\tau = W_{fw}h_{fw} - W_dh_d + (1-x_0)W_rh_r. \quad (3)$$

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Table1 Meanings of variables in the model equations

Variables	Meanings
G	mass
C	specific heat
T	temperature
W	mass flow
ρ	density
h	specific enthalpy
c	circulation
a	coefficient
Ga	steam flow
s	entropy
ka	resistance coefficient
J	moment of inertia
D	diameter of impeller
v	velocity
L	length of pipe
M	moment of momentum
V	volume
K	heat transfer coefficient
Ha	heat transfer area
x	dryness fraction
F/A	area of section
k	resistance coefficient
P	pressure
b	coefficient
Wp	power
η	efficiency
Va	valve position
r	transmission gear ratio
n	rotate speed
H	lift
fu	water loss
Q	flow of pipe

Table2 Meanings of subscripts in the model equations

Subscripts	Meanings
p	coolant
m	heat-transfer conduit
o	out
i	in
e	water region
d	descend fragment
fw	feedwater
r	ascent fragment
gs	saturated steam
Hdr	new steam
exh	exhaust
1	control volume inlet
2	control volume outlet
T	turbine rotor
sa	output shaft and impeller
t	suction
a	average
g	steam
s	saturation
pr	preheat segment
br	evaporation segment
se	steam separator
sr	working substance of ascend channel
so	outlet of ascend channel
fs	saturated water
SZ	impeller to turbine rotor
S	turbine-driven feed pump

2) Ascending segment

Mass balance equation:

$$V_r \mathrm{d}\rho_r / \mathrm{d}\tau = W_d - W_r; \tag{4}$$

Energy balance equation:

$$V_r \mathrm{d}(\rho_r h_r) / \mathrm{d}\tau = W_d h_d - W_r h_{\mathrm{ro}} + KHa(T_{\mathrm{pa}} - T_{\mathrm{gs}}). \tag{5}$$

3) Steam space

Mass balance equation:

$$\mathrm{d}[(L_{\mathrm{so}} - L) F_e \rho_{\mathrm{gs}}] / \mathrm{d}\tau = x_0 W_r - W_{\mathrm{s}}. \tag{6}$$

4) Kinematics equation of working fluid

$$L\rho_d = L_{\mathrm{pr}}\rho_{\mathrm{pr}} + L_{\mathrm{br}}\rho_r + L_{\mathrm{se}}\rho_{\mathrm{ro}} + k_d \frac{W_d^2}{2g\rho_d F_d^2} + k_r \frac{W_r^2}{2g\rho_r F_r^2} + k_{\mathrm{se}} \frac{W_r^2}{2g\rho_{\mathrm{ro}} F_{\mathrm{se}}^2} + \frac{L_{\mathrm{pr}} + L_{\mathrm{br}}}{F_r g}\frac{\mathrm{d}W_r}{\mathrm{d}\tau} + \frac{L_{\mathrm{se}}}{F_{\mathrm{se}} g}\frac{\mathrm{d}W_r}{\mathrm{d}\tau} + \left(\frac{L - L_{\mathrm{pr}} - L_{\mathrm{br}}}{F_e g} + \frac{L_{\mathrm{pr}} + L_{\mathrm{br}}}{F_d g}\right)\frac{\mathrm{d}W_d}{\mathrm{d}\tau}. \tag{7}$$

5) State equations:

$$h_{\mathrm{ro}} = h_{\mathrm{fs}}(t_1 - \tau_1);$$

$$h_{\mathrm{do}} = h_{\mathrm{di}}(t_2 - \tau_2);$$

$$x_0 = (h_{\mathrm{ro}} - h_{\mathrm{fs}})/(h_{\mathrm{gs}} - h_{\mathrm{fs}}) = 1/c;$$

$$\rho_{\mathrm{sr}} = \rho_{\mathrm{gs}} / x_0 \ln(1 + x_0 \rho_{\mathrm{fs}} / \rho_{\mathrm{gs}});$$

$$\rho_{\mathrm{so}} = \rho_{\mathrm{fs}} / (1 + x_0 \rho_{\mathrm{fs}} / \rho_{\mathrm{gs}});$$

$$h_{\mathrm{fs}} = a_{13} T_{\mathrm{fs}} + b_{13};$$

$$T_{\mathrm{gs}} = a_{14} P_{\mathrm{s}} + b_{14};$$

$$P_{\mathrm{s}} = a_{15} \rho_{\mathrm{gs}} + b_{15};$$

$$h_{\mathrm{ro}} = 2h_{\mathrm{r}} - h_{\mathrm{d}};$$

$$T_{pi} = 2T_{pa} - T_{po}.$$

3 Mathematical model of turbine

The schematic diagram of feed pump turbine structure is shown in Fig.1. Four parts are taken into account to build the mathematic model: the steam flow model, the turbine power model, the rotary speed model, and the load model.

3.1 The steam flow model

Considering the valves and steam pipe resistances, Bernoulli equation is applied to the *AB* segment in Fig.2. Due to practical situation of steam pipes, the kinetic head of working fluid could be omitted, and $z_1 = z_2$.The Bernoulli equation can be simplified as

$Ga = adm\sqrt{p_1 - p_2}$, where adm is fluid conductor, $adm = \sqrt{2\rho A^2 g_c / K_{loss}}$, where g_c is the Newton scale factor, K_{loss} is friction loss coefficient. Taking into account of the influence of steam regulating valve, and then the steam flow is given by

$$Ga_i = kaVa\sqrt{P_{hdr} - P_{exh}}. \tag{8}$$

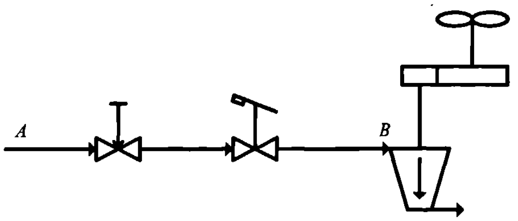

Fig.1 Schematic diagram of turbine structure

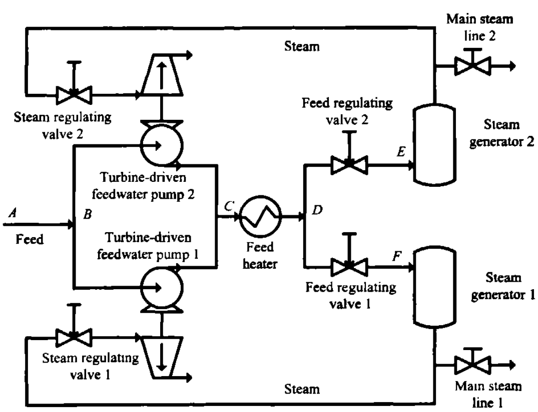

Fig.2 Schematic diagram of steam generator feedwater system structure

3.2 The turbine power model

The working process of turbine can be considered as a thermal insulation and isentropic process. Get the perfect enthalpy drop based on the isentropic process equation, and then obtain the power of the turbine based on the perfect enthalpy drop. According to the temperature-entropy diagram, $s_1 = f(p_1, h_1)$, $s_1 = s_2$ $h_2 = f(p_2, s_2)$, and $\Delta h = \eta(h_1 - h_2)$, so the power of the turbine:

$$Wp = Ga_i \times \Delta h. \tag{9}$$

3.3 The rotary speed model

Applying the theorem of momentum to the rotor and the output shaft of turbine, then $J\frac{d\omega}{d\tau} = M_T - M_{SZ}$, and $J_{sa}\frac{d\omega_{sa}}{d\tau} = M'_{SZ} - M_S$. The power equation of the turbine is $Wp = M\omega$, and $\omega = 2\pi n/60$, gear retarder equation is $n = rn_{sa}$, then $\eta = 1$ approximately, so $M_{SZ} \approx M'_{SZ}$. The rotary speed model is

$$\frac{dn_{sa}}{d\tau} = \frac{900}{\pi^2(r^2 J + J_{sa})n_{sa}}(Wp_T - Wp_S). \tag{10}$$

3.4 The load model

According to the principle of similarity, the power of feed pump and the cube of rotary speed are in direct proportion, namely,

$$Wp_S = \pi B\rho D^5 n^3 / 30, \tag{11}$$

where B is torque coefficient, which can be decided by the operating condition of feed bump.

4 Mathematical model of feedwater pipe

The schematic diagram of steam generator feedwater system structure is shown in Fig.2. The condensation water is pumped to the steam generators separately by the turbine-driven feed pumps in parallel flowing across the feedwater heater and the feed regulating valves. The rotary speeds of feed pumps are controlled by the steam regulating valves. The steam is drawn from the main steam pipes.

According to the unitary unstable pipe flow, an integral of working fluid kinematics equation is made along the pipe. Assuming the cross-sectional area of pipe is unchangeable, then the basic kinematics equation of unstable pipe flow can be got. Apply the equation to the pipe *ABCDE(F)*, as described in Fig.2. Assume there is only one pump in the feedwater system. Consider the local loss coefficient of two feedwater control valves as a whole. Assume the pipe flow will become turbulent flow immediately after the pump starts, and the feedwater is incondensable. The resistance of pipeline is ξ , including local friction loss and streamwise friction loss. Kinetic head is expressed as the function of flow. The mathematical model of feedwater pipes can be described as

$$\frac{L}{gA}\frac{dQ}{d\tau} = H_S + P_t - P_s - \xi Q. \tag{12}$$

The total feedwater flow can be obtained by Eq. (22).

To get the flow of feedwater through the two pumps and that of feedwater control valves respectively, the operating condition points of the pumps and the pipes should be known.

The resistance coefficient of feed regulating valves and the opening of the valves are relational. The opening of the feed regulating valve and the pressure difference of valves are relational[5].

$$f = Q/(C_{100}\sqrt{\Delta p/\rho}), \tag{13}$$

where C_{100} is the rating coefficient of flow. The value of the resistance coefficient can be obtained from reference[7].

5 Mathematical models of feed pumps in parallel

5.1 The mathematical model of feed pump

The method based on the external characteristic of pump is used to establish the mathematical model of feed pump. Namely, this method is based on the test data and the pump principle of similarity, so a series of characteristic curves are got. Fitting the test data of feed pump on rated condition, H is

$$H = 3.59137n^2/5\,000^2 + 0.008\,45Qn/5\,000 - 3.361\times10^{-4}Q^2. \tag{14}$$

The characteristic curve of pumps in parallel can be derived from the characteristic curve of single pump. When two pumps are in parallel, the lifts are equal to that of single pump, and the flow is the sum of the two pumps.

5.2 Operating condition of the feed pumps

The location of the operating point of feed pump is complicated[8]. As shown in Fig.3, assume the characteristic curves of the two pumps are the same, denoted as I, the characteristic curve of pumps in parallel become III. Curve V is the characteristic of the parallel feedwater pipe. Consider the influence of parallel feedwater pipe, the characteristic curve of feed pump is II. The characteristic curve of feedwater pipe is IV, so point M is the operating condition point of feed pumps in parallel. The flow of point E is the flow of feed pump. Point F is the real operating condition of the two feed pumps.

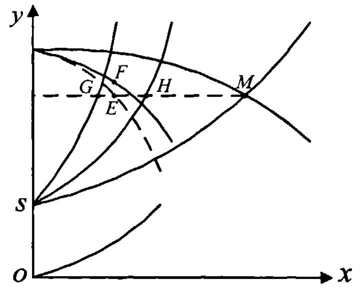

Fig.3 Operating condition of the feed pumps and pipes

Assume the characteristic curves of two feed regulating valves are different, one is VI and another is VII. The influence of two feed regulating valves is curve IV, so the flow of point G and H is the flow of the two feed regulating valves separately. It is known that although the total flows of pumps and regulating valves are equal, the flow of separate pump and that of regulating valve are usually not equal. When the control system is running, the rotary speed of the two pumps will be changed. It is the same in the valve positions of the two feed regulating valves. The curves I, II and curves VI, VII will be changed simultaneously, the corresponding operating condition point will be changed too.

Apply the Chebyshev curve fitting method to find the operating points of feed pumps, assume there are n data points, $(x_i,y_i), i=0,1,2,\cdots,n-1$, find a polynomial expression $P_{m-1}(x) = a_0x + a_1x + \cdots + a_{m-1}x^{m-1}$, so that $\max_{0\le i\le n-1} |P_{m-1} - y_i| = \min$, $m < n$, and $m \le 20$.

Collect 100 points of the characteristic curve of feed pump. Take a converse fit of these data points to get the expression of the feed pump flow and lift. Superpose the flow of pump to obtain the characteristic curves of the feed pumps in parallel. The method of finding the characteristic curve of feedwater pipes is the same as that of the feed pumps. Superpose the characteristic curves of the two feed regulating valves and the other resistance characteristic, and then fit the data to get the total characteristic curve of the feedwater pipes. The point of intersection of the two characteristic curves is the operating condition of the feed pump.

6 Feedwater control system

Feedwater control system of steam generator consists of the water level control system of steam generator and the rotary speed control system of turbine-driven pump. Feed flow is controlled automatically by a three-element controller using steam generator water level, steam flow, and feed flow to control the feed regulating valve to each steam generator. The controlled objective is water level of steam generator, the disturbing quantity is steam flow, and the control quantity is water flow. This controller is essentially a cascade PID controller, which can depress the affectation water level in effect. The first level of the cascade PID controller is water level controller, and the second level is flow controller. The equation of the rotary speed controller is to keep the differential pressure of the feed regulating valve to be a definite value. This controller is essentially a PI controller. The mathematical models described above are solved by four order Range-Kutta methods.

7 Simulation results

Assume that the feed pumps in parallel are in the same operating condition, and the variables of the two steam generators are equal expected water level. Simulate the dynamic characteristics of feedwater control system under the condition that the secondary loop load increases 10 percent of the full-load, and compare the results with that of analogue machine. The dynamic characteristics of the steam generator feed water system can be simulated accurately by the simulator. As shown in Fig.4, the water level rose sharply due to influence of the affectation water level when the load increased. The water level controller can control the water level to a reasonable level in time. From Fig.5, it can be seen that the secondary loop pressure decreased due to the increasing load. The opening of feed regulating valve increased because of the increasing feedwater consumption as shown in Fig.6. The opening of steam regulating valve increased because of the decrease of differential pressure of the feed regulating valve, as shown in Fig.7 and Fig.8. From Fig.9 and Fig.10, it can be seen that the water flows of the two feed pumps are not equally influenced by the regulating valves, but the water flows of the separate regulating valves are almost equal. The difference of the simulation results between the simulator and the mathematical models results from the model establishing methods and the simplified heat transfer process of the steam generator.

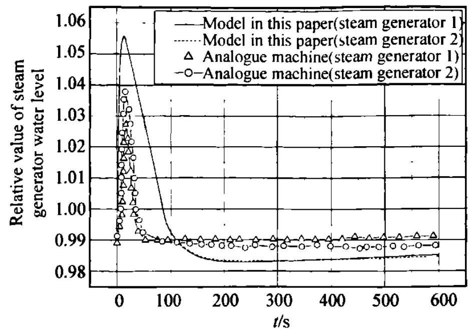

Fig.4 Water level curves of steam generators

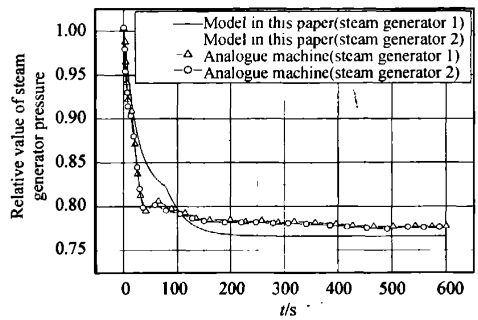

Fig.5 Pressure curves of steam generators

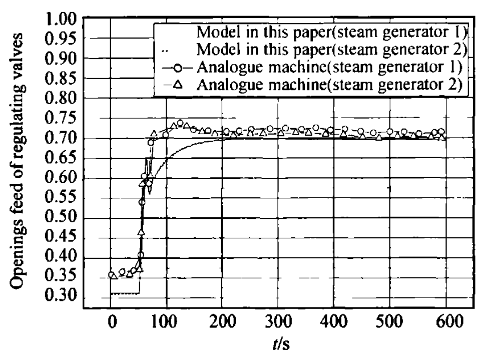

Fig.6 Opening curves of feed regulating valves

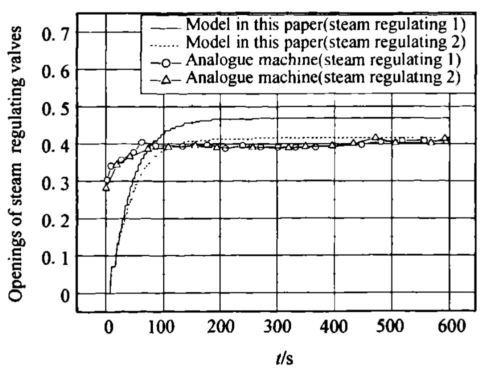

Fig.7 Opening curves of steam regulating valves

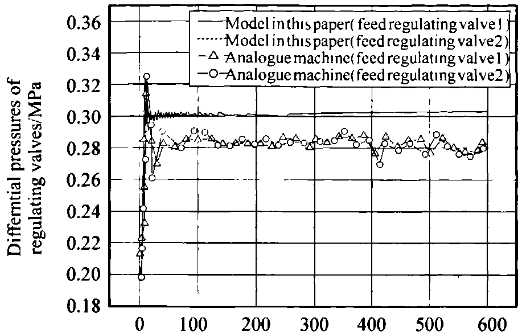

Fig.8 Differential pressure curves of feed regulating valves

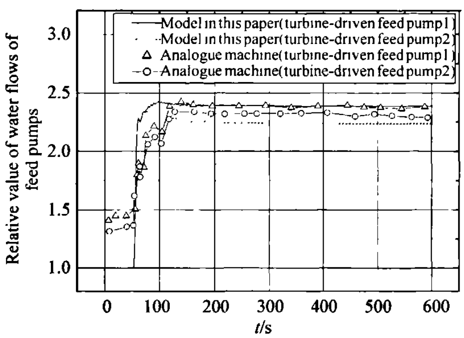

Fig.9 Water flow curves of feed pumps

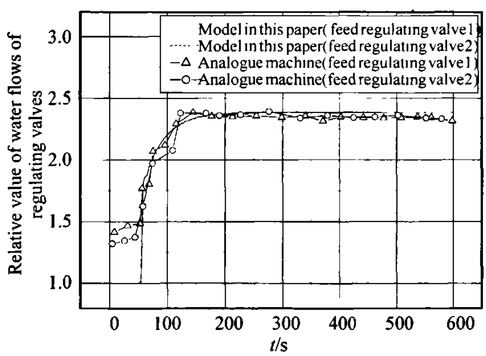

Fig.10 Water flow curves of feed regulating valves

8 Conclusions

Compared with the results of simulator, it is verified that the model of marine steam generator feedwater control system under the condition of turbine-driven feed pumps in parallel can be used to describe the dynamic characteristics of the steam generators, the feed pumps, and the feed pipes accurately. The water level controller of the steam generator and the rotary speed controller of turbine-driven feed pump can control the water level to a reasonable level in time. The simulation models introduced in this paper could provide a simulation platform for the development of feed water control system, and have a definite engineering practical significant.

Acknowledgement

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benchmarked against existing plant data. Benchmarking results are presented along with data on initialization to steady state. Once the benchmarking effort is completed, the control systems in the model are altered to allow testing of the digital RFWCS in real time. An interface is developed to allow communications with the digital RFWCS and operator interaction, which allows the test platform to be used to determine control system response to various transients, Descriptions of the RELAPS model and hardware and software for the interface are provided. [References: 24]

4. 外文期刊 Younkins. T.D..Chow. J.H. Multivariable feedwater control design for a steam generator

A multivariable feedwater control design for drum water-level regulation in a heat-recovery steam generator is presented. The control design is based on a projective output feedback scheme and is used to coordinate the tandem-connected feedwater valves of a low-pressure and a high-pressure drum. One of the design objectives is to minimize the blowdown from the drums during start-ups. Results demonstrating the control performance and the improvement over a traditional single-loop feedwater control design are shown.

5. 外文期刊 Mowrey JA..Abdel-Khalik SI..Boylan PR. Modeling of boiling water reactor feedwater control algorithms

A RELAP5/MOD3.1 model of a boiling water reactor and an interface originally developed as a real-time test platform for the Browns Ferry Unit 2 feedwater control system and turbine governors have been expanded to include feedwater heater systems and controls and to change the reactor recirculation pump controls from the current fluid-coupled drive to a future variable speed drive. The expanded model includes feedwater heater shell-side components, associated piping, steam supplies, and condensers, and allows simulation of the Fox-boro digital feedwater heater level control system. The model was updated to RELAP5/MOD3.1.1, while the interface was expanded to handle additional communications and operator actions. The simulated feedwater heater level controls were tuned and benchmarked; benchmarking was performed against steady-state data at various power levels from plant hear balance data. After the model was benchmarked, various transients were simulated to identify potential flaws in the feedwater heater level control system. [References: 14]

6. 期刊论文 邱志强.邹海.孙建华.QIU Zhi-qiang.ZOU Hai.SUN Jian-hua 船用蒸汽发生器给水控制系统仿真试验平台的设计与实现 -舰船科学技术2008,30(1)

针对船用汽轮给水泵转速控制系统中自能源进汽调节阀改为电动进汽调节阀的改进方案,设计并实现了一种船用蒸汽发生器给水控制系统仿真试验平台,建立了船用蒸汽发生器给水控制系统数学模型,包括蒸汽发生器数学模型、汽轮给水泵数学模型、给水管道及给水调节阀数学模型,设计了蒸汽发生器水位控制器以及汽轮给水泵转速控制器,通过与模拟机仿真结果比较验证了仿真试验平台的有效性.

7. 期刊论文 邱志强.邹海.孙建华.QIU Zhi-qiang.ZOU Hai.SUN Jian-hua 船用蒸汽发生器给水控制系统半物理仿真技术研究 -舰船科学技术2009,31(2)

针对船用蒸汽发生器给水控制系统,研发了一套半物理仿真试验平台.该平台包括HRT-1000型半物理仿真计算机、仿真管理计算机、模型计算机、PLC冗余控制器以及外围电路等.建立了船用蒸汽发生器给水控制系统的数学模型.半物理仿真计算机、仿真管理计算机以及模型计算机通过以太网互联,通过网络通讯进行数据交互.采用VC++6.0编制了仿真管理计算机软件与模型计算机软件,采用Tornado2.0与Control Builder M编制了半物理仿真机软件与控制软件.通过与航行试验数据比较,验证了半物理仿真平台的准确性.

8. 外文会议 Chuan-Chung Chen TUNING AND OPTIMIZING ADVANCED FEEDWATER CONTROL SYSTEM OF PWR

From operational experience, the parameters of a PID controller may need to be tuned occasionally to obtain a more desirable system behavior. However, the tuning process in nuclear power plant tends to be more conservative than fossil power plant since more operational constraints have been placed. As a result, the tuned parameter set may be tuned gradually away from optimum. The above scenario occurred in Maanshan Nuclear Power Station and was identified during Unit 1 Power Ascension Test (PAT) of 7300 retrofit project during EOC-14. The data collected during Unit 1 PAT is further utilized to improve the control algorithm of single element feedwater controller and feedwater pump speed controller for Unit 2. Programmed different pressure curve is also extended to widen the automatic control area of feedwater pump controller. A satisfactory Steam Generator (S/G) water level control capability is achieved. The experience of Unit 2 will be feedback to Unit 1 in EOC-15.

9. 外文会议 Borys E. Symkin.Francis Thaulez.Oleg Brenman Minimum Throttling Feedwater Control in VVER-1000 and PWR NPPs

This paper presents an approach for the design and implementation of advanced digital control systems that use a minimum-throttling algorithm for the feedwater control. The minimum-throttling algorithm for the feedwater control, i.e. for the control of steam generators' level and of the feedwater pumps speed, is applicable for NPPs with variable speed feedwater pumps. It operates in such a way that the feedwater control valve in the most loaded loop is wide open, steam generator level in this loop being controlled by the feedwater pumps speed, while the feedwater control valves in the other loops are slightly throttling under the action of their control system, to accommodate the slight loop imbalances. This has the advantage of minimizing the valve pressure losses hence minimizing the feedwater pumps power consumption and increasing the net MWe. The benefit has been evaluated for a specific plant as being roughly 2.4 MW. The minimum throttling mode has further advantages of lowering the actuator efforts with potential positive impact in actuator life and of minimizing the feedwater pipelines vibrations. The minimum throttling mode of operation has been developed by the Ukrainian company LvivORGRES. It has been applied with great deal of success on several VVER-1000 NPPs, six units of Zaporizhzha in Ukraine plus, with participation of Westinghouse, Kozloduy 5 and 6 in Bulgaria and South Ukraine 1 to 3 in Ukraine. The concept operates with both ON-OFF valves and true control valves. A study, jointly conducted by Westinghouse and LvivORGRES, has just been completed to demonstrate the applicability of the concept to PWRs. Following the positive results of this study, the minimum throttling mode of operation can reliably be implemented on PWRs having variable speed feedwater pumps and having, or installing, digital feedwater control, standalone or as part of a global digital control system. The implementation of the algorithm at VVER-1000 plants provided both safety imp

10. 外文期刊 Wei Dong.J. Michael Doster.Charles W. Mayo Steam Generator control in Nuclear Power Plants by water mass inventory

Control of water mass inventory in Nuclear Steam Generators is important to insure sufficient cooling of the nuclear reactor. Since downcomer water level is measurable, and a reasonable indication of water mass inventory near steady-state, conventional feedwater control system designs attempt to maintain downcomer water level within a relatively narrow operational band. However, downcomer water level can temporarily react in a reverse manner to water mass inventory changes, commonly known as shrink and swell effects. These complications are accentuated during start-up or low power conditions. As a result, automatic or manual control of water level is difficult and can lead to high reactor trip rates. This paper introduces a new feedwater control strategy for Nuclear

Steam Generators. The new method directly controls water mass inventory instead of downcomer water level, eliminating complications from shrink and swell all together. However, water mass inventory is not measurable, requiring an online estimator to provide a mass inventory signal based on measurable plant parameters. Since the thermal-hydraulic response of a Steam Generator is highly nonlinear, a linear state-observer is not feasible. In addition, difficulties in obtaining flow regime and density information within the Steam Generator make an estimator based on analytical methods impractical at this time. This work employs a water mass estimator based on feedforward neural networks. By properly choosing and training the neural network, mass signals can be obtained which are suitable for stable, closed-loop water mass inventory control. Theoretical analysis and simulation results show that water mass control can significantly improve the operation and safety of Nuclear Steam Generators.