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空冷机组协调控制系统鲁棒性分析

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摘　要: 与传统水冷机组相比, 空冷机组易受环境因素变化影响, 对象特性更为复杂。建立空冷机组负荷—压力对象动态模型, 分析其主要参数的变化规律及范围, 在此基础上, 采用机跟炉和炉跟机两种控制方式, 仿真分析负荷—压力工作点、排汽压力、燃料发热量变化对控制系统性能的影响。结果表明: PID 控制器具有较好鲁棒性, 能够克服机组排汽压力、燃料发热量变化对控制系统的影响; 负荷—压力工作点变化造成模型中制粉惯性和迟延、锅炉蓄热系数的变化以及对象自身非线性仍然是影响空冷机组控制品质的主要因素。

关　键　词: 空冷机组; 自动控制; 协调控制; 鲁棒性; 仿真分析

中图分类号: TM311; TP273　　文献标识码: A

引　言

火电单元机组机炉协调控制系统被控对象具有多变量强耦合、非线性、大惯性、大延迟和慢时变等特性[1~3], 除此之外, 大型机组还将面对以下问题: 参与电网一次调频和深度调峰, 负荷波动频繁且幅度增加; 在能源供应紧张环境下, 燃煤煤质变化剧烈; 对于空冷机组, 环境气温的改变还要影响机组运行状态。这些因素导致空冷机组更多地工作在变工况下, 需要控制系统不断地进行调节以维持机组参数在允许范围内。

空冷机组协调控制系统大多沿用传统水冷机组的设计方案。与水冷机组不同, 空冷机组排汽压力受环境因素影响大幅变化, 进而影响整个机组的工作状态。有必要对其进行系统性的分析, 寻找影响系统性能的主要因素以做出有针对性的改进。

1　对象模型

空冷机组协调控制系统对象动态模型可简化为一双入双出多变量系统, 输入为燃料量 u_B(kg/s), 汽轮机调门开度 u_T(%); 中间变量为进入磨的实际煤量 r'_m(kg/s), 锅炉燃烧率 r_B(kg/s), 汽包压力 p_b(MPa), 汽轮机一级压力 p_1(MPa); 输出为机前压力 p_t(MPa), 机组负荷 N_E(MW)。其动态模型可以描述为[4~5]:

$$r'_m = u_B(t-\tau) \tag{1}$$

$$T_f \frac{dr_B}{dt} = -r_B + r'_m \tag{2}$$

$$C_b \frac{dp_b}{dt} = -K_3 p_t \mu_T + K_1 r_B \tag{3}$$

$$T_t \frac{dN_E}{dt} = -N_E + K_3 K_4 p_t \mu_T \tag{4}$$

$$p_t = p_b - K_2 (K_1 r_B)^{1.5} \tag{5}$$

$$p_1 = 0.01 p_t \mu_T \tag{6}$$

式中: K_1—燃料增益, MJ/kg; K_2—过热器阻力系数; K_3—汽轮机增益, MW/MPa%; K_4—无量纲汽轮机效率修正系数; τ—制粉过程迟延时间, s; T_f—制粉惯性时间, s; C_b—锅炉蓄热系数, MJ/MPa; T_t—汽轮机动态时间, s。

本研究对象为大同发电有限公司 600 MW 直冷式空冷机组, 锅炉型号 DG2060/17.6－Ⅱ1, 汽轮机型号 NZK 600－16.7/538/538, 空冷装置由德国成套引进。其额定负荷—压力下对象模型为:

$$r'_m = u_B(t-12) \tag{7}$$

$$90 \frac{dr_B}{dt} = -r_B + r'_m \tag{8}$$

$$3500 \frac{dp_b}{dt} = -0.402 p_t \mu_T + 9.04 r_B \tag{9}$$

$$16 \frac{dN_E}{dt} = -N_E + 0.402 K_4 p_t \mu_T \tag{10}$$

$$p_t = p_b - 0.00364 r_B^{1.5} \tag{11}$$

$$p_1 = 0.01 p_t \mu_T \tag{12}$$

汽轮机效率修正系数 K_4 受汽轮机排汽压力 p_e(kPa)影响, 在 p_e 设计值为 15 kPa 时, K_4 为 1, 两者之间的动态关系可拟合为:

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$$21\ \frac{\mathrm{d}K_4}{\mathrm{d}t}=-K_4+(0.958+0.00278p_e)^{-1} \quad (13)$$

2　模型参数变化情况分析

模型中 K_1 的物理意义是单位燃料量对应的机组发电量, 主要受煤发热量和机组基本发电效率的影响。根据 2006 年机组运行统计数据, 煤发热量在[19.5±3.6] (MJ/kg)范围变化, 变化范围超过 20%; 另外机组基本发电效率在[40.9±0.2] (%)范围变化, 表现为发电效率随机组负荷降低而下降。两个因素共同导致 K_1 在[9.04±1.67] (MJ/kg)范围变化。

模型中 K_4 的物理意义是排汽压力变化影响汽轮机效率变化的无量纲系数。根据现场统计数据, 汽轮机排汽压力在[5, 60] (kPa)之间变化, 影响 K_4 变化范围在[1.03, 0.89] 之间。

模型中 T_f 受磨负荷和煤可磨性指数变化影响, 当磨负荷降低时, 煤粉在磨中的循环倍率增加, 导致制粉惯性增加。同样, 由于给煤机转速和一次风速降低, 低负荷下制粉系统的迟延 τ 也要增加。大型锅炉一般采用多台磨并列运行的方式, 不同负荷下投运不同台数的磨, 因此 T_f 与机组负荷并不呈现明显对应关系, 根据大量辨识数据统计, 得到 T_f 变化范围在[90, 130] (s)之间。由于 τ 难以辨识, 采用机理分析结果, τ 变化范围在[12, 22] (s)之间。

影响锅炉蓄热系数 C_b 的主要因素是负荷－压力工作点和锅炉水质, C_b 随锅炉负荷降低而增加。一方面是由于机组采用滑压运行方式, 低压力下水的蓄热能力增加; 另一方面是由于低负荷时锅炉汽包、水冷壁汽泡容积减少, 使有效饱和水容积增加。实验数据表明, 50%负荷时 C_b 要增加 40%左右[4], 由此确定本机组 C_b 的变化范围在[3 500, 4 900] (MJ/MPa)之间。锅炉水质变坏时, 汽包水冷壁内汽泡率增加, 导致有效水容积减小使得锅炉蓄热系数减小。

3　控制系统鲁棒性分析

火电机组负荷－压力协调控制系统的设计基本上为机跟炉或炉跟机加入各种前馈和解耦环节构成, 因此采用基本的机跟炉和炉跟机控制方式分析系统的鲁棒性。影响系统控制品质的对象自身特性变化主要有:

(1) 负荷工况点的改变;

(2) 排汽压力的改变;

(3) 燃料发热量的改变;

(4) 制粉惯性的改变;

(5) 锅炉蓄热系数的改变。

机理分析表明: 对制粉惯性, 一次风量变化的影响大于煤可磨性变化, 而一次风量随负荷变化。对锅炉蓄热系数, 负荷－压力工作点的影响要大于锅炉水质变化[4], 这两项因素对控制系统的影响主要体现在其随负荷工作点变化上, 因此不再单独讨论。

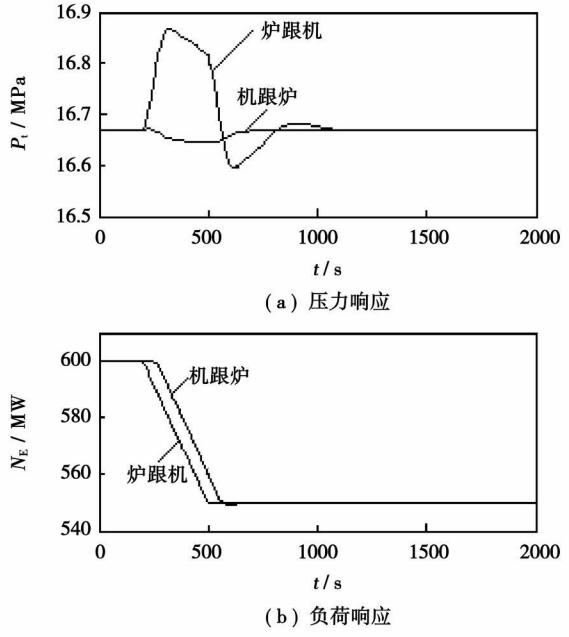
实验过程为: 在MATLAB 环境下设计控制系统, 采用穷举寻优的方法整定好初始状态 PID 控制器参数。对比模型参数改变前后的负荷－压力指令扰动响应曲线, 分析系统鲁棒性。

3.1　负荷工作点变化

一些对象参数随负荷工作点变化, 100%负荷和 50%负荷模型参数变化统计数据如表 1 所示。100%负荷工作点进行负荷指令扰动实验如图 1 所示, 负荷指令变化速率为 10 MW/min (下同)。50%负荷工作点实验如图 2 所示。

表 1　100%负荷和 50%负荷模型参数变化

负荷 /%	K_1 /MJ·kg^{-1}	τ/ s	T_f/ s	C_b / MJ·MPa^{-1}
100	9.04	12	90	3 500
50	8.95	22	130	4 900



(a) 压力响应

(b) 负荷响应

图 1　100%负荷工作点负荷指令扰动

由图 1 和图 2 对比可见, 按 100%负荷工作点优

化后的PID 参数, 在 50%工作点出现控制品质下降的情况, 炉跟机控制方式甚至出现压力不稳定的情况。在现场中为了避免此情况, 往往采用保守的 PID 参数整定方案, 以牺牲控制品质为代价获得全负荷范围内的鲁棒性。以炉跟机为基础的协调控制比机跟炉为基础的协调控制对负荷工作点的变化更为敏感, 这同工程实际情况一致。

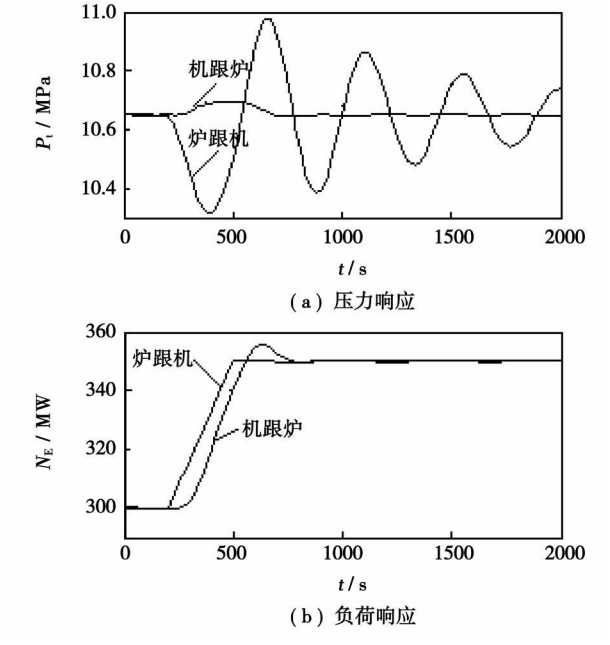
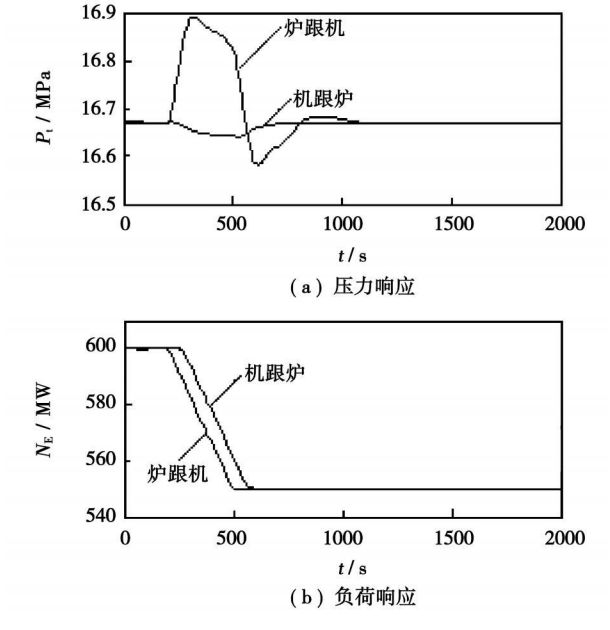


图 2 50%负荷工作点负荷指令扰动

3.2 排汽压力变化



3 汽轮机效率修正系数降低 10%负荷指令扰动

100%负荷下, 排汽压力由 6.95 kPa 变化到 55 kPa, 导致汽轮机效率修正系数降低 10%后, 负荷指令扰动曲线如图 3 所示。可见, 在确定的工作点, PID 控制系统适应汽轮机排汽压力变化的能力较好。在现场中, 空冷侧扰动主要是阵风天气排汽压力波动造成的内扰, 而对控制系统稳定性不会产生实质影响。

3.3 燃料发热量变化

燃料发热量降低 20%, 即由 18.5 MJ/kg 降低至 14.9 MJ/ kg 时, 100%负荷下负荷指令响应曲线如图 4 所示。可见, 在确定的工作点, PID 控制系统适应燃料发热量变化能力较好。在现场中, 燃料侧扰动主要是燃料发热量突然变化造成的内扰, 而对控制系统稳定性不会产生实质影响。

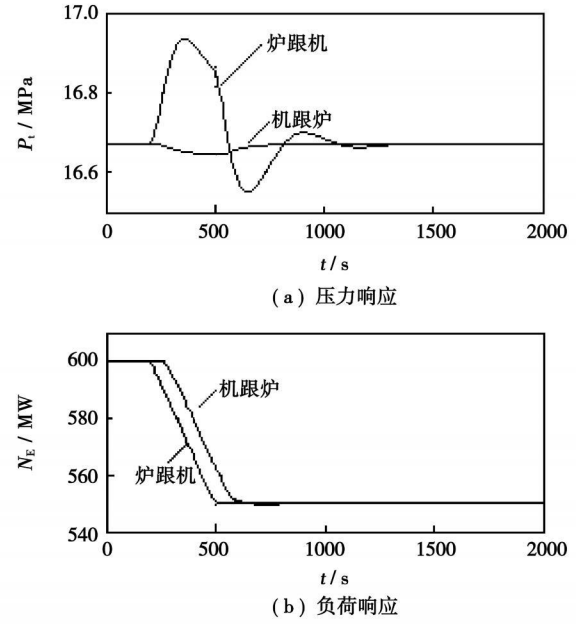


图 4 燃料发热量降低 20%负荷指令扰动

在工程中, 由于以上各种因素可能迭加在一起产生最坏的情况, 而且不允许反复进行扰动实验优化 PID 参数, 所以需要找出主要矛盾, 进行针对性设计。

4 结 论

在对空冷机组模型特性进行分析的基础上, 以机跟炉和炉跟机两种方式研究机组协调控制系统的鲁棒性, 仿真实验表明:

在正常情况下, 协调控制系统依靠其自身鲁棒性, 能够较好地克服机组燃料发热量、排汽压力等因

素变化的影响; 负荷工作点变化造成的制粉惯性、迟延、锅炉蓄热系数的变化以及系统自身非线性仍然是影响系统控制品质的主要因素。

实际的协调控制系统针对被控对象静态参数变化, 设计中都或多或少地采取了一些措施, 如文献[7]控制器参数根据负荷—压力工作点做自适应等; 进行燃料发热量校正; 进行汽轮机排汽压力修正等等。但对被控对象动态参数变化往往未做过多考虑。为了提高控制品质, 协调控制系统应该考虑模型动态参数变化情况并进行有针对性的设计。

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(编辑　伟)

新技术、新工艺

考虑显微损坏的剩余寿命的估算

据《Теплоэнергетика》2008 年 2 月号报道, 按照现行规则, 在下列情况下可以延长动力设备的使用期限:

·没有裂纹形式的损伤;

·金属强度特性降低范围值(10%～15%额定值);

·保证关于平均应力的标准的安全系数;

·限制平均的永久蠕变变形。

进行的计算及其与利用显微损坏金相检验方法测定的金属状态的比较表明:

·为了预测金属显微损坏的程度, 可以利用描述已使用寿命部分的参数;

·显微损伤实际检查的数据与损伤特性计算的结果满意地相吻合;

·使用提出的方法允许根据实际的应力级审定金属显微损伤中间检查所采用的期限。

提供了强度计算结果与在高温条件下运行过程中发生的金属结构变化的比较。

(吉桂明　供稿)

and fuel, promoted, thus enhancing the combustion efficiency of the CFB boiler burning low-volatile coals. **Key words**: CFB (circulating fluidized bed) boiler, secondary air distribution, mixing of gas and fuel in a furnace, boiler combustion condition

电厂送粉系统煤粉浓度和速度的在线测量技术研究＝**Study of the Technology of On-line Pulverized-coal Concentration and Velocity Measurement for Power Plant Pulverized-coal Conveyance Systems**[刊, 汉] / SUN Meng, LEI Jing (Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing, China, Post Code: 100080), LIU Shi, LI Zhi-hong (Education Ministry Key Laboratory on Power Plant Equipment Condition Monitoring and Control, North China Electric Power University, Beijing, China, Post Code: 102206) // Journal of Engineering for Thermal Energy & Power. — 2009, 24(2). —211 ~215

The accurate measurement of pulverized coal concentration in each air pipe and its guidance role for regulation during a combustion process are very important to the safe and cost-effective operation of a boiler. By using capacitance tomography, tested and studied were the concentration and velocity of solids conveyed by a dilute-phase pneumatic force at a normal temperature. To overcome the impact of the nonuniformity of the sensitive field of a capacitance sensor on image formation, a cyclone separator was set up in the test system. The role of the cyclone separator is to concentrate the solid particles mainly in the wall-surface zone with the electrodes of the sensor being located on the straight pipe of the separator. The concentration distribution was obtained by using a single-layer 8-pole capacitance sensor and adopting a pre-iterative image reconstruction algorithm. An analysis of the probability and frequency spectrum characteristics of flows at the upstream and downstream of the cyclone separator has verified that the flows can meet relevant requirements for capacitance measurement. In this connection, the axial velocity was obtained by measuring relevant capacitance signals from the poles in the upper and lower layers, and the tangential velocity was ascertained by measuring the relevant capacitance signals from a pair of adjacent poles in the same layer of the sensor. The measurement and contrast analysis of the volume fraction, axial and tangential velocity in the pipe section have proven that the method under discussion can ensure reliable measurement results. **Key words**: capacitance tomography, pulverized coal concentration, volume fraction, velocity measurement, gas-solid two-phase flow

非预混燃烧中喷嘴结构布局影响火焰长度的变化＝**Influence of Nozzle Structure Layout on the Change of Flame Length in a Non-premixed Combustion Process**[刊, 汉] / XU Qiong-hui, ZHAN Jie-min (Department of Applied Mechanics and Engineering, Zhongshan University, Guangzhou, China, Post Code: 510275) // Journal of Engineering for Thermal Energy & Power. — 2009, 24(2). —216 ~221

Verified was the reliability of numerical methods on the study of turbulent combustion. Under the condition of the gas flow rate and the total area of spouts being kept unchanged, by adjusting the number and spacing of spouts, several burner spout layout versions were determined. The influence of the number and spacing of spouts on the flame length in a non-premixed combustion process was discussed. It is believed that the change in the number and spacing of the spouts will cause not only a change of the air and gas mixing degree but also make the disturbance degrees between various gas streams different. Hence, the spout layout should be properly adjusted to change the burner flame configuration and temperature distribution and make the high-temperature combustion zone more centralized, thus enhancing the thermal efficiency of a gas-fired boiler. **Key words**: non-premixed combustion, number of spouts, spout spacing, flame length

空冷机组协调控制系统鲁棒性分析＝**Robustness Analysis of a Coordinated Control System for Air-cooled Units**[刊, 汉] / TIAN Liang, LIU Xin-ping, LIU Ji-zhen (Automation Department, North China Electric Power University, Baoding, China, Post Code: 071003) // Journal of Engineering for Thermal Energy & Power. — 2009, 24(2). —222 ~

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Compared with traditional water-cooled units, air-cooled units are susceptible to the changes of environmental factors, and, as a result, their object characteristics become more complicated. A load-pressure object dynamic model of the air-cooled units was established, and the variation regularity and range of their main parameters were analyzed. On this basis, by employing two control modes, namely, boiler operation based on turbine control and turbine operation based on boiler control, simulated and analyzed was the influence of the load-pressure operating point, exhaust steam pressure and the change of fuel heat value on the performance of the control system. It has been found that PID (proportional, integral-differential) controllers can boast a relatively good robustness, and can overcome the influence of the change of exhaust steam pressure and fuel heat value of the power unit on the control system. The pulverized-coal milling inertia and time delay as well as the change of boiler heat accumulation coefficient in the model both caused by the change of load-pressure operating point, and the self nonlinearity of an object under study still constitute the main factors influencing the control quality of the air-cooled unit. **Key words**: automation control technology, direct air-cooled unit, coordinated control, robustness, simulation analysis

船用相继增压柴油机 1TC/2TC 切换过程仿真分析＝**Simulation Analysis of the 1TC/2TC Switch-over Process of a Marine Sequentially Supercharged Diesel**[刊, 汉] /CHEN Hua-qing (Department of Thermal Energy, Tsinghua University, Beijing, China, Post Code: 100161) Journal of Engineering for Thermal Energy &Power. — 2009, 24(2). —226 ~229

The sequential turbocharging technology is one of the main measures for improving the low-load performance of a marine diesel. The 1TC/2TC switch-over time and process exercise a relatively big influence on the transient performance of a sequentially supercharged diesel. The authors have established a quasi-steady-state mathematical model for the foregoing diesel, and simulated and analyzed the dynamic performance of the 1TC/2TC switch-over process of a 16PA6STC type sequentially turbocharged marine diesel. The research results show that as far as the 1TC/2TC switch-over process of the diesel in question is concerned, a comparatively appropriate switch-over time has been determined as follows: after the gas valve to the controlled turbocharger has been opened when the rotating speed of the controlled turbocharger slightly exceeds that of the basic turbocharger, open promptly the air valve of the controlled turbocharger. It is more appropriate that the time delay for the 1TC/2TC switch-over process of the 16PA6STC diesel should be chosen at 2.7 seconds. **Key words**: diesel, sequential turbocharging, performance simulation

低热值燃料对微型燃气轮机运行特性的影响＝**Influence of Low-heating-value Fuels on the Operating Characteristics of a Miniature Gas Turbine**[刊, 汉] / LIU Ai-guo, WENG Yi-wu, WENG Shi-lie, et al (Education Ministry Key Laboratory on Power and Mechanical Engineering, Shanghai Jiaotong University, Shanghai, China, Post Code: 200240) / / Journal of Engineering for Thermal Energy &Power. — 2009, 24(2). —230 ~235

Biomass gas features a low heat value and different combustible constituents, leading to various problems during its application in miniature gas turbines. When a miniature gas turbine designed for burning natural gas uses a low-heat-value fuel, a change of working medium flow rate and thermodynamic characteristics may result, bringing about a change of the operating characteristics of the gas turbine. To use the low-heat-value fuel for the gas turbine, proposed were several methods for adjusting and improving the miniature gas turbine to adapt it to such a fuel. By using a mathematical model, calculated was the influence of using these methods on the operating characteristics of the gas turbine. It has been found that after the use of the low-heat-value fuel, a conspicuous change may occur to the operating characteristics of the gas turbine. Among the methods under discussion, the improvement of the compressor and turbine to accommodate to a new matching of the flow rates is the most suitable one. Apart from the matching problem, the authors have also mentioned other problems yet