中间再热抽汽式汽轮机调节系统的自整条件

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［摘要］ 本文推导了再热抽汽式汽轮机调节系统的静态自整条件，结果表明再热抽汽机组的动态自整条件与凝汽抽汽机组动态自整条件是不同的。所得结论对调节系统设计具有指导意义。

关键词　再热抽汽式汽轮机　调节系统　自整性

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1　引言

发展热电联供是节约能源的重要措施，我国自 80 年代以来城市集中供热有很大的发展，生产了大量热电联供汽轮机，并将部分原凝汽式汽轮机改造成抽汽供热机组，供热机组的容量已从原来的 25 MW 和 50 MW 发展到 200 MW 和 300 MW 大功率中间再热机组，预期在 90 年代还会有更大的发展。

除了供热以外，还有很多工业部门，例如：纺织、制糖、造纸、锻压等许多工业部门需要蒸汽。目前生产的热电联供机组有单抽汽、双抽汽、背压式和抽汽背压式等各种类型。

调节系统是汽轮机安全和经济运行的保证，对于抽汽机组而言，除了和凝汽式汽轮机共同的要求以外，还要求调节系统保证供热与供电的自整性，而且由于增加了压力调节回路，大大增加了调节系统的复杂程度，其稳定性问题和甩负荷后的转速飞升问题均较凝汽式汽轮机更为复杂。对于一般凝汽式抽汽汽轮机，无论是自整条件还是稳定性方面都作了比较充分的研究，但是对于中间再热抽汽机组来说，由于在近年来有较大发展，所以对它们还缺少全面的研究，特别是在动态特性方面更是如此。

本文将重点讨论中间再热式抽汽汽轮机的自整条件问题。

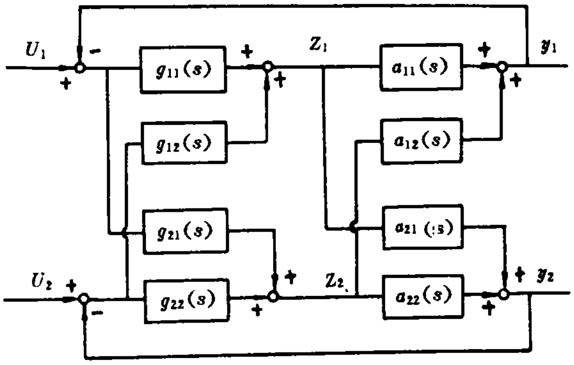

图 1

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2　抽汽式汽轮机调节系统自整性(解耦)设计的方法

由于抽汽式汽轮机是一个多输入多输出的调节对象，它有几个被调节参数，也有几个调节机构。图 1 是单抽汽汽轮机调节系统的简化传递函数方块图，图中 y_1y_2 是被调节量，例如转速(功率)和抽汽压力(抽汽量)，Z_1Z_2 是调节机构位移，为高低压油动机行程，而 u_1u_2 则分别是转速(功率)和抽汽压力(流量)的给定值。

由图 1 可见，以矩阵表示输入输出关系时，有

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} a_{11}(s) & a_{12}(s) \\ a_{12}(s) & a_{22}(s) \end{bmatrix} \begin{bmatrix} Z_1 \\ Z_2 \end{bmatrix}$$

$$\begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \begin{bmatrix} g_{11}(s) & g_{12}(s) \\ g_{12}(s) & g_{22}(s) \end{bmatrix} \begin{bmatrix} u_1 - y_1 \\ u_2 - y_2 \end{bmatrix}$$

消去中间变量 $[z_1\ z_2]^{T}$，则有

$$\begin{aligned} \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} &= \begin{bmatrix} a_{11}(s) & a_{12}(s) \\ a_{12}(s) & a_{22}(s) \end{bmatrix} \begin{bmatrix} g_{11}(s) & g_{12}(s) \\ g_{21}(s) & g_{22}(s) \end{bmatrix} \begin{bmatrix} u_1 - y_1 \\ u_2 - y_2 \end{bmatrix} \\ &= \begin{bmatrix} a_{11}(s)g_{11}(s) + a_{12}(s)g_{21}(s) & a_{11}(s)g_{12}(s) + a_{12}(s)g_{22}(s) \\ a_{21}(s)g_{11}(s) + a_{22}(s)g_{21}(s) & a_{21}(s)g_{12}(s) + a_{22}(s)g_{22}(s) \end{bmatrix} \begin{bmatrix} u_1 - y_1 \\ u_2 - y_2 \end{bmatrix} \end{aligned} \tag{1}$$

则当

$$a_{11}(s)g_{12}(s) + a_{12}(s)g_{22}(s) = 0 \tag{2}$$

$$a_{21}(s)g_{11}(s) + a_{22}(s)g_{21}(s) = 0 \tag{3}$$

时，矩阵 A(s)G(s) 成为对角阵，输出量 y_1 只与 $u_1 - y_1$ 有关，而 y_2 只与 $u_2 - y_2$ 有关，即满足了自整(解耦)条件。

如果在 $t \to \infty$，即 $S = 0$ 时，满足条件式(2)和(3)，则称系统是静态自整的；如果对任何 S 值时条件式(2)和(3)均能得到满足，则称系统是动静态完全自整的。

3　中间再热单抽汽汽轮机调节系统的数学模型及自整条件

图 2 是中间再热单抽汽汽轮机调节系统的数学模型，图中虚线框内为调节对象，Z_1、Z_2 分别为高压及低压油动机位移，P_T 和 q_T 分别为汽轮机功率和抽汽量。虚线框外为调节系统，其中 e_1、e_2 分别为调速器和压力调节器的输出，$g_{11}(s)$、$g_{21}(s)$、$g_{12}(s)$、$g_{22}(s)$ 为解耦矩阵(在液压系统中为综合滑阀)。

对于图 2 所示系统，有

$$\begin{bmatrix} Z_1 \\ Z_2 \end{bmatrix} = \begin{bmatrix} \dfrac{g_{11}(s)}{T_{s1}s+1} & \dfrac{g_{21}(s)}{T_{s1}s+1} \\ \dfrac{g_{12}(s)}{T_{s2}s+1} & \dfrac{-g_{22}(s)}{T_{s2}s+1} \end{bmatrix} \begin{bmatrix} e_1 \\ e_2 \end{bmatrix} \tag{4}$$

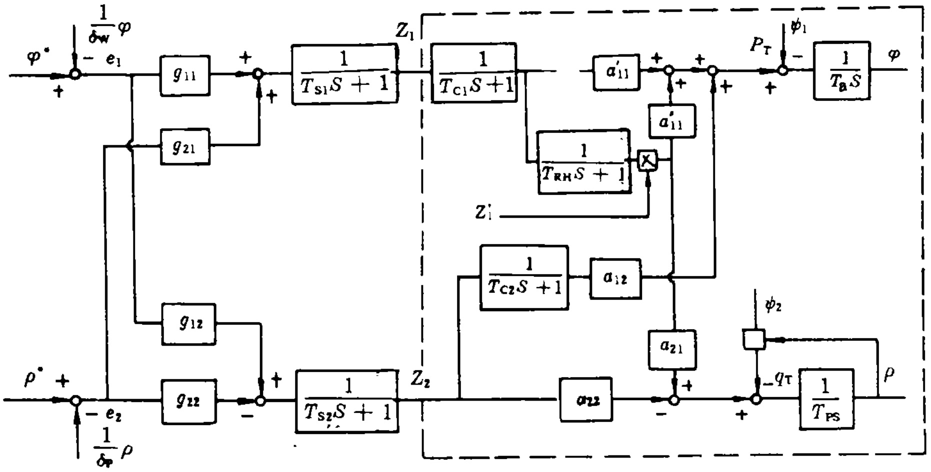

图 2

$$\begin{bmatrix} p_T \\ q_T \end{bmatrix} = \begin{bmatrix} \dfrac{a'_{11}}{T_{c1}s+1} + \dfrac{a''_{11}}{(T_{c1}s+1)(T_{RH}s+1)} & \dfrac{a_{12}}{T_{c2}s+1} \\ \dfrac{a_{21}}{(T_{c1}s+1)(T_{RH}s+1)} & -a_{22} \end{bmatrix} \begin{bmatrix} Z_1 \\ Z_2 \end{bmatrix} \tag{5}$$

将式(5)代入式(4)，则有：

$$\begin{bmatrix} p_T \\ q_T \end{bmatrix} = \begin{bmatrix} \left\{\dfrac{g_{11}(s)}{T_{s1}s+1}\left[\dfrac{a'_{11}}{T_{c1}s+1} + \dfrac{a''_{11}}{(T_{c1}s+1)(T_{RH}s+1)}\right] + \dfrac{a_{12}g_{12}(s)}{(T_{c2}s+1)(T_{s2}s+1)}\right\} & \left\{\dfrac{g_{21}(s)}{T_{s1}s+1}\left[\dfrac{a'_{11}}{T_{c1}s+1} + \dfrac{a''_{11}}{(T_{c1}s+1)(T_{RH}s+1)}\right] - \dfrac{a_{12}g_{22}(s)}{(T_{c2}s+1)(T_{s2}s+1)}\right\} \\ \dfrac{a_{21}g_{11}(s)}{(T_{c1}s+1)(T_{RH}s+1)(T_{s1}s+1)} - \dfrac{a_{22}g_{12}(s)}{T_{s2}s+1} & \dfrac{a_{21}g_{21}(s)}{(T_{c1}s+1)(T_{RH}s+1)(T_{s1}s+1)} - \dfrac{a_{22}g_{22}(s)}{T_{s2}s+1} \end{bmatrix} \begin{bmatrix} e_1 \\ e_2 \end{bmatrix} \tag{6}$$

根据自整条件，要求式(6)的传递矩阵为对角阵，所以要适当选择调节系统的各参数，使得各非对角线上的元素均等于零，即要求：

$$\frac{g_{21}(s)}{T_{s1}s+1}\left[\frac{a'_{11}}{T_{c1}s+1}+\frac{a''_{11}}{(T_{c1}s+1)(T_{RH}s+1)}\right]-\frac{a_{12}g_{22}(s)}{(T_{c2}s+1)(T_{s2}s+1)}=0 \tag{7}$$

$$\frac{a_{21}g_{11}(s)}{(T_{c1}s+1)(T_{RH}s+1)(T_{s1}s+1)}-\frac{a_{22}g_{12}(s)}{T_{s2}s+1}=0 \tag{8}$$

令 $S=0$,即 $t\to\infty$,则得静态自整条件如式(9)和式(10)所示。

$$(a'_{11}+a''_{11})g_2(0)-a_{12}g_{22}(0)=0 \tag{9}$$

$$a_{21}g_{11}(0)-a_{22}g_{12}(0)=0 \tag{10}$$

它们和一般凝汽式抽汽机组的自整条件相同,由式(7) 和式(8) 可以看到,在动态过程中,即 $s\neq 0$ 时,要满足自整要求是比较复杂的,对于一般凝汽式供热机组的准则 $T_{s1}=T_{s2}$ 已经不再适用。为了简化分析,考虑到中间再热时间常数 T_{RH} 远远大于 T_{s1}、T_{c1} 和 T_{c2},可以近似令 $T_{s1}=T_{c1}=T_{c2}=0$,则式(9) 和(10) 可简为

$$g_{21}(s)\left(a'_{11}+\frac{a''_{11}}{T_{RH}s+1}\right)-\frac{a_{12}g_{22}(s)}{T_{s2}s+1}=0 \tag{11}$$

$$\frac{a_{21}g_{11}(s)}{T_{RH}s+1}-\frac{a_{22}g_{12}(s)}{T_{s\star\gtrless}s+1}=0 \tag{12}$$

由式(11) 及(12) 可见,当满足静态自整条件,且令 $g_{11}(s)=g_{11}(0)$、$g_{22}(s)=g_{22}(0)$、$g_{12}(s)=g_{12}(0)$ 时,则得动态自整条件为

$$T_{s2}=T_{RH}$$

$$g_{21}(s)=\frac{g_{21}(0)(a'_{11}+a''_{11})}{a'_{11}T_{RH}s+a'_{11}+a''_{11}} \tag{13}$$

如果低压油动机为液压的,所选用的时间常数比较小,即 $T_{s2}\ll T_{RH}$,则当满足静态自整条件,且令 $g_{11}(s)=g_{11}(0)$,则由式(11)及(12)可得动态自整条件为

$$g_{12}(s)=\frac{g_{12}(0)}{T_{RH}s+1}$$

$$g_{22}(s)=\frac{1}{T_{RH}s+1}$$

$$g_{21}=\frac{g_{21}(0)(a'_{11}+a''_{11})}{a'_{11}T_{RH}s+a'_{11}+a''_{11}} \tag{13'}$$

4 中间再热双抽汽汽轮机调节系统的数学模型及自整条件

图 3 是中间再热双抽汽汽轮机调节系统的数学模型，假设高压抽汽压力低于中间再热压力。图中虚线框内为调节对象，框外为调节系统，符号与单抽汽相同。输入输出关系为：

$$\begin{bmatrix} Z_1 \\ Z_2 \\ Z_3 \end{bmatrix} = \begin{bmatrix} \frac{g_{11}}{T_{s1}s+1} & \frac{g_{21}}{T_{s1}s+1} & \frac{g_{31}}{T_{s1}s+1} \\ \frac{g_{12}}{T_{s2}s+1} & \frac{g_{22}}{T_{s2}s+1} & \frac{g_{32}}{T_{s2}s+1} \\ \frac{g_{13}}{T_{s3}s+1} & \frac{g_{23}}{T_{s3}s+1} & \frac{g_{33}}{T_{s3}s+1} \end{bmatrix} \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} \tag{14}$$

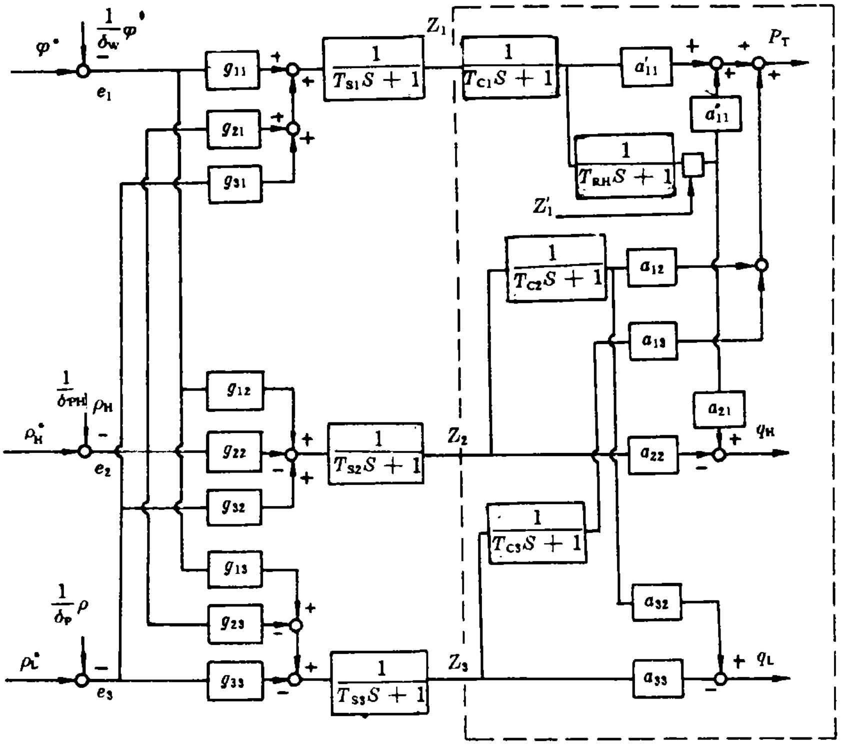

图 3

$$\begin{bmatrix} p_T \\ q_H \\ q_L \end{bmatrix} = \begin{bmatrix} \frac{1}{T_{c1}+1}\left(a'_{11}+\frac{a''_{11}}{(T_{RH}s+1)}\right) & \frac{a_{12}}{T_{c2}s+1} & \frac{a_{13}}{T_{c3}s+1} \\ \frac{a_{21}}{(T_{c1}s+1)(T_{RH}s+1)} & -a_{22} & 0 \\ 0 & \frac{a_{32}}{T_{c2}s+1} & -a_{33} \end{bmatrix} \begin{bmatrix} Z_1 \\ Z_2 \\ Z_3 \end{bmatrix} \tag{15}$$

将式(15)代入式(14)，消去$[Z_1 \quad Z_2 \quad Z_3]^T$，得：

$$\begin{bmatrix} p_T \\ q_H \\ q_L \end{bmatrix} = \begin{bmatrix} C_{11}(s) & C_{12}(s) & C_{13}(s) \\ C_{21}(s) & C_{22}(s) & C_{23}(s) \\ C_{31}(s) & C_{32}(s) & C_{33}(s) \end{bmatrix} \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} \tag{16}$$

式中

$$C_{11}(s) = \frac{g_{11}(s)}{(T_{c1}s+1)(T_{s1}s+1)}\left[a'_{11}+\frac{a''_{11}}{T_{RH}s+1}\right] + \frac{a_{12}g_{12}(s)}{(T_{c2}s+1)(T_{s2}s+1)} + \frac{a_{13}g\ 13(s)}{(T_{c3}s+1)(T_{s3}+1)}$$

$$C_{12}(s) = \frac{g_{21}(s)}{(T_{c1}s+1)(T_{s1}s+1)}\left[a'_{11}+\frac{a''_{11}}{T_{RH}s+1}\right] - \frac{a_{12}g_{22}(s)}{(T_{c2}s+1)(T_{s2}s+1)} - \frac{a_{13}g_{23}(s)}{(T_{c3}s+1)(T_{s3}+1)}$$

$$C_{13}(s) = \frac{g_{31}(s)}{(T_{c1}s+1)(T_{s1}s+1)}\left[a'_{11}+\frac{a''_{11}}{T_{RH}s+1}\right] + \frac{a_{12}g_{32}(s)}{(T_{c2}s+1)(T_{s2}s+1)} + \frac{a_{13}g_{33}(s)}{(T_{c3}s+1)(T_{s3}+1)}$$

$$C_{21}(s) = \frac{a_{21}g_{11}(s)}{(T_{c1}s+1)(T_{RH}s+1)(T_{s1}s+1)} - \frac{a_{22}g_{12}(s)}{T_{s2}s+1}$$

$$C_{22}(s) = \frac{a_{21}g_{21}(s)}{(T_{c1}s+1)(T_{RH}s+1)(T_{s1}s+1)} + \frac{a_{22}g_{22}(s)}{T_{s2}s+1}$$

$$C_{23}(s) = \frac{a_{21}g_{31}(s)}{(T_{c1}s+1)(T_{RH}s+1)(T_{s1}s+1)} - \frac{a_{22}g_{32}(s)}{T_{s2}s+1}$$

$$C_{31}(s) = \frac{a_{32}g_{12}(s)}{(T_{c2}s+1)(T_{s2}s+1)} - \frac{a_{33}g_{13}(s)}{T_{s3}s+1}$$

$$C_{32}(s) = \frac{-a_{32}g_{22}(s)}{(T_{c2}s+1)(T_{s2}s+1)} + \frac{a_{33}g_{23}(s)}{T_{s3}s+1}$$

$$C_{33}(s) = \frac{a_{32}g_{32}(s)}{(T_{c2}s+1)(T_{s2}s+1)} + \frac{a_{33}g_{33}(s)}{T_{s3}s+1}$$

与前面一样，为了实现自整调节，要求所有非对角线元素均为零，即令

$$C_{12}(s) = C_{13}(s) = C_{21}(s) = C_{23}(s) = C_{31}(s) = C_{32}(s) = 0 \tag{17}$$

当$s=0$时，可得静态自整条件为

$$\left.\begin{aligned}
&(a'_{11} + a''_{11})g_{21}(0) - a_{12}g_{22}(0) - a_{13}g_{23}(0) = 0\\
&(a'_{11} + a''_{11})g_{31}(0) - a_{13}g_{32}(0) - a_{13}g_{33}(0) = 0\\
&a_{21}g_{11}(0) - a_{22}g_{12}(0) = 0\\
&a_{21}g_{31}(0) - a_{22}g_{32}(0) = 0\\
&a_{32}g_{12}(0) - a_{33}g_{13}(0) = 0\\
&- a_{32}g_{22}(0) - a_{33}g_{23}(0) = 0
\end{aligned}\right\} \tag{18}$$

考虑到各容积时间常数 T_{c1}、T_{c2}、T_{c3} 相对再热器时间常数 T_{RH} 来说都很小，而且高压油动机时间常数 T_{s1} 从甩负荷角度必须设计得很小，故可令 $T_{c1} \approx T_{c2} \approx T_{c3} \approx T_{s1} \approx 0$，则可得自整条件为：

$$C_{12}(s) = g_{21}(s)(a'_{11} + \frac{a''_{11}}{T_{RH}s + 1}) - \frac{a_{12}g_{22}(s)}{T_{s2}s + 1} - \frac{a_{13}g_{23}(s)}{T_{s3}s + 1} = 0 \tag{19}$$

$$C_{13}(s) = g_{31}(s)(a'_{11} + \frac{a''_{11}}{T_{RH}s + 1}) - \frac{a_{12}g_{32}(s)}{T_{s2}s + 1} - \frac{a_{13}g_{33}(s)}{T_{s3}s + 1} = 0 \tag{20}$$

$$C_{21}(s) = \frac{a_{21}g_{11}(s)}{T_{RH}s + 1} - \frac{a_{22}g_{12}(s)}{T_{s2}s + 1} = 0 \tag{21}$$

$$C_{23}(s) = \frac{a_{21}g_{31}(s)}{T_{RH}s + 1} - \frac{a_{22}g_{32}(s)}{T_{s2}s + 1} = 0 \tag{22}$$

$$C_{31}(s) = \frac{a_{32}g_{12}(s)}{T_{s2}s + 1} - \frac{a_{33}g_{13}(s)}{T_{s3}s + 1} = 0 \tag{23}$$

$$C_{32}(s) = - \frac{a_{32}g_{22}(s)}{T_{s2}s + 1} + \frac{a_{33}g_{23}(s)}{T_{s3}s + 1} = 0 \tag{24}$$

当静态自整条件得到满足，而且令 $g_{11}(s) = g_{11}(0)$，$g_{12}(s) = g_{12}(0)$，$g_{13}(s) = g_{13}(0)$，$g_{22}(s) = g_{22}(0)$，$g_{23}(s) = g_{23}(0)$，$g_{32}(s) = g_{32}(0)$，$g_{33}(s) = g_{33}(0)$，即与时间无关，则由式(21)～(24)可得动态自整条件之一为：

$$T_{s2} = T_{s3} = T_{RH} \tag{25}$$

再由式(19)与(20)可得动态自整条件之二为：

$$g_{21}(s) = g_{21}(0) / \frac{a'_{11}}{a'_{11} + a''_{11}}(T_{RH}s + 1) \tag{26}$$

$$g_{31}(s) = g_{31}(0) / \frac{a'_{11}}{a'_{11} + a''_{11}}(T_{RH}s + 1) \tag{27}$$

所以，双抽汽中间再热式汽轮机的动态自整条件为式(25)、(26)及(27)。

5 仿真验算

为了验证下述结论的正确性，对图 2 所示的中间再热式单抽汽汽轮机调节系统进行了仿真验算，在其他参数相同的条件下取不同的低压油动机时间常数：1) $T_{s2} = T_{RH} = 9$ 秒，2) $T_{s2} = 0.2$ 秒，3) $T_{s2} = 25$ 秒。图 4(a)是当功率给定值由 0.725 阶跃减低为 0.625 时的仿真曲线，由图可见，当电功率改变时，曲线 1($T_{s2} = 9$ 秒) 的压力波动最小，曲线 2($T_{s2} = 0.2$ 秒) 和曲线 3($T_{s2} = 25$ 秒) 的压力波动均大于曲线 1。曲线 4、5、6 是汽机功率随给定值而减小的过程。图 4(*b*) 是抽汽量阶跃降低 10% 时功率的变化过程，曲线 1 最佳。仿真计算的其他参数为：$a'_{11} = a''_{11} = 0.33$，$a_{12} = 0.2178$，$a_{21} = 1.2$，$a_{22} = 0.61$，$T_a = 7$，$T_P = 1$，$K_{11} = 1$，$T_{12} = 1.78$，$K_{21} = 0.38$，$K_{22} = -1$，$K_{s1} = 0.2$，$T_{c1} = 0.25$，$T_{o2} = 0.15$

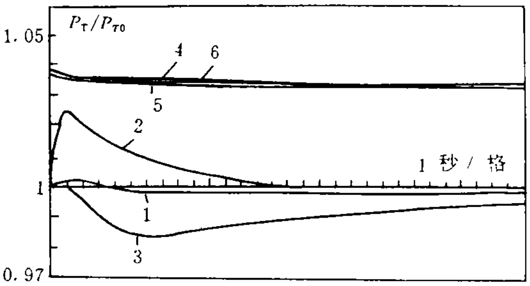

图 4(a)

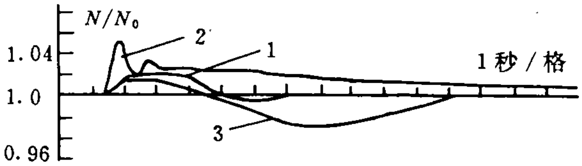

图 4(b)

6　结论

1. 中间再热抽汽式汽轮机调节系统的静态自整条件和一般凝汽式抽汽汽轮机相同。

2. 一般凝汽式抽汽汽轮机调节系统的动态自整条件 $T_{s1} = T_{s2} = T_{s3}$ 对中间再热式不再适用，如果采用 $T_{s2} = T_{s3} = T_{RH}$ 则可以实现单向自整，即电负荷改变不影响热负荷，而热负荷改变在动态过程中仍对电负荷有影响。

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(37) **An Analysis of the Oscillation Failure Mechanism of a Small-Sized Gas Trubine Controlled by a PG-PL Speed Governor** ······ Yu Daren, Xu Jiyu (*Harbin Insititute of Technology*)

This paper deals with the mathematical model of a PG-PL speed governor under a failure condition with the characteristics of various oscillation failures being analysed by way of simulation. The ablve-mentioned model can serve as a helpful tool in conducting failure diagnostics. **Key words:** *small-sized gas turbine*, PG-PL *speed governor*, *oscillation failure*

(42) **Self-regulating Conditions for the Control System of a Reheat Extraction Steam Turbine** ······ Xu Jiyu, Yu Daren (*Harbin Polytechnical University*) Zhang Hongguang, Wu Guoxian (*Harbin Turbine Works*)

The authors have worked out the static and dynamic self-regulating conditions for the control system of a reheat extraction steam turbine. It has been shown that the dynamic self-regulating conditions of a reheat extraction steam turbine are different from those of a condensing extraction steam turbine. Such a conclusion may be advantageously used in guiding the design of the turbine control system. **Key words:** *reheat extraction steam turbine*, *control system*, *self-regulation*

(50) **The Application of a Single Chip Microcomputer in a Metro Blower Electric Control System** ······ Yang Chengyi (*Harbin Marine Boiler & Turbine Research Institute*)

A metro blower blade regulation and control system with a 8031 single chip microcomputer serving as its core has been created, which can change the regulation program of rotor and stator blades, depending on the requirements of various ventilation environments. In addition, it can also be connected to a computation center control station. **key words:** *single chip microcomputer*, *metro blower*, *blade regulation*

(54) **A Study on the Strength of Spherical Gears** ······ Chang Shan, et al (*Harbin Marine Boiler & Turbine Research Institute*)

This paper presents the formulas for calculating the contact stress and bending stress of spherical gear transmission and the trsults of a study on gear cam columns by use of a finite element method. A comprehensive analysis of the bending stress distribution variation relationship of spherical gear cam columns has been performed along with their experimental stress analysis. The test results are in full agreement with those of a theoretical analysis. **Key words:** *spherical gear transmission*, *finite element method*, *stress analysis*

(59) **The Optimum Operating Temperature of Solar Collectors for an Irreversible Solar Energy Heat Engine System** ······ Chen Jincan (*Xiamen University*)

With the help of the model of an irreversible Carnot heat engine and the linear heat loss model of solar collectors the overall efficiency of a solar energy heat engine system has been determined.