Optimal Tuning of Controllers for Cascade Temperature Control of Superheater Using Nelder Mead Algorithm

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Abstract: A superheater is a vital part of the steam generation process in the boiler-turbine system. Reliable control of temperature in the superheated steam temperature system is important to ensure high efficiency and high load-following capability in the operation of modern power plant. The PI and PID controllers are widely applied in cascade control of secondary superheated steam temperature process and the tuning method of PI and PID controller parameters is still a hot research area. A Nelder mead based optimization tuning scheme is developed for cascade control of superheater steam temperature process. It is an efficient and fast tuning scheme compared to other conventional tuning techniques. The mathematical model of the superheater is derived by sets of nonlinear partial differential equations. From the dynamical model of the superheater, a FOPTD (First order plus dead time model) model is derived using frequency response method. Then optimum gains for PI and PID controllers in the cascade control loop are determined based on the value of ITAE (Integral Time absolute error).

*Keyword***s**: Superheater, dynamical model, FOPTD, ITAE

1 Introduction

Thermal energy is the chief source of electric power generation in India. More than 60% of total electric power generated by steam plants in India. Steam power plant basically operates on Rankin cycle. The main parts of steam power plant are generator, boiler, turbine and their auxiliaries. Steam produced in boiler at certain temperatures and pressure, supplied to turbine which is coupled to the generator. The generator converts mechanical energy into electrical energy. Continuous process in a power plant and power station are complex systems characterized by uncertainty, nonlinearity and load disturbance. The superheater is a quintessential part of the steam generation process in the boiler-turbine system where steam is superheated before entering the turbine that drives the generator. Generation of steam from the superheater is a highly nonlinear process and the temperature and the pressure in the superheater are extremely high. Hence, controlling superheated steam is not only technically difficult, but also economically important. The steam generated from the boiler drum passes through the low-temperature superheater before it enters the radiant-type platen superheater. Water is sprayed onto the steam to control the superheated steam temperature. Proper control of the superheated steam temperature is very important to ensure the overall efficiency and safety of the power plant, as the temperature in the superheater is the highest in the plant. It is undesirable to have the temperature too high or too low, as it can damage the superheater or lower the efficiency of the power plant respectively. Therefore, the superheated steam temperature (SST) has to be controlled by adjusting the flow of spray water to ±10 °c during the transient states, and ±5 °c at the steady state. It is also necessary to lessen the temperature fluctuations inside the superheater, as it helps to decrease the mechanical stress that causes micro-cracks in the unit, in order to extend the life of the unit and to lessen the maintenance costs [15]. In industrial process control area, the proportional-integral-derivative controllers are still commonly used because of their simple structure, easy operations and robust performance in a wide range of operating conditions. It has been reported that more than 95% of the controllers in industrial process control applications are of the PID type controller. Recent years, more and more PID tuning methods are being proposed to deal with various processes. In practise, the complex power plant is often controlled manually by experienced operators based on their knowledge of the plant, when the range of the load change is large .In[14] G.Sreenivasulu et al.(2003), G.Sreenivasulu et al proposed different conventional tuning methods for superheater steam temperature control system, but those controllers are tuned without any objective function. The multi-step,multi variable adaptive regulator has been proposed to control the steam temperature in a boiler [5].A predictive control was implemented to control the steam temperature[5] and pressure. Numerous approaches are presented in the literature for modelling the superheater. The dynamic behaviour of superheater is the main output of these models. Zima (2001) proposed a model [2] which used finite difference method for the solution of the partial differential equations. In his model, he assumed the heat transfer coefficients [2] to be a priori known and constant. The distributed parameter problem was also explained by the Profos model (Profos 1962). The model is based on the one-pipe approximation of the process [4].

2 Description of the Controlled Plant

The power plant under investigation is a 200MW subcritical coal-fired boiler-turbine-generator unit [1]. The structure of the superheater process under consideration is shown in Fig. 1.Its basic task is to keep constant steam temperature 540 °C at the superheater outlet (corresponding to set-point = 540 °C), while hot flue gas 1100 °C is brought to the superheater, heating up the working media. The temperature regulation is carried out by injection of a certain amount of the water in the mixer, corresponding to manipulated value in the control circuit, using a cascade control structure. Cascade heating up the working media. The temperature regulation is carried out by injection of a certain amount of the water in the mixer, corresponding to manipulated value in the control circuit, using a cascade control structure.

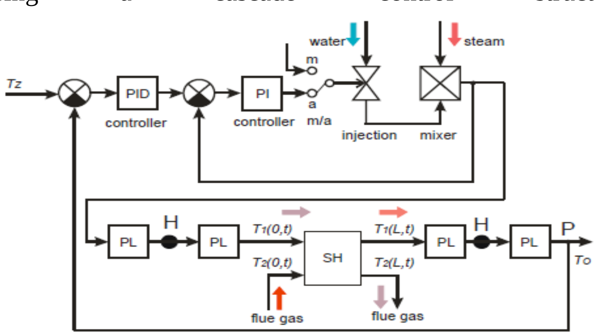

Fig.1: Superheater steam temperature control Circuit

Cascade Control circuit of the superheater includes two basic control loops. The main control loop keeps the constant value of temperature at the output of the superheater. The controller of this loop is nonlinear PID controller. Parameters of this controller vary with the steam flow through the superheater, and they are assigned by function generators [1].

3 Development of Mathematical Model for Secondary Superheater

Applying the energy equations, Newton's equation, and heat transfer equation, and principle of continuity the behaviour of five state variables of superheater can be well described by five nonlinear partial differential equations [1].
Reduced energy equation for flue gas is given by

$$\frac{c_2\rho_2 F_2}{\alpha_{S2}O_2}\left[u_2\frac{\partial T_2}{\partial x}+\frac{\partial T_2}{\partial t}\right]+(T_2-T_S)=0 \qquad (1)$$

Heat transfer equation describes the transfer of heat from burned gases to steam via the wall is given as

$$\frac{\partial T_S}{\partial t}-\frac{T_1-T_S}{\frac{c_S G}{\alpha_{S1}O_1}}-\frac{T_2-T_S}{\frac{c_S G}{\alpha_{S2}O_2}}=0 \qquad (2)$$

The Principle of continuity for steam is given by

$$\frac{1}{F\rho_1}\left\{Fu_1\left(\frac{\partial\rho_1}{\partial p_1}\frac{\partial p_1}{\partial x}+\frac{\partial\rho_1}{\partial T_1}\frac{\partial T_1}{\partial x}\right)+u_1\rho_1\left(\frac{\partial F}{\partial p_1}\frac{\partial p_1}{\partial x}+\frac{\partial F}{\partial T_1}\frac{\partial T_1}{\partial x}\right)+\rho_1\left(\frac{\partial F}{\partial p_1}\frac{\partial p_1}{\partial t}+\frac{\partial F}{\partial T_1}\frac{\partial T_1}{\partial t}+F\left(\frac{\partial\rho_1}{\partial p_1}\frac{\partial p_1}{\partial t}+\frac{\partial\rho_1}{\partial T_1}\frac{\partial T_1}{\partial t}\right)\right\}+\frac{\partial u_1}{\partial x}=0 \qquad (3)$$

The Newton's equation for steam is given by[1]

$$\frac{\partial p_1}{\partial x}+\rho_1 u_1\frac{\partial u_1}{\partial x}+\rho_1\frac{\partial u_1}{\partial t}+\rho_1 g\sin(\theta)+\frac{\rho_1\lambda_1 u_1|u_1|}{2d_n}=0 \qquad (4)$$

Energy equation for steam is given by

$$\frac{\partial}{\partial t}\left\{\rho_1\left(c_1T_1+\frac{u_1^2}{2}\right)\right\}+\frac{\partial}{\partial x}\left\{\rho_1u_1\left(c_1T_1+\frac{u_1^2}{2}\right)\right\}+\frac{\partial}{\partial x}\{c_1u_1\}+\frac{\partial}{\partial x}\{\rho_1u_1\,g.z\}-\alpha_{1S}O_1(T_s-T_1)\frac{1}{F}=0 \qquad (5)$$

Table.1: Relevant parameters for superheater dynamic model

Symbol	Description
T_1(x,t)	Steam temperature
T_2 (x,t)	Fluegas temperature
T_S (x,t)	Wall temperature of the heat exchanging surface of the superheater
P_1(x,t)	Steam pressure
u_1 (x,t)	Steam velocity
P_2(0,t)=P_2 (x,t) = P_2 (L, t)	Flue gas Pressure
u_2(0,t)=u_2(x,t) = u_2 (L,t)	Flue gas velocity
X	the space variable along the active

	length of the wall of the heat exchanging surface of the superheater
T	Time
$c_1 = c_1(P,T)$	Specific heat capacity of steam at constant pressure
$c_2 = c_2(P,T)$	Specific heat capacity of flue gas at constant pressure
c_S	Specific heat capacity of superheater's wall material
dn	diameter of pipeline
F1 = F1(x)	steam pass crossection
F2 = F2 (x)	flue gas channel crossection
g	acceleration of gravity
G = G(x)	weight of wall per unit of length in x direction
L	Length of the wall
$O_1 = O_1(x)$	surface of wall per unit of length in x direction for steam
$O_2 = O_2(x)$	surface of wall per unit of length in x direction for flue gas
z = z(x)	ground elevation of the superheater
$\alpha S_1\ 1K^{-1}$	heat transfer coefficient between wall and steam
αS_2	heat transfer coefficient between the wall and flue gas
$\lambda_1(x)$	steam friction coefficient
θ	superheater's constructional gradient
$\rho_1 = \rho_1(P,T)$	density of steam
$\rho_2 = \rho_2(P,T)$	density of flue gas

4 System Identification

Modeling refers to representation of physical system in mathematical form. The order of the system can be expressed based on the mathematical equation of the physical system. There are different models like integrating process, integrating with dead time process, first order process, first order with dead time process, second order process and second order with dead time process. First order with dead time and second order with dead time process models are widely used to analyze the many real time systems obtaining the model parameters of the first order plus dead time model. System identification of the first order plus dead time process is to determine the model parameters like system gain, time constant and dead time. Different methods are used for obtaining the model parameters of the first order plus dead time model. The two common and effective methods of FOPTD identification are transfer function identification algorithm and frequency response method system identification algorithm [12].

5 Transfer function identification algorithm

The first order model with delay is given by[12]

$$G_p(s) = \frac{ke^{-Ls}}{Ts+1} \tag{6}$$

The first order derivative of $G_p(s)$ with respect to s is given by

$$\frac{G_p'(s)}{G_p(s)} = -L - \frac{T}{1+Ts} \tag{7}$$

$$\frac{G_p''(s)}{G_p(s)} - \left(\frac{G_p'(s)}{G_p(s)}\right)^2 = \frac{T^2}{1+Ts^2} \tag{8}$$

Evaluating the values at s=0 results in

$$T^2 = \frac{G_p''(0)}{G_p(0)} - T_{ar}^2 \tag{9}$$

$$T_{ar} = -\frac{G_p'(0)}{G_p(0)} = L + T \tag{10}$$

The identified first order plus dead model using transfer function approach is given by

$$\mathrm{G_p(s)} = \frac{0.8247}{65.7709\,\mathrm{s}+1}\, \mathrm{e}^{-47.8911\,\mathrm{s}} \tag{11}$$

6 Frequency Response based system Identification Algorithm

For a given plant modelled as a first order plus dead time system

$$\mathrm{G_p(s)} = \frac{\mathrm{K}}{\mathrm{Ts}+1}\, \mathrm{e}^{-\mathrm{Ls}} \tag{12}$$

where, K is the process gain, L is the dead time and T is the time constant

The frequency response of a first order model is given by

$$\mathrm{G(jw)} = \frac{\mathrm{K}}{\mathrm{Tj}\omega+1}\, \mathrm{e}^{-\mathrm{j}\omega \mathrm{L}} \tag{13}$$

Also the ultimate gain K_c is determined at the crossover frequency ω_c. .ω_c is determined from the first intersection of a Nyquist plot with the negative part of the real axis .The resulting equations are (8)

$$\begin{cases} \frac{\mathrm{K}(\cos\omega_c \mathrm{L} - \omega_c \mathrm{T}\sin\omega_c \mathrm{L}}{1+\omega_c^2\mathrm{T}^2} = -\frac{1}{\mathrm{K_c}} \\ \sin\omega_c\mathrm{L} + \omega_c \mathrm{T}\cos\omega_c \mathrm{L} = 0 \end{cases} \tag{14}$$

Where k is gain of the system and it can be calculated directly from the given transfer function. The two variables x_1 = L and x_2 =T is defined as[12]

$$\begin{cases} \mathrm{f_1(x_1, x_2)} = \mathrm{k\,K_c}(\cos\omega_c x_1 - \omega_c x_2 \sin\omega_c x_1) + 1 + \omega_c^2 x_2^2 = 0 \\ \mathrm{f_1(x_1, x_2)} = \sin\omega_c x_1 + \omega_c x_2 \sin\omega_c x_1 = 0 \end{cases} \tag{15}$$

The Jacobian matrix J is denoted as

$$J = \begin{bmatrix} \partial f_1/\partial x_1 & \partial f_1/\partial x_2 \\ \partial f_2/\partial x_1 & \partial f_2/\partial x_2 \end{bmatrix} \quad (16)$$

The Jacobian matrix is calculated as

$$= \begin{bmatrix} -kK_c\omega_c sin\omega_c x_1 - kK_c\omega_c^2 x_2 cos\omega_c x_1 & 2\omega_c^2 x_2 - kK_c\omega_c sin\omega_c x_1 \\ \omega_c sin\omega_c x_1 - \omega_c^2 x_2 sin\omega_c x_1 & \omega_c cos\omega_c x_1 \end{bmatrix} \quad (17)$$

The two variables x_1 and x_2 is solved using quasi-Newton algorithm and it is given as.The first order plus dead time model thus identified using frequency response method [9] and the transfer function is given by

$$G_p(s) = \frac{0.8247}{174s+1} e^{-37s} \quad (18)$$

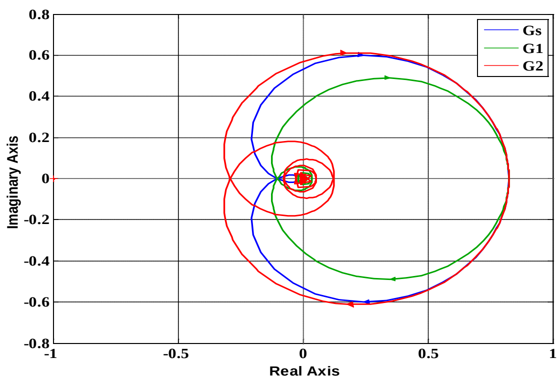

Fig.2. Nyquist diagrams

Gs: Nyquist diagram of the plant

G1: Nyquist diagram for the identified first order plus dead time model using transfer function method

G2: Nyquist diagram for the identified first order plus dead time model using frequency response method

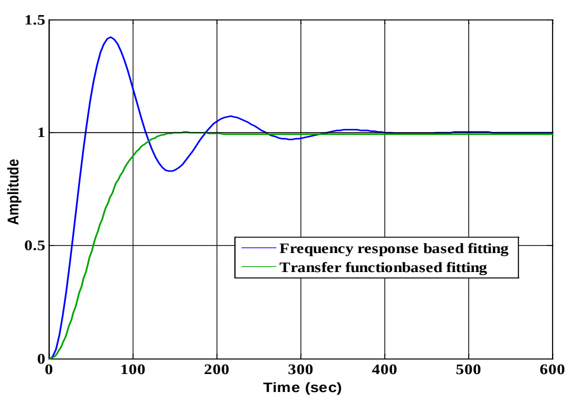

Fig. 3.Closed Loop step responses

The simulation results are shown in fig 4 .From the responses it can be seen that although the PID controller designed with the transfer function identification algorithm looks better, it does not show the overshoot characteristics of Ziegler–Nichols tuning, most probably due to the inaccurately identified parameters of a First order plus dead time model. Hence FOPTD parameters identified using frequency response based approach is used for tuning of controllers for optimal supeheater steam temperature control.

7 Zeigler-Nichols Method

Zeigler and Nichols proposed a very useful tuning formula in early 1942.The tuning formula is obtained when the plant model is given by a first order plus dead time model which can be expressed by[12]

$$G(s) = \exp(-sL) * \frac{K}{Ts+1} \quad (19)$$

Table 2: Zeigler-Nichol's tuning formula

Controller type	From step response		
	K_p	T_i	T_d
PI	0.9/a	3L	
PID	1.2/a	2L	L/2

where a= KL/T

8 Nelder- Mead Simplex Algorithm

Nelder- Mead simplex algorithm includes the following steps

Step 1:X(i) represents the list of points in the current simplex= i = 1,...,n+1

Step 2: Order the points in the simplex from lowest function value f(x(1)) to highest f(x(n+1)). Discard the current worst point x(n+1), and accepts another point into the simplex at each step in the iteration.

Step 3: Determine the reflected point r = 2m – x(n+1), where m = Σx(i)/n, i = 1...n, and calculate f(r)

Step 4: Check if f(x(1)) ≤ f(r) < f(x(n)), accept r and terminate the iteration

Step 5: Calculate the expansion point if f(r) < f(x(1))
s = m +2(m-x(n+1)) and calculate f(s).

a. Check if f(s) < f(r), accept s and terminate the iteration. Expand

b. Otherwise, accept r and terminate the iteration. Reflect

Step 6: Perform a contraction between m and the better of x(n+1) and r if f(r) ≥ f(x(n))

a. Calculate c = m + (r – m)/2 if f(r) < f(x(n+1)). Calculate f(c)

b. If f(c) < f(r), accept c and terminate the iteration. Contract outside Otherwise; continue with Step 7 (Shrink)

c. Calculate cc = m + (x(n+1) – m)/2 if f(r) ≥ f(x(n+1)). If f(cc) < f(x(n+1)), accept cc and terminate the iteration. Contract inside Otherwise; continue with Step 7 (Shrink).

Step 7:Calculate v(i) = x(1) + (x(i) – x(1))/2 and calculate f(v(i)), i = 2,...,n+1.The simplex at the next iteration is x(1), v(2),...,v(n+1).Shrink. The iterations proceed until they meet a stopping criterion [13]

a) Objective Function

The objective function used here is error criteria. Performance of the controller is best evaluated in terms of error criterion.

$$\text{ITAE}=\int_0^\infty t|e(t)|dt \qquad (20)$$

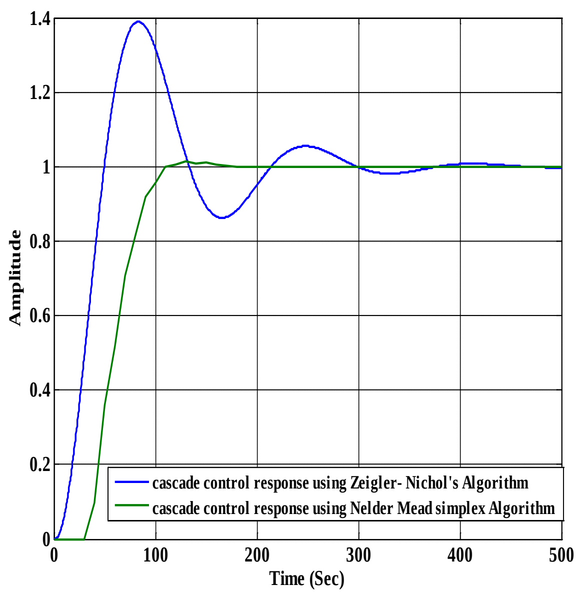

Fig.4. Cascade control responses using Zeigler-Nichols's algorithm and Nelder Mead Simplex algorithm

The simulation results are shown in fig 5 .As shown in figure we can clearly see that the proposed tuning technique is better than the conventional technique.

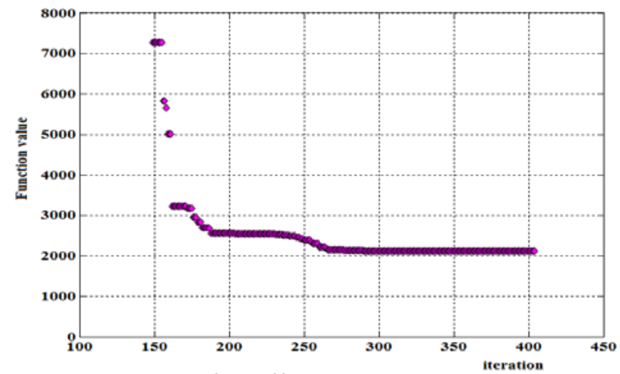

Fig.5.ITAE values for different controller gains tuned using Nelder Mead Simplex algorithm

Table.3: Comparison of performance indices

Performance Indices	Zeigler-Nichols Algorithm	Nelder- Mead simplex algorithm
Rise time	32.5329	48.1976
Settling Time	285.3175	105.4848
Settling Min	0.8626	0.9176
Settling Max	1.3894	1.0146
Overshoot	39.2726	1.4618
Undershoot	0	0
Peak	1.3894	1.0146
Peaktime	83.1663	130
ITAE	4691	2126.1

9 Conclusion

This paper has established that Nelder- Mead based tuning technique for temperature control of superheated steam temperature system. Using the dynamical model of superheater, we presented the FOPTD model identification using Frequency response method and transfer function method. Based on the FOPTD model derived using frequency response function approach ,it was shown that PI and PID controllers tuned using Nelder- Mead method for superheated steam temperature control has least value of ITAE. Compared with other tuning techniques, the controllers tuned using this technique for superheated steam temperature control system has obtained good setpoint tracking with very less overshoot.

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