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Model Reference Adaptive Control Based PID Controller Designs for Steam Turbine Speed

Sherin A Kochummen[1], Nasar A[2]

[1]PG student, Department of Electrical & Electronics Engineering, TKM College of Engineering, Kollam, India

[2]Assistant Professor, Department of Electrical & Electronics Engineering, TKM College of Engineering, Kollam, India

Abstract: ***A steam turbine, key part of the power plant that allows the conversion of the heat energy to electricity via mechanical energy. Steam turbine control systems are being designed with today's technology to operate a turbine in a safe and reliable manner. Tandem compound reheat steam turbine is introduced to increase the thermodynamic efficiency by multistage steam expansion. Adaptation of PID controller using certain adaptation techniques improves the performance of the system. This paper investigates Model Reference Adaptive Controller for speed control of Tandem compound reheat steam turbine using MIT Rule and Lyapunov rule to bring up quick tracking and steady state control over the turbine speed thus comparing the result with conventional PID controller.***

Keywords: Steam turbine, speed control, PID controller, Linear modeling of Steam Turbine, Model Reference Adaptive Control(MRAC), MIT rule, Lyapunov rule.

1. Introduction

Steam turbines, one of the most versatile and oldest prime mover technologies convert stored energy of high pressure and high temperature steam into rotary energy to drive a generator or mechanical machinery. Power generation using steam turbines has been in use for about hundred years, when they replaced reciprocating steam engines due to their higher thermal efficiencies by multistage steam expansion and lower costs. The turbine may drive an electric generator or equipment such as boiler feedwater pumps, process pumps, air compressors, paper mills and refrigeration chillers. The thermodynamic cycle for the steam turbine, Rankine cycle is the basis for conventional power generating stations where water is first pumped to elevated pressure, which is medium to high pressure depending on the type of turbine unit and then most frequently superheated. The pressurized steam is expanded to lower pressure in a multistage turbine, then exhausted either to a condenser at vacuum conditions or into an intermediate temperature steam distribution system that delivers the steam to the industrial or commercial application and condensate is utilized back.

Various important milestones in the different types of steam turbine modelling and speed control techniques were proposed. In[3] the behavior of the shaft torque is simulated with load and proportional control algorithm but with a simplified first order system. Speed deviation control, with Proportional(P) and Proportional Integral(PI) controllers, at different load deviations and load set points is done in paper [10]. Adaptation of PID Controller using AI Technique like fuzzy logic, Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Bacterial Particle Swarm Optimization (BPSO) and Neuro fuzzy controller(ANFIS) for Speed Control of Isolated Steam Turbine was the work done by Mohamed .M. Ismail [4]. The turbine is considered just as a first order system along with an electro-hydraulic governor. PID controllers, the most commonly used controller structures in industry present some challenges to control and instrumentation engineers in the tuning of the gains required for stability and good transient performance. There are several prescriptive rules used in PID tuning. In this paper, Model Reference Adaptive Control based PID controller is designed for speed control of tandem compound reheat steam turbine based on MIT rule and Lyapunov rule and is compared with with conventional PID controller response.

The structure of this paper is as follows. Section 2 describes about speed governing in steam turbine. The linear mathematical modelling of steam turbine is explained in section 3. Tuning of the conventional PID controller in section 4. Section 5 discuses about Model Reference Adaptive Control(MRAC) and designing of PID controller for steam turbine speed control system using MRAC based on MIT rule and Lyapunov rule. Simulation results is given in section 6. Conclusion is discussed in section 7.

2. Speed Governing In Steam Turbine

A typical governor model for steam turbines includes only those components and control elements that are responsive to speed and speed reference and that supply an input signal to the control mechanism for the purpose of controlling speed which are the control mechanism and steam control valve, whose output is effective control valve area in response to speed deviation of the machine, and a section modeling the turbine, whose input is steam flow and output is mechanical power applied to the generator rotor.

Capability of the speed control system to position the control valve so that a sustained oscillation of the turbine speed as produced by the speed control system, stays within a specified range during operation under steady-state load demand or following a change to a new steady-state load demand to protect the turbine from over speeding, monitors all critical turbine parameters to avoid conditions that could cause equipment damage, to follow the load in a stable and efficient manner.

The steam from this through the control valve enters the high pressure(HP) section of the turbine, develops some power in the high pressure section the steam temperature and pressure thus reduced send to re heater after re heating the steam in the superheated condition again and then it enters the next stage of the turbine is called medium pressure turbine section, MP. The steam leaving from the MP section enters the low pressure (LP) sections through cross over pipings and then exhausted to the condenser as shown in figure 1.

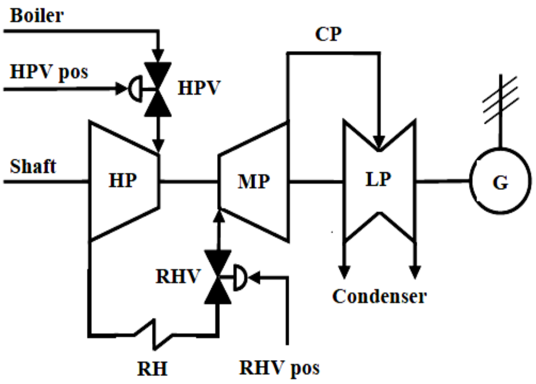

Figure 1: Tandem compound steam turbine configuration

The turbine-generator coupling should run at a constant speed for its safe operation, so we have to control the steam flow to the turbine thus involves the use of control valves to modulate the steam flow by adjusting its position.

3. Linear Modelling Of Steam Turbine

The steam, generated in the boiler flows through the various stages of steam turbine and then ultimately exhausted to the condenser. In order to develop the model a simple steam turbine unit with volume V is considered.

The mathematical modelling of the steam turbine unit, developed based on the continuity equation[1,3]:

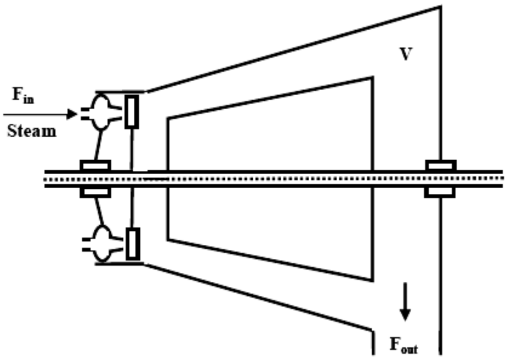

Figure 2: A basic steam turbine unit

Steam mass flow rate,

$$\frac{dw}{dt} = V.\frac{d\rho}{dt} \quad (1)$$

$$\frac{dw}{dt} = F_{in}(t) - F_{out}(t) \quad (2)$$

In the above equations, W is the weight of steam in turbine [kg], V is the volume of turbine [m3], ρ is the density of steam [kg/m3], F is the steam mass flow rate [kg/s], t is time [sec.].

Assuming the flow out of the turbine to be proportional to pressure in the turbine

$$F_{out} = P.\frac{F_0}{P_0} \quad (3)$$

Where: P is pressure of steam in the turbine [kPa],
P_0 – rated pressure; F_0 – rated flow out of turbine.

With constant temperature in the turbine:

$$\frac{d\rho}{dt} = \frac{dP}{dt}.\frac{d\rho}{dP} \quad (4)$$

$$\frac{dP}{dt} = \frac{P_0}{F_0}.\frac{dF_{out}}{dt} \quad (5)$$

$$F_{in}(t) - F_{out}(t) = V.\frac{P_0}{F_0}.\frac{d\rho}{dP}.\frac{dF_{out}}{dt} \quad (6)$$

$$F_{in}(t) = F_{out}(t) + T_t.\frac{dF_{out}}{dt} \quad (7)$$

General model for a single steam turbine unit is

$$H_T(s) = \frac{1}{sT_t+1} \quad (8)$$

As the steam turbine configuration varies the complete turbine model can obtained accordingly. The complete model transfer function can be obtained using the parameters from the following table.

Table 1: Steam turbine parameters

Parameter	*HP section*	*MP section*	*LP section*
Power fraction	$K_{HP} = 0.3$	$K_{MP} = 0.3$	K_{LP}=0.4
Time constant (sec)	T_{HP}= 0.25	T_{RH}=7.5	T_{LP}= 0.5

The overall transfer function of tandem compound reheat steam turbine is

$$G_T(s) = \frac{1.125s^2+2.55s+1}{0.9375s^3+5.75s^2+8.25s+1} \quad (9)$$

Servomotor used in speed control systems converts the electrical signal into angular displacement thus used for actuating purpose by governing the valve opening. The suitability of the motor for a particular application depends on the characteristics, purpose and operating conditions of the system to control with stability, the speed of the turbine at power output between zero and maximum, inclusive, when the generator is operating isolated.

$$G_{SM}(s) = \frac{1}{0.3s+1} \quad (10)$$

$$G_L(s) = \frac{1}{12s} \quad (11)$$

Thus the complete proposed system is

$$G(s) = \frac{1.125s^2+2.55s+1}{3.375s^5+31.95s^4+98.7s^3+102.6s^2+12s} \quad (12)$$

4. Tuning of Conventional PID Controller

The Ziegler–Nichols closed loop method of tuning a PID controller. The P (proportional) gain, is then increased (from zero) until it reaches the ultimate gain , at which the output of the control loop oscillates with a constant amplitude and the oscillation period are used to set the P, I, and D gains. The bode plot is plotted for the open loop transfer function.

The critical frequency obtained (ω_c) is 3.46 rad/sec, magnitude of the open loop transfer function is 0.0186

Ultimate gain, $K_U = \frac{1}{|G(s)|} = 92.047$

Oscillation period, $P_U = \frac{2\pi}{\omega_c} = 1.8159$

The parameters of PID controller,

$K_P = \frac{K_U}{1.7} = 54.145$

$T_I = \frac{P_U}{2} = 0.9079$

$T_D = \frac{P_U}{8} = 0.2269875$

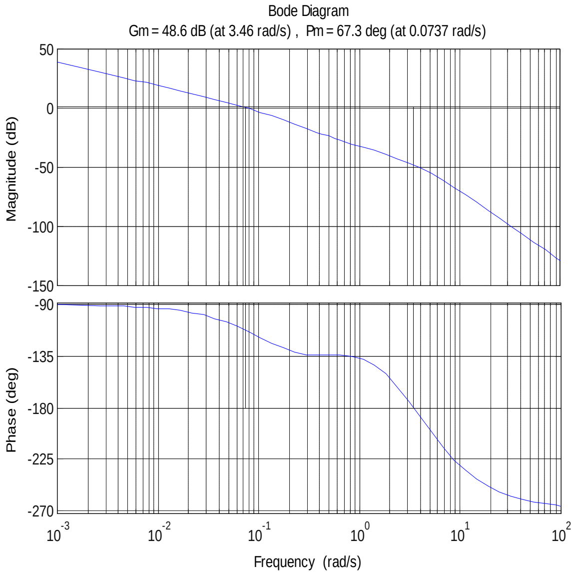

Figure 3: Bode plot of steam turbine system

Transfer function of PID controller

$$\text{PID}(s) = K_P\left(1 + \frac{1}{T_I s} + T_D s\right)$$

$$= 54.145\left(1 + \frac{1}{0.9079\ s} + 0.227\ s\right) \qquad (13)$$

5. Model Reference Adaptive Control

The Model Reference Adaptive Systems(MRAS) derived for deterministic continuous-time signals is an important adaptive control where desired performance expressed in terms of reference model thus responding to the command signal, other than the normal feedback loop there is another to change the controller parameters with respect to the error. The parameter adjustment mechanism can be gradient method or by using stability theory[2].

The MIT(Massachusetts institute of technology) rule central to the adaptive nature of the controller aims to minimize the squared model cost function by which the error function minimized for perfect tracking between actual plant output (y) and reference model output (y_m).

Tracking error,

$$e(t) = y_p(t) - y_m(t) \qquad (14)$$

One possibility to adjust parameters in a way that loss function

$$J(\theta) = \frac{e^2(\theta)}{2} \qquad (15)$$

To make J small, negative gradient make the update rule,

$$\frac{d\theta}{dt} = -\gamma\frac{\partial J}{\partial \theta} = -\gamma e\frac{\partial e}{\partial \theta} \qquad (16)$$

θ = controller parameter vector
γ= Adaptive gain

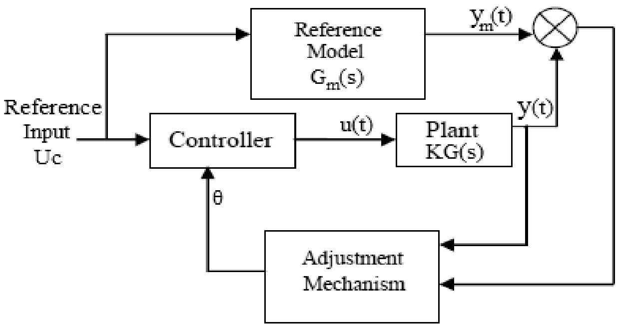

Figure 4: Basic block diagram of a MRAC system

If the process is linear with transfer function $KG(s)$ and K is unknown. The underlying design gives a system with transfer function $K_0G(s)$, where K_0 is a known parameter.

$$E(s) = KG(s)U(s) - KoG(s)Uc(s) \qquad (17)$$

Defining a control law,

$$u = \theta u_c \qquad (18)$$

$$\frac{\partial e}{\partial \theta} = KG(s)U_c(s) = \frac{K}{K_0}Y_m(s) \qquad (19)$$

$$\frac{de}{dt} = -\gamma e\frac{K}{K_0}y_m = -\acute{\gamma} e y_m \qquad (20)$$

5.1 Design of PID Controller using MIT rule

When the parameter of any systems changes with respect to time then the conventional controller action is not effective. In case of MRAC based design the adjustable parameters corresponding to changes in plant will be determined by referring to reference model specifying the property of desired control system. For designing purpose the reduced order model of our plant is

$$G(s) = \frac{0.01323s + 0.01187}{s^2 + 0.1424s - 8.003e^{-17}} \qquad (21)$$

And the reference model chosen here is

$$G_M(s) = \frac{64}{s^2 + 16s + 64} \qquad (22)$$

The characteristics or system parameters are usually not always the same. For these reasons, tuning of the traditional PID controller parameters to control this system for the required performance faces a strong challenge, so it is better to adapt the tuning parameters by an adaptation rule.

PID Controller output,

$$U = K_p(1 + \frac{1}{T_i s} + T_d s)(U_c(s) - Y(s)) \qquad (23)$$

Plant output,

$$Y(s) = \frac{(\alpha_1 s+\alpha_2)\theta_1 U_c}{\alpha_3 s^2+\alpha_4 s-\alpha_5+(\alpha_1 s+\alpha_2)(\theta_2+\theta_3 s+\frac{\theta_5}{s})} \qquad (24)$$

Error = $Y(s) - Y_m(s)$

$$\frac{\partial e}{\partial \theta_1} = \frac{(\alpha_1 s+\alpha_2)\, U_c}{\alpha_3 s^2+\alpha_4 s-\alpha_5+(\alpha_1 s+\alpha_2)(\theta_2+\theta_3 s+\frac{\theta_5}{s})} \qquad (25)$$

$$\frac{\partial e}{\partial \theta_2} = \frac{(\alpha_1 s+\alpha_2)\, \frac{U_c}{s}}{\alpha_3 s^2+\alpha_4 s-\alpha_5+(\alpha_1 s+\alpha_2)(\theta_2+\theta_3 s+\frac{\theta_5}{s})} \qquad (26)$$

$$\frac{\partial e}{\partial \theta_3} = \frac{-(\alpha_1 s+\alpha_2)\, y}{\alpha_3 s^2+\alpha_4 s-\alpha_5+(\alpha_1 s+\alpha_2)(\theta_2+\theta_3 s+\frac{\theta_5}{s})} \qquad (27)$$

$$\frac{\partial e}{\partial \theta_4} = \frac{-(\alpha_1 s+\alpha_2)\, sy}{\alpha_3 s^2+\alpha_4 s-\alpha_5+(\alpha_1 s+\alpha_2)(\theta_2+\theta_3 s+\frac{\theta_5}{s})} \qquad (28)$$

$$\frac{\partial e}{\partial \theta_5} = \frac{(\alpha_1 s+\alpha_2)\, \frac{y}{s}}{\alpha_3 s^2+\alpha_4 s-\alpha_5+(\alpha_1 s+\alpha_2)(\theta_2+\theta_3 s+\frac{\theta_5}{s})} \qquad (29)$$

Approximating with reference model

$$\frac{(\alpha_1 s+\alpha_2)}{\alpha_3 s^2+\alpha_4 s-\alpha_5+(\alpha_1 s+\alpha_2)(\theta_2+\theta_3 s+\frac{\theta_5}{s})} = \frac{16s+64}{s^2+16s+64}$$

5.2 Design of PID Controller With Lyapunov Rule

The adjustment rule obtained by Lyapunov rule is simpler. The proportional, integral and derivative parameters in control law are adapted using the adjustment mechanism.

Controller output,

$$U = K_p(1 + \frac{1}{T_i s} + T_d s)(U_c(s) - Y(s)) \qquad (30)$$

Let plant transfer function is

$$G(s) = (\frac{\alpha_1 s+\alpha_2}{\alpha_3 s^2+\alpha_4 s-\alpha_5}) = \frac{Y(s)}{U(s)} \qquad (31)$$

$$\ddot{y} = \frac{1}{\alpha_3}(\alpha_1 \dot{u}+\alpha_2 u-\alpha_4 \dot{y}-\alpha_5 y) \qquad (32)$$

Let model transfer function,

$$G_M(s) = \frac{64}{s^2+16s+64} = \frac{Ym(s)}{Uc(s)} \qquad (33)$$

$$\ddot{y} = 64U_C - 16y' + 64y \qquad (34)$$

Error = $Y(s) - Y_m(s)$

From the Lyapunov function, V(e, θ_1, θ_2, θ_3, θ_4, θ_5)

Therefore,

$$\frac{d\theta_1}{dt} = -\gamma u_c e \qquad (35)$$

$$\frac{d\theta_2}{dt} = -\gamma \frac{u_c}{s} e \qquad (36)$$

$$\frac{d\theta_3}{dt} = \gamma y e \qquad (37)$$

$$\frac{d\theta_4}{dt} = \gamma \dot{y} e \qquad (38)$$

$$\frac{d\theta_5}{dt} = -\gamma \frac{y}{s} e \qquad (39)$$

Thus integrating these values we obtain adapted parameter values which can direct plant output o desired output.

6. Simulation Results

The simulation results were presented to illustrate the performance, and to compare the proposed strategy with the existing PID controller. Figures 8 provide the responses of the PID controller under disturbances in load for different operating conditions. Test results demonstrated the feasibility and effectiveness of proposed approach. Its performance comparison proved its superior disturbance rejection response to variations in load and reference pressure. The convergence rate depends directly on the value of adaptation gain, γ. Simulation results indicate it is true for small values of γ but behavior is quite unpredictable for large values and so the selection of γ is crucial.

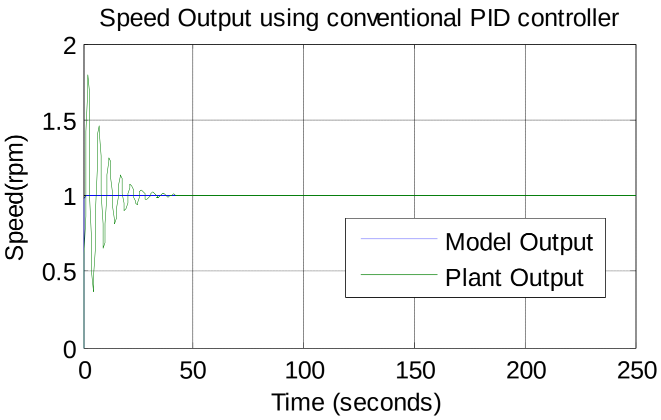

Figure 5: Speed Control using Conventional PID controller

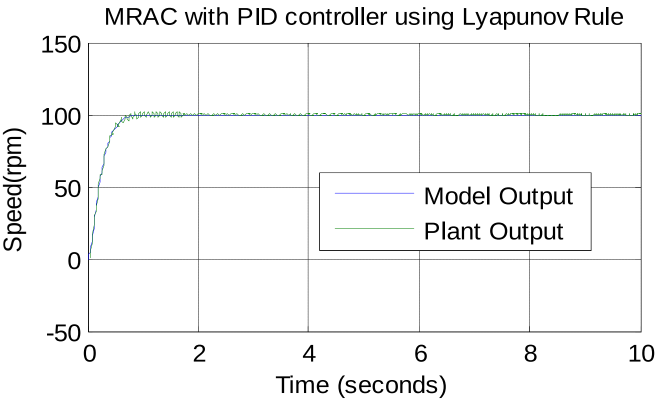

Figure 6: Speed control using MRAC Lyapunov rule with PID controller

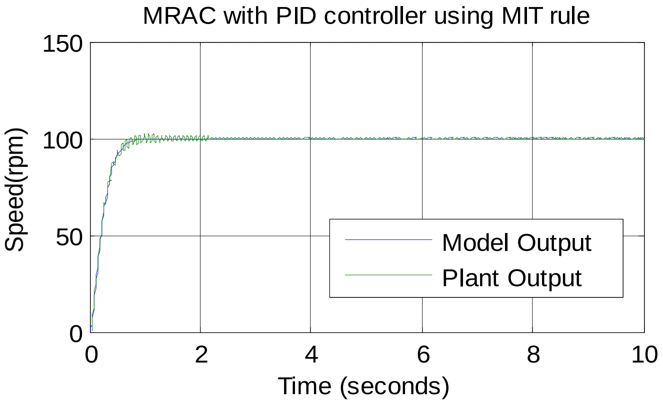

Figure 7: Speed control using MRAC MIT rule with PID controller

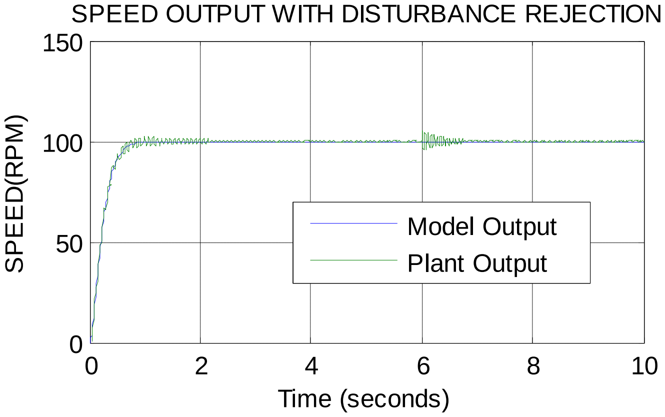

Figure 8: Speed control using MRAC with PID controller

Table 2: Performance comparison using different controllers

Adaptation mechanism	*Controller*	*Peak Overshoot*	*Settling time(sec)*
Zeigler-Nichols tuning	PID	180	40
MIT rule	PID	103	4
Lyapunov rule	PID	102	4.5

7. Conclusion

It is obvious that the MRAC controller,applied to more complicated problems which is designed based on the main system, does not impose any overshoot to the system for an increase in reference pressure as the design requires approximations to obtain sensitivity derivatives. The convergence driving error to zero increases with increasing gain. The turbine speed is achieved by coordinate control of steam pressure with improved precision, reduced steady state error and fast response.

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Author Profile

Sherin A Kochummen was born in Kerala, India in 26/10/1991. She received B.Tech degree in Electrical and Electronics Engineering from Baselios Mathews II College of Engineering, Kollam, India in 2013.Currently, she is pursuing her M Tech degree in Industrial Instrumentation & Control from TKM College of Engineering, Kollam, India. Her research interests include Control Systems. (sherinakoc@gmail.com)