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汽轮机控制系统对锅炉汽压对象动态特性的影响

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摘　要: 针对目前大型单元火电机组运行中功频调节对锅炉汽压有不稳定因素的现象, 分析指出了 DEH 控制系统采用不同的控制方式对锅炉对象动态特性的影响具有本质的区别, DEH 控制系统为功频调节时机组锅炉汽压对象表现为无自平衡过程, DEH 控制系统为纯速度调节时为有自平衡过程, 并通过仿真给出了燃料扰动和负荷扰动对采用不同 DEH 控制系统的单元火电机组动态特性的影响, 最后提出了机组工况不稳定或外干扰频繁时机组的运行方式, 这对大型单元火电机组安全运行具有重要的现实意义。

关　键　词: 汽轮机组; DEH 控制系统; 锅炉对象动态特性
中图分类号: TK323　　文献标识码: A

1　引言

大型火电单元机组是一个复合对象, 受控过程是一个多输入、多输出的过程, 在输入和输出之间存在着相互关联和耦合, 在认定锅炉系统正常燃烧和正常给水前提下, 锅炉锅筒单元机组可简化为一个具有双输入双输出的被控对象, 机组的输出功率和机前压力为被控量, 主汽门开度和燃料量为控制量。

机炉主要特性表现为锅炉是一个相对慢速的响应过程, 热惯性较大[1,8], 汽轮机则是一个相对快速的响应过程, 热惯性较锅炉小得多; 锅炉对象动态特性受到多种因素的影响, 是可变的和复杂的, 这种特性阻碍了对机组负荷和主蒸汽压力的控制。

在汽轮机和锅炉本身进行自动调节时, 由于锅炉—汽轮机之间存在复杂的耦合性, 这些调节会影响到对方的对象动态特性。因此, 控制系统的设计, 要求充分考虑机组的特性, 研究控制系统对机炉对象动态特性影响, 特别是对锅炉对象动态特性的影响。事实上, 不同的汽轮机控制系统(或控制方式)对锅炉对象动态特性的影响是有本质区别的。

2　汽轮机组机炉动态特性

汽轮机组的机炉动力学系统包括燃烧系统, 蒸汽发生系统和汽轮发电机等, 为了研究方便, 汽轮发电机组的调节系统中的过程进行适当的简化。

2.1　蒸汽锅炉系统的动态特性

燃烧系统的动态特性, 有一个纯延时 τ 和一个惯性环节组成, T_F 为时间常数。

其传递函数:　$E_{(p)} = e^{-\tau s}/(1 + T_F S)$　　(1)

蒸汽发生系统中, 燃烧强度 F, 储热能力和等效压降对于锅筒蒸发量 S_v, 汽轮机主蒸汽流量 S_a, 锅炉汽压 P_B 以及汽轮机主蒸汽压力 P_T 之间的影响关系为:

$F = S_V + T_V \mathrm{d}S_V/\mathrm{d}t$	燃烧蒸发方程
$S_V + S_B = S_X$	锅炉物质平衡式
$S_B = T_B \mathrm{d}P_B/\mathrm{d}t$	锅炉储蓄方程
$S_X = T_X(P_B - P_T)$	等效压降
$S_a = S_X + S_P$	管道物质平衡方式
$S_P = -T_P \mathrm{d}P_T/\mathrm{d}t$	管道储蓄方程

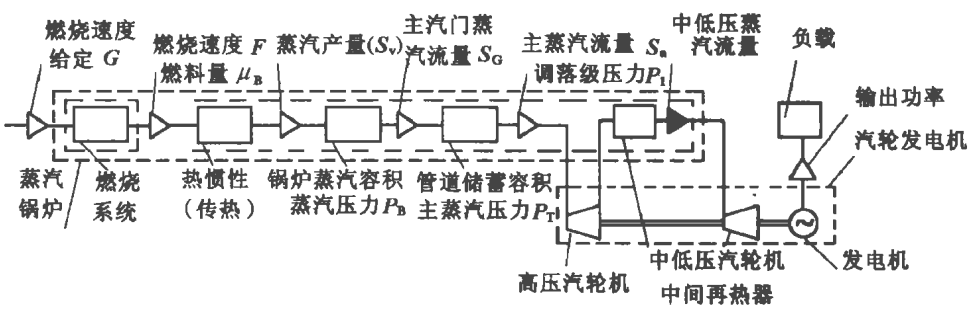

图 1　汽轮发电机组调节过程简化图

得蒸汽系统的动态特性:

$$F - S_a - (T_V + T_B/T_X)\mathrm{d}S_a/\mathrm{d}t - T_V \times T_B/T_X \mathrm{d}^2 S_a/\mathrm{d}^2 t = (T_B + T_P)\mathrm{d}P_T/\mathrm{d}t + [(T_B + T_P)T_V + T_B \times T_P/T_X]\mathrm{d}^2 P_T/\mathrm{d}^2 t + T_P T_V T_B/T_X \mathrm{d}^3 P_T/\mathrm{d}^3 t \quad (2)$$

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当实际蒸汽流量 S_a 不变时，主蒸汽压力 P_T 对燃烧强度 F 的传递特性为无自平衡对象特性。

2.2 汽轮发电机与主蒸汽压力的特性关系：

汽轮发电机功率与蒸汽流量的关系为：

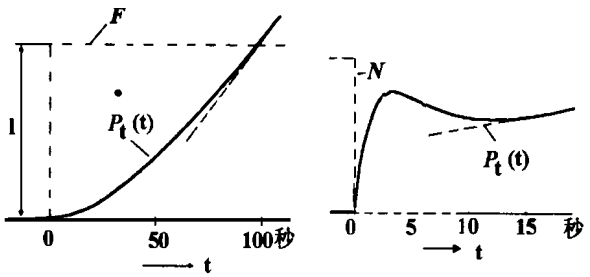
$N_{HP}+N_{IP}=N$ 汽轮机功率平衡式

$N_{HP}=n\times h\times S_a$ 高压缸功率

$N_{LP}=(1-n)\times h\times S_{LP}$ 中低压缸功率

$S_a=S_{LP}+T_{RH}\times dS_{LP}/dt$ 中间过热储蓄方程

得：$h\times S_a+n\times h\times T_{RH}\times dS_a/dt=N+T_{RH}\times dN/dt$ (3)



a 实际蒸汽流量不变时 P_t 与 F 关系　b 燃烧强度 F 不变时，P_t 与 N 关系

图 2 主蒸汽压力时域响应特性

T_{RH} 为中间再热器储热特性时间常数，h 为有效总焓降，n 为功率分配取 1/3。在火电机组中发电机功率(或负荷) 和燃料量(或燃烧强度) 是扰动变量参数。

由式(2) 和式(3) 得汽轮发电机功率与主蒸汽压力的关系，当燃料量(或燃烧强度) 不变的情况下，主汽压对发电机功率的扰动表现为无自平衡方式。

3 汽轮机控制系统对锅炉汽压对象动态特性的影响

3.1 汽轮机组控制和对象系统

在锅炉跟随系统(BFC) 中，锅炉主调节器的主要任务是控制主汽压力，而汽机主调节器则控制机组的功率，见图 3(a)。

其中 $G_B(S)$ 为锅炉主调节器传递函数，$G_T(S)$ 为汽机主调节器传递函数。理论和实践都证明汽轮机对象的动态特性相对于锅炉要简单得多，受外界影响相对较弱、较小。根据这一特性，汽轮机对象可以从机组系统对象中分离出来，见图 3(b)。

3.2 相对于主汽压控制的锅炉蒸汽系统

锅炉蒸汽系统包括了燃烧、传热和热辐射、蒸汽蒸发、管道阻力等，其蒸汽系统传递函数见图 4。

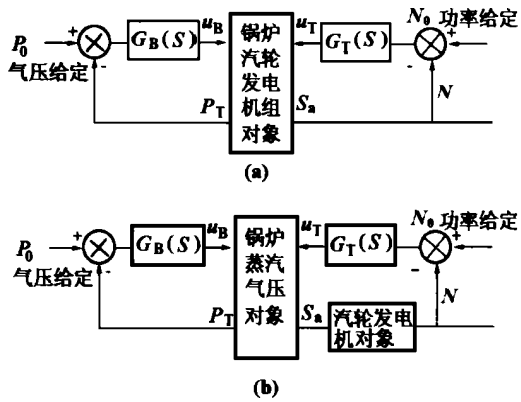


图 3 汽轮机组(BFC) 系统框图

其中 $e^{-\tau s}/(T_F S+1)$ 为燃烧和传热传递函数，$1/C_B S$ 为锅筒蒸汽容积，K_{sh} 为蒸汽过热器管道阻力，其特性正比于管道蒸汽流量的平方，$W_f(S)$ 为主汽门(调节门) 蒸汽管道阻力特性，可以简化为一阶惯性环节。

3.3 汽轮机控制系统对锅炉汽压对象动态特性的影响

锅炉跟随系统(BFC) 的汽轮机组的传递函数系统见图 4，采用了中间再热器的汽轮机动态特性，以及低级同步发电机组模型和无穷大电网假设。

汽轮机 DEH 主调节器采用的方式有两种，一种是功频调节方式(即采用功率和频率(或转速) 反馈，用 PI 调节方式)；另一种为纯速度调节方式(采用频率或转速反馈)。

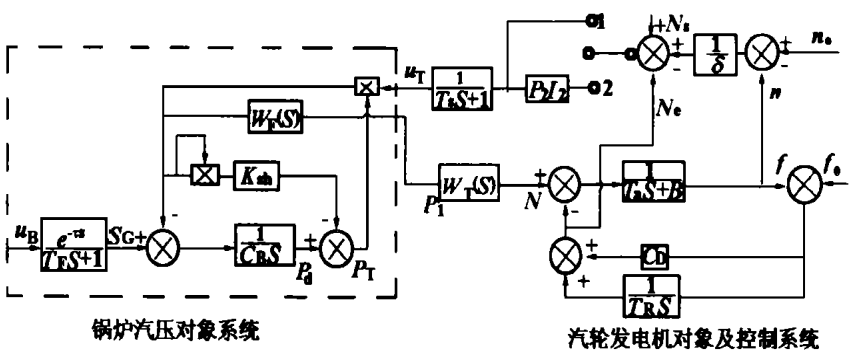


图 4 锅炉跟随系统(BFC) 的汽轮机组的传递函数

当燃料量 μ_B 出现一个扰动(阶跃增加)，势必引起蒸汽量(S_G) 增加，进入汽轮机作功的蒸汽流量(S_a) 也随之增加，汽轮机功率也增加。下面分别分析

汽轮机主调节器采用不同方式时的情况。

当采用功频调节(PI)时，引入了功率 Ne 反馈和转速反馈，在调节器作用下，将使汽轮机功率 N 趋于等于给定功率N_0，这个过程是通过减小 μ_T 关小主汽门来实现的，同时引起 P_T 的不断增加，即主汽压 P_T 和燃料量 μ_B 阶跃增加的关系为一无自平衡过程。

采用纯速度调节时，仅引入了转速反馈，汽轮机功率 N 增加引起转速差值增大，汽轮机增加的功率全部输入给电网，主汽门开度几乎不变，进入汽轮机的蒸汽流量($S_a = \mu_T * P_T$)将稳定在一个新的数值上，主汽压 P_T 也在一个新的值上稳定，即主汽压 P_T 和燃料量 μ_B 增加的关系，为一有自平衡过程。

功频调节汽轮发电机侧传递特性为：

$$\frac{-16.67(S+0.5)(S+0.3333)(S+0.125)}{S(S+10)(S+1.25\pm0.9682\,i)(S+0.1111)}$$

纯速度调节汽轮发电机侧传递特性为：

$$\frac{-8.333\,S(S+0.3333)}{(S+10)(S+1.25\pm0.9682\,i)(S+0.1111)}$$

比较以上两式显然功频调节(PI)比纯速度调节的不稳定因素相对要大一些。

4　研究及分析

燃烧和传热传递函数 $e^{-\tau s}/(T_F S+1)$：　$e^{-9s}/(1+48S)$

锅炉蓄热系数 C_B：　$176S$

过热器管道阻力系数 K_{sh}：　0.07

主汽阀门阻力传递函数 $W_F(S)$：　$1/(0.1S+1)$

汽轮机及中间再热容积 $W_T(S)$：　$(1+3S)/(1+9S)$

转子传递函数 $1/(T_\alpha S+\beta)$：　$1/(8S+0.010)$

油动机传递函数 $1/(T_S S+1)$：　$1/(1+0.2S)$

发电机传递函数 C_D：　20

发电机传递函数 $1/T_R S$：　20/s

锅炉主调节器 P_1I_1：　$P=1, KI=200$

汽轮机功频调节器 P_2I_2：　$P=1, KI=8$, $P=0.5, KI=20$

汽轮机纯速度调节 $1/\delta$：　20

对图4的传递函数进行仿真研究，可得出图5汽轮机控制系统对锅炉汽压对象动态特性的影响，燃料量 μ_B 的扰动为阶跃增加 2% 的情况，当采用功频调节(PI)时，锅炉汽压对象动态特性为一无自平衡过程；采用纯速度调节时，锅炉汽压对象动态特性为一有自平衡过程，这种现象和 3.3 节的分析是一致的。

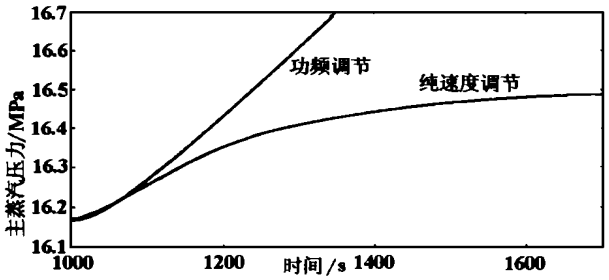


图 5　汽轮机控制系统对锅炉汽压对象动态特性的影响

对单元机组(BFC)进行仿真试验，锅炉主调节器为 P_1I_1 见图 6，当燃料量 μ_B 出现 2% 的扰动时，

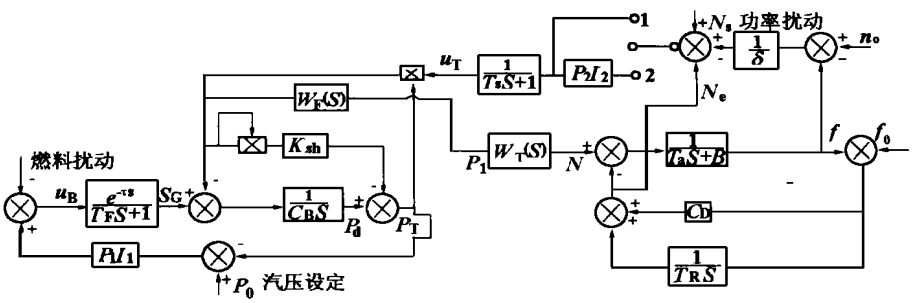


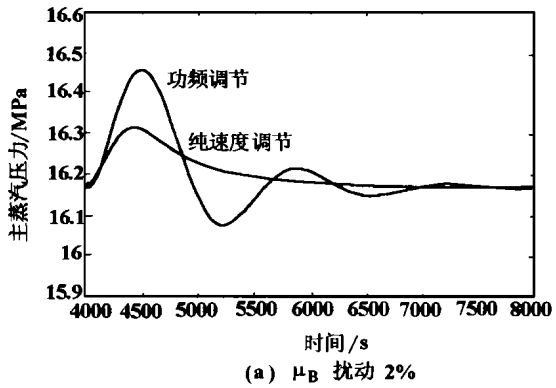
图 6　单元机组(BFC)控制系统传递函数框图

DEH 采用纯速度调节和采用功频调节(PI)对锅炉汽压对象的影响有显著差别；当发电机功率 N 出现 2% 的扰动，DEH 采用纯速度调节和采用功频调节(PI)对锅炉汽压对象的影响同样有显著差别。结果表明采用纯速度调节对燃料量 μ_B 和发电机功率 N 扰动的调节特性比功频调节(PI)要好，见图 7。

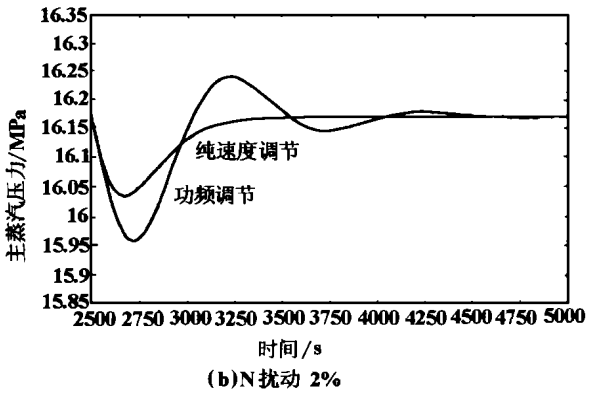
汽轮机主调节器采用功频调节(PI)，其比例系数 P 和积分系数KI 不同，对锅炉汽压对象的影响有差别，比例系数 P 减小，波动幅值相应减小；积分系数 KI 增加，稳定时间增长见图 8。

5　结束语

锅炉 — 汽轮机之间存在复杂的耦合性，不同的

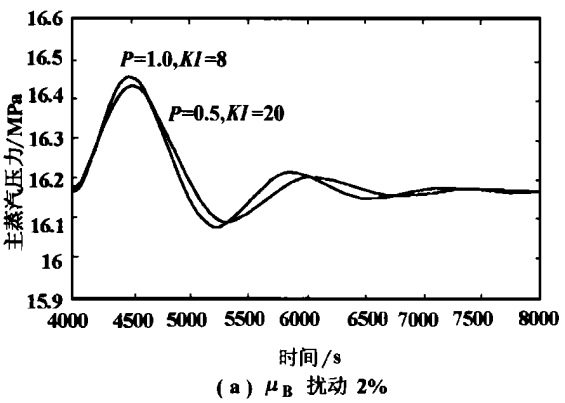


(a) μ_B 扰动 2%

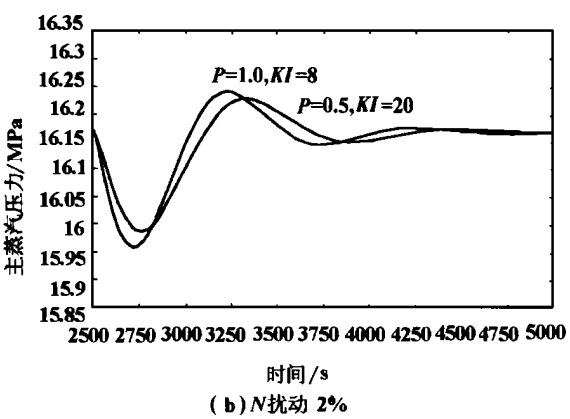


(b)N 扰动 2%

图 7 单元机组(BFC)汽压对象时域特性



(a) μ_B 扰动 2%



(b)N 扰动 2%

图 8 不同功频调节器(PI)的汽压对象时域特征

汽轮机控制系统(或控制方式)对锅炉对象动态特性的影响是有本质区别的。汽轮机主调节器采用功频调节(PI)时,锅炉汽压对象动态特性为一无自平衡过程;采用纯速度调节时,锅炉汽压对象动态特性为一有自平衡过程。

锅炉跟随系统(BFC)方式的单元机组,汽轮机主调节器采用纯速度调节对燃料量 μ_B 和发电机功率 N 扰动的调节特性比功频调节(PI)要好,汽轮机主蒸汽压力 P_T 的波动要小得多,稳定时间短得多。功频调节时,发电机功率反馈对系统稳定有不良影响。

大型机组运行中,出现锅炉、汽机的工况不稳定,外界扰动(如煤质变化,电网波动等)频繁时,采用纯速度调节控制、功频调节器(PI)跟踪、无扰动切换方式,是有利于机组安全稳定运行的。适当选择汽轮机主调节器比例系数 P 和积分系数 KI,对锅炉运行的稳定性控制是有效的。

通过本文的研究同时说明了大型火电机组工作时,锅炉运行人员不希望汽轮机 DEH 功频调节投入使用的本质原因。

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locity excursions in the horizontal flue. The swirl intensity profile of the in-furnace gas along the furnace height has also been analyzed, leading to the determination of a suitable furnace height. The conclusions reached in the present paper can serve as a major guide for achieving a decrease in gas velocity excursions in a horizontal flue and an optimization of the furnace configuration. **Key words**: tangentially fired boiler, swirl intensity, furnace height, flue gas velocity excursion

风扇磨煤机润滑系统的传热机理分析及改进设计＝**An Analysis of the Heat Transfer Mechanism of a Fan Mill Lubrication System and Its Improved Design** [刊, 汉] / Liu Xiao-zhou, Hui Shi-en, Xu Tong-mo (Xi'an Jiaotong University, Xi'an, China, Post Code: 710049), Li Zhan-guo (Changchun Electric Power Generation Equipment General Works, Changchun, China, Post Code: 130022), Li Ping (Changchun Electric Power Engineering Technical School, Changchun, China, Post Code: 130021), Jin Yu-feng (Northeast Electric Power Design Institute, Changchun, China, Post Code: 130021) // Journal of Engineering for Thermal Energy & Power. —2001, 16(1). —49 ~ 50, 82

Described in this paper is an improved design scheme for the lubrication system of a fan mill and its relevant calculation method. A comparison of the lubrication system prior to and after the technical modification shows that the modified lubrication system has gained a significant improvement in its performance. **Key words**: lubrication system modification, finned tube cooler, contrast of effectiveness, economic benefit

汽轮发电机密封油系统的仿真数学模型＝**Simulation-based Mathematical Model for the Sealing Oil System of a Turbogenerator** [刊, 汉] / Shi Xiao-ping, Xu Tian-shu (Simulation Center under the Harbin Institute of Technology, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy & Power. —2001, 16(1). —51 ~ 54

This paper expounds the structural design and operating mode of the sealing oil system of a turbogenerator with a detailed description of its simulation-based mathematical model set up for the system. In comparison with traditional mechanism models the simulation-based model recommended in the present paper features simplicity in form, low computation load, enhanced real time function and high fidelity, etc. **Key words**: turbogenerator, sealing oil system, mathematical model, simulation

基于神经网络模型的锅炉广义预测控制＝**A Neural Net Model-based General Predictive Control Strategy for Use on Boilers** [刊, 汉] / Lu Yong, Xu Xiang-dong (Department of Thermal Energy Engineering, Tsinghua University, Beijing, China, Post Code: 100084) // Journal of Engineering for Thermal Energy & Power. —2001, 16(1). —55 ~ 58, 69

In an effort to rectify deficiencies commonly encountered during the operation of current utility boilers, such as poor control performance, low thermal efficiency, etc., the authors have come up with a neural net model-based general predictive control strategy to improve the relevant control device performance. Through numerous computer simulations the proposed control strategy has been adequately verified. Moreover, an improved Elman network model was utilized to replace the original multi-layer feedforward model in order to simplify model configuration and facilitate on-line real-time calculations. A contrast test of the above two models shows that a satisfactory result in terms of effectiveness has been attained through the use of the improved Elman network model. Finally, on the basis of the simulation results, expounded were the selection of the parameters of the neural net model-based general predictive control and some specific issues in engineering applications. **Key words**: general predictive control (GPC), multi-layer perceptrons, Elman neural network, multi-variable control

汽轮机控制系统对锅炉汽压对象动态特性的影响＝**The Influence of a Steam Turbine Control System on the Dynamic Characteristics of Boiler Steam Pressure as a Controlled Object** [刊, 汉] / Weng Yi-wu, Xu Zhi-qiang, Yu Da-ren, *et al* (Harbin Institute of Technology, Harbin, China, Post Code: 150001) // Journal of Engineering for

Thermal Energy &Power. —2001, 16(1). —59 ~ 62

In view of the presence of destabilizing factors in boiler steam pressure caused by the power-frequency control of current large-sized mono-block thermal power plant units the authors have performed an analysis of the digital electric-hydraulic (DEH) control modes. It is noted that there exists a substantial difference in the influence on the dynamic characteristics of a boiler object when various DEH control modes are put into use. In case the DEH control assumes the form of power-frequency one the boiler steam pressure as a controlled object can be viewed as a self balancing-absent process. When the DEH control functions as a pure speed regulation, the former represents a self-balancing process. By way of simulations the effect of fuel and load perturbations on the dynamic characteristics of a mono-block thermal power plant unit has been determined when different DEH control modes are used. At the end of the paper presented are the operating modes of the mono-block unit under unstable working conditions or in case of a high frequency of outside perturbations. In sum, the paper has provided some hints of highly practical value for ensuring the safe operation of large-sized mono-block thermal power plants. **Key words**: steam turbine unit, digital electric-hydraulic control system, dynamic characteristics of boiler as a controlled object

改进 BP 神经网络在流型判别中的应用=**The Application of an Improved BP Neural Network in the Discrimination of Various Flow Patterns** [刊, 汉] / Wang Yan-peng, Lin Zong-hu (Energy Source and Power Engineering Institute under the Xi' an Jiaotong University, Xi' an, China, Post Code: 710049) //Journal of Engineering for Thermal Energy &Power. —2001, 16(1). —63 ~ 65, 90

A new method for the discrimination of flow patterns is proposed in this paper, which is based on the use of an artificial neural network. With the help of a self-adaptive gradient reduction method and an improved simulation annealing approach, etc the convergence rate of a BP network can be accelerated. There emerged, as a result, an enhancement in the network' s ability to avoid a local minimum magnitude, which contributes to an increased capability of the network to simulate a nonlinear system. In addition, an analysis was made of the network input and output parameters, which can be used for pattern discrimination. To demonstrate the feasibility of the recommended method, the authors have employed the experimental data of scholars-forerunners to check and verify their work procedures. It has been proved that the above method can be assessed as a very effective one for the discrimination of two-phase and multi-phase flow patterns. **Key words**: neural network, two-phase flow, multi-phase flow, flow pattern discrimination

板式换热器可视化计算机辅助设计系统的研制=**The Development of a Visualized Computer-aided Design System for Plate Heat Exchangers** [刊, 汉] / Dong Chao-jun, (Wuyi University, Jiangmen, Guangdong Province, China, Post Code: 529020) //Journal of Engineering for thermal Energy &Power. —2001, 16(1). —66 ~ 69

Plate heat exchangers represent a kind of highly compact and efficient heat exchange device. As such heat exchangers feature an extremely complicated heat exchange and flow characteristics, there still lacks, to date, a unified formula for calculating their heat transfer and resistance. At present they are designed and calculated mainly by relying on manual work. However, a manual design and calculation process often suffers from both a high complexity and an extreme inaccuracy. With the comprehensive utilization of such a variety of software as Visual Basic, AutoCad and Turbo C, etc the author has on the platform of Windows 95 developed a visualized computer-aided design system. Through the use of that system a designer only needs to input some relevant parameters and the system will automatically complete the whole process starting from the design and calculation and ending with the completion of all design drawings. The system has a user-friendly interface and can be conveniently used in practical design work. **Key words**: plate heat exchanger, computer-aided design system, Visual Basic, AutoCad

非对称转子—轴承系统的稳定性分析=**An Analysis of the Stability of an Asymmetrical Rotor-bearing System** [刊, 汉] / Liu Zhang-sheng, Huang Sen-lin, Su Jie-xian, *et al* (College of Energy Source under the Harbin Institute of