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AUTOMATIC ADJUSTMENT OF FEEDFORWARD SIGNAL IN BOILER CONTROLLERS OF THERMAL POWER PLANTS

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Abstracts This paper proposes an auto-tuning method of feedforward signal in boiler control of thermal power plants by using the neural network. The neural network produces an optimal feedforward signal by tuning the weights of the network. The weights are adapted effectively by using the teaching signal of PI control output. The proposed method was evaluated based on a detailed simulator which expressed non-linear characteristics of the 600MW actual thermal power plant at load changing operations, showed effectiveness in the learning of the weights of the neural network, and gave an accurate control performance in the temperature control of the system. Through the evaluation, the proposed method was proved to be effectively applicable to the actual thermal plants as the automatic adjustment tool.

Keywords Thermal power plant, Once-through boiler, Feedforward signal, Automatic adjustment, Neural network

1. INTRODUCTION

Load changing operation is required in the operation of thermal power plants for the large difference of power demand in day and night, mainly due to the cooperative use of nuclear power generation for a base load. Improvement of the load changing rate is the key point in the load changing operation for the thermal power plants with large capacities and large time constants. Generally, controllers of thermal power plants are operated by use of PI controllers with additional feedforward signal in order to improve the control performance at load changing operation. As adjustment of these controllers (especially feedforward signal) are very important but difficult, it is generally done by skilled workers in power stations. Automation of the adjustment is desirable for the reduction of the labor of skilled workers. There are many researches about the power system control[1]-[4] and feedforward signal for disturbance rejection[5]. However, these method are scarcely applicable to actual plants due to their complex algorithms and so on. We had proposed an auto-tuning method of feedforward signal in boiler control of thermal power plants by use of neural network(NN)[6]. The proposed method had been evaluated based on a simple simulator.

In this paper, we developed the proposed method for applying actual power plants. The neural network produced an optimal feedforward signal by tuning the initial weights of the network. By using the relationship between weights(and structure) of the NN and its output, we were able to construct the NN with a simple structure, and produced feedforward signal for any load changing patterns. The proposed method was evaluated in this study based on a detailed simulator which adequately expressed characteristics of actual thermal power plants.

2. INITIAL ADJUSTMENT OF THE CONTROLLER

2.1 Structure of Controllers of Thermal Power Plants

A typical thermal power plant and its controllers are illustrated in **Fig. 1**. The right hand side of the figure illustrates the power plant, and the left hand side illustrates the controller part. The plant consists of a boiler which produces steam, turbine and generator that generate electrical energy from steam and condenser that plays the role of condensating steam. Electric power(MW) of once-through boiler is controlled under the condition that the steam pressure and temperature are kept constant by main steam control valve, since MW mainly depends on pressure, temperature and flow of the steam. A feed pump is employed to control the water flow, and the fuel flow(U) is controlled by fuel control valve. Electric power MW, main steam pressure(MSP) and main steam temperature(MST) are the manipulated variables of thermal power plants. Generally thermal power plant is a multi input-output system and the responses of MSP and MST are greatly affected by water flow(U_{MWD}) and fuel flow(U), respectively. Since the response of MST is slower than that of MSP, control of fuel flow(U) is the most important in the boiler control.

Structure of the controller is based on boiler-turbine coordinated control method. This method first decides whether the main steam flow(MSF) is suitable for MW demand(MWD) and then decides whether the water flow(U_{MWD}) is suitable for MSF . The output of PI Pressure controller is appended to water flow control for the compensation of MSP error.

Fuel flow(U) is composed of three elements as

$$U = U_{MWD} + U_p + U_{NN} \qquad (1)$$

where U_{MWD} is suitable for MSF, U_p the PI temperature

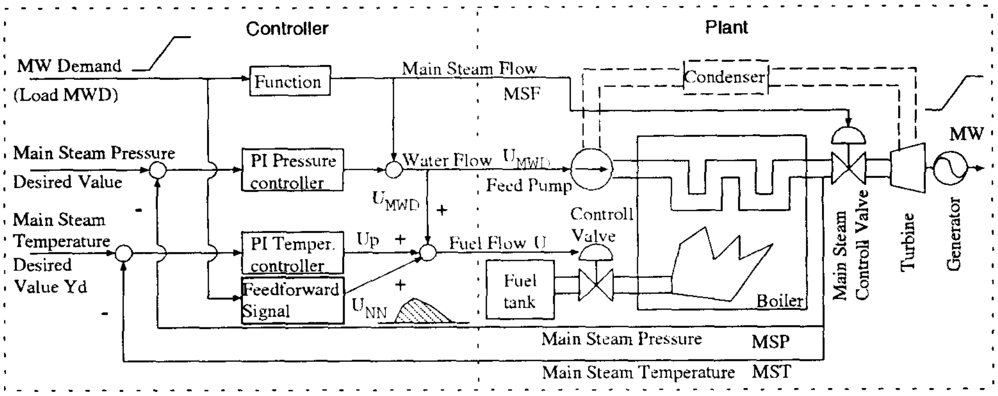

Fig. 1. Construction of a thermal power plant.

controller output, and U_{NN} the feedforward signal output. Decision of U_{NN} is the most important in fuel flow control, because it works to restrain variation of MST at load changing operation.

2.2 Problem of Initial Adjustment

The shape of the feedforward signal U_{NN} corresponding to load changing pattern(MWD) is illustrated in the shaded portion in Fig.1. Since the relationships between U_{NN} and MWD are non-linear, adjustment of the feedforward signal U_{NN} for each of the load changing pattern has been done by skilled workers and laborious for them.

Width (Zone)% \ Rate %/min		r_1	r_2	r_3	...	r_{N-1}	r_N
Up		Domain 1		Domain 2		Domain N-1	
	d_1	M^1	M^4	M^1	M^4	M^1	M^4
	d_2	M^2	M^5	M^2	M^5 ...	M^2	M^5
	d_3	M^3	M^6	M^3	M^6	M^3	M^6
Down		Domain N		Domain N+1		Dom. 2(N+1)	
	d_1	M^1	M^4	M^1	M^4	M^1	M^4
	d_2	M^2	M^5	M^2	M^5 ...	M^2	M^5
	d_3	M^3	M^6	M^3	M^6	M^3	M^6

Fig. 2. Typical load changing patterns and linear division of domain.

3. AUTOMATIC ADJUSTMENT BY USE OF NEURAL NETWORK

3.1 Orientation of the Solution for Problem of Initial Adjustment

Objective of this study is an automatic adjustment of the feedforward signal for the fuel control without a skilled worker. The adjustment of the feedforward signal corresponding to typical load changing patterns is implemented by use of neural network(NN). Feedforward signal corresponding to arbitrary load changing pattern is calculated by use of linear interpolation of the feedforward signals corresponding to typical load changing patterns. Paragraph 3.2 shows the selection of typical load changing patterns for the preparation of automatic adjustment, 3.3 the construction and learning algorithm of the NN for automatic adjustment of feedforward signal for typical load changing patterns. Paragraph 3.4 shows transformation of the feedforward signal for arbitrary load changing patterns.

3.2 Preparation of Automatic Adjustment

Typical load changing patterns(6N patterns) of initial adjustment are illustrated in **Fig. 2**. These patterns are expressed as a combination of parameters for load changing width(d_1 , d_2 , d_3) up and down and load changing rate(r_1 , r_2 , ... , r_N), where d_1 , d_2 and d_3 are expressed from minimum load to maximum load, from minimum load to middle load(m_m =(minimum load + maximum load)/2) and from middle load to maximum load at normal operation conditions, respectively. Symbols r_1 and r_N are minimum and maximum load changing rates at normal operation conditions, and r_2,...,r_{N-1} are intermediate load changing rates, respectively. The designer must decide the number(N) and the value of load changing rate, before starting the adjustment.

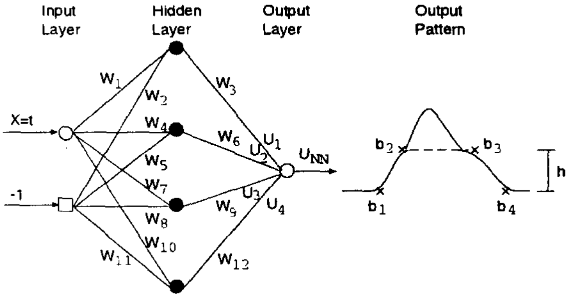

Fig. 3. Structure and output pattern of neural network.

3.3 Adjustment of Typical Load Changing Patterns

3.3.1 NN Structure and Value of Link Weights for Feedforward Signal. The structure of NN for the fuel feedforward signal of once-through boiler is described in this section. Three layered NN(hidden layer has four units) is adopted as illustrated in **Fig. 3**. The shape of the feedforward signal is approximately expressed as a combination of two trapezoids(reference shaded portion of Fig.1). The feedforward signal is realized by the output U_{NN} (of output layer) of NN. A trapezoid is approximately expressed by two units of hidden layer(ex. $U_1 + U_2$, $U_3 + U_4$). Open circle(○), open square(□) and black circle(●) in **Fig. 3** express linear unit $f(x) = x$, bias unit $f(-1) = -1$ and non-linear unit $f(x) = 1/(1 + exp(-x))$, respectively. Notation Wi expresses link weights, and inputs of input layer

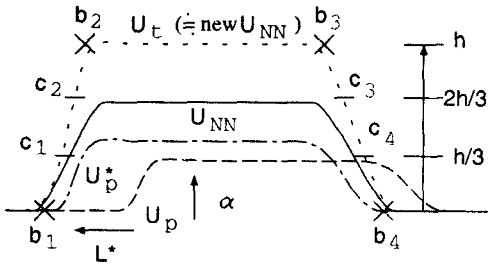

Fig. 4. Desired output pattern of feedforward

of NN are $X = t$ (time, value of the axis of abscissas) and bias(−1). The output of output layer, the feedforward signal(value of the axis of ordinates), is expressed as

$$
\begin{aligned}
U_{NN} &= (U_1 + U_2) + (U_3 + U_4) \qquad (2)\\
U_1 &= W_3/(1 + exp(-W_1 X + W_2))\\
U_2 &= W_6/(1 + exp(-W_4 X + W_5))\\
U_3 &= W_9/(1 + exp(-W_7 X + W_8))\\
U_4 &= W_{12}/(1 + exp(-W_{10} X + W_{11}))
\end{aligned}
$$

where $W_1, W_7 = 4/(b_2 - b_1)$, $W_2, W_8 = 2(b_1 + b_2)/(b_2 - b_1)$, $W_3, W_9 = h$, $W_4, W_{10} = 4/(b_4 - b_3)$, $W_5, W_{11} = 2(b_3 + b_4)/(b_4 - b_3)$, $W_6, W_{12} = -h$. Definition of trapezoid parameters(b_1 , b_2 , b_3 , b_4 , h) are illustrated in **Fig. 3**. The parameters b_1 , b_2 , b_3 and b_4 express the value of the axis of abscissas of four vertexes(×) of the trapezoid respectively, and h expresses height of the trapezoid. The upper trapezoid in Fig.3 is also determined as the same way as described up to now. Thereafter, the feedforward signal which can be approximated by use trapezoid will be explained as for simple explanation.

3.3.2 Learning Algorithm of Link Weights. Learning of NN is done by using the information of control results. The teaching signal of NN is made by PI temperature controller output pattern, and the link weights of NN are adjusted by this teaching signal. Creation of teaching signal U_t is illustrated in **Fig. 4**. Teaching signal U_t is created from feedforward signal U_{NN} and compensated PI output U_p^* is expressed as

$$
\begin{aligned}
U_t &= U_{NN} + U_p^* \qquad (3)\\
U_p^* &= \alpha\ exp(+L^* s) U_p
\end{aligned}
$$

where $exp(+L^*s)$ is compensation for the time delay of the system, and α is learning coefficient. Adjustment of link weight of NN is as follows (instead of back propagation method for shortening of adjustment time); $b_1 = 2c_1 - c_2$,$b_2 = -c_1 + 2c_2$,$b_3 = 2c_3 - c_4$,$b_4 = -c_3 + 2c_4$. Maximum value of U_t is h, and c_1 , c_2 , c_3 and c_4 express the values of the axis of abscissas of U_t ($h/3$ or $2h/3$) in **Fig. 4**.

3.4 Transformation for Arbitrary Load Changing Patterns

Feedforward signal U_{NN}^o corresponding to arbitrary load changing pattern M^o is produced from the feedforward signals for the typical load changing patterns $M^1 - M^6$ in Fig.2. A domain in Fig.2 characterizes an arbitrary load changing rate r^o . If r^o exists between r_1 and r_2, either domain 1(up) or domain N(down) is selected.

The transformation for any load changing patterns is characterized by a linear interpolation, and illustrated conceptually in **Fig. 5**. Features of any load changing patterns

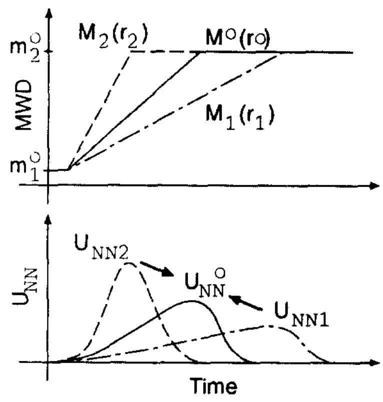

Fig. 5. Transformation for arbitrary load changing patterns by linear interpolation.

are expressed by load changing rate(r^o), value of the starting point of load changing(m_1^o) and value of end point of load changing(m_2^o). The Fig.5 illustrates the case in which the current load changing pattern M^o is different only from load changing rate r^o (load changing width and load changing zone are same) corresponding to typical load changing patterns M_1 (rate r_1) and M_2 (rate r_2). Feedforward signal U_{NN}^o for the current load changing pattern M^o is produced by the linear combination of the feedforward signal U_{NN1} and U_{NN2} for M_1 and M_2.

The linear interpolation for any cases of different load changing rate, load changing width and load changing zone is expressed by the following equation as

$$
\begin{pmatrix} b_1^o \\ b_2^o \\ b_3^o \\ b_4^o \\ h^o \end{pmatrix} = \sum_{m=1}^{6} k_1^m \left(k_2^m \begin{pmatrix} b_1^m \\ b_2^m \\ b_3^m \\ b_4^m \\ 0 \end{pmatrix} + k_3^m \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ h^m \end{pmatrix} \right) \qquad (4)
$$

where (b_1^o , b_2^o , b_3^o , b_4^o , h^o) express trapezoid parameters for current load changing pattern, (b_1^m , b_2^m , b_3^m , b_4^m , h^m) trapezoid parameters for typical load changing patterns. Superscript m corresponds to the load changing patterns M in Fig.2. The coefficients in eq.(4) are calculated as follows: $k_{11} = (r)(d)$, $k_{12} = (r)(1-d)(z)$, $k_{13} = (r)(1-d)(1-z)$, $k_{14} = (1-r)(d)$, $k_{15} = (1-r)(1-d)(z)$, $k_{16} = (1-r)(1-d)(1-z)$ where $r = (r_L - r^o)/(r_L - r_S)$, r_L is the largest rate, and r_S the smallest rate respectively in respective domain. Other variables are defined as follows: if $d^o \geq d_1/2$ then $d = 2d^o/d_1 - 1$ else $d = 0$, $d^o = |m_1^o - m_2^o|$, $z = |m_1^o - m_m|/d^o$, $k_{21} = (d^o/d_1)(r_S/r^o)$, $k_{22}, k_{23} = (2d^o/d_1)(r_S/r^o)$, $k_{24} = (d^o/d_1)(r_L/r^o)$, $k_{25}, k_{26} = (2d^o/d_1)(r_L/r^o)$, $k_{31}, k_{32}, k_{33} = (r^o/r_S)$, $k_{34}, k_{35}, k_{36} = (r^o/r_L)$.

4. VERIFICATION OF PROPOSED METHOD

The effectiveness of the proposed method was evaluated based on a detailed simulator.

4.1 Detailed Simulator

Detailed simulator for 600MW actual thermal power plant under the load changing operations was composed of the numerical model for a once-through boiler, turbine, generator, control valve and feed pump parts. The numer-

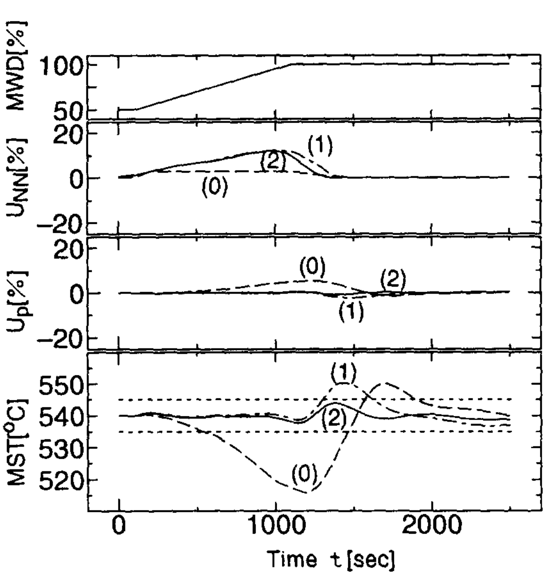

Fig. 6. Control and adjustment result of typical load changing pattern.

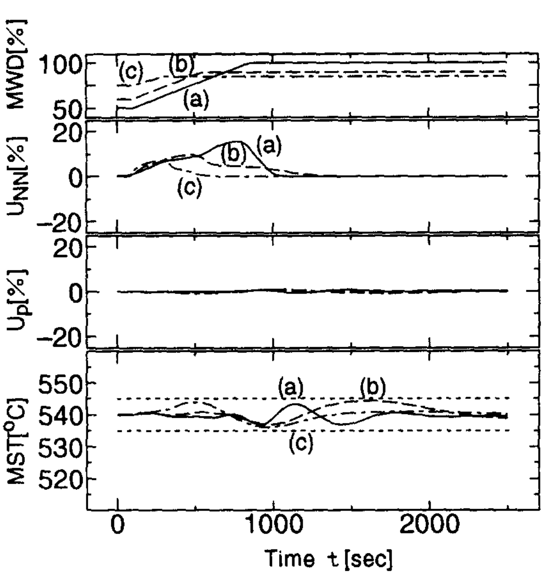

Fig. 7. Control result of optional load changing patterns.

ical model consisted of several thousands of variables and showed the faithful properties to the actual plant.

4.2 Adjustment of Typical Load Changing Patterns

Fig. 6 illustrates control and adjustment results for a typical load changing pattern by use of the proposed method. The first graph of Fig.6 illustrates the behavior of MWD (load changing: 50-100%,3%/min) and the second graph illustrates the behavior of feedforward signal U_{NN}, The behavior of PI temperature controller output U_p is given in the third graph, and the last graph shows the behavior of main steam temperature MST with 540 ^oC desired value and $\pm$ 5 ^oC permissible control performance.

$U_{NN}(0)$ shows an initial form of feedforward signal for MWD. $MST(0)$ shows the control result by use of $U_{NN}(0)$ and $U_p(0)$. The $MST(0)$ deviated from the desired value at load changing interval, then after $MST(0)$ approached to desired value with an overshoot property. Since the feedforward signal $U_{NN}(0)$ was not approximate, the new feedforward signal $U_{NN}(1)$ was produced from $U_{NN}(0)$ and $U_p(0)$ by use of the proposed method(eq.(2),(3)). The deviation of $MST(1)$ became smaller than that of $MST(0)$ and then $MST(2)$ satisfied demand of control performance at all time. Automatic adjustment of feedforward signal corresponding to this MWD was completed. Automatic adjustment of feedforward signal for other load changing patterns was also successful.

4.3 Transformation for Any Load Changing Patterns

Fig. 7 illustrates control results of a load changing pattern which is not included in the typical load changing pattern by the proposed method. The way of interpretation of Fig.7 is the same as Fig.6. The values of the simulation conditions are as follows: (a)50-100%,4%/min; (b)60-90%,4%/min; (c)75-85%,3%/min.

Feedforward signals $U_{NN}(a)$, (b) and (c) for respective $MWD(a)$, (b) and (c) are produced from the linear combination of the feedforward signals for typical load changing patterns by use of the transformation (eq.(4)). $MST(a)$, (b) and (c) show the control results by use of U_{NN} and U_p (a), (b) and (c), respectively and always included in the acceptable range of dotted lines in Fig.7. The effectiveness of transformation of feedforward signal corresponding to various optional load changing patterns is confirmed.

5. CONCLUSION

The proposed method showed its effectiveness in automatic adjustment (and transformation) of feedforward signal and gave an accurate control performance in the temperature control of thermal power plant. Through this evaluation, the proposed method was proved to be successfully applicable to actual thermal power plants.

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