Optimal Adaptive Fuzzy Controller Design Using Memetic Algorithm to Control Boiler System

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ABSTRACT

To achieve proper functioning of a boiler, dynamic variables such as drum pressure, steam pressure, and water level of drum should be controlled. As the boiler model may be associated with uncertainties such as parametric uncertainties and unmodeled dynamics of boiler system, an optimal adaptive fuzzy controller is designed and implemented. To achieve the desired optimal controller, a nested Memetic Algorithm based on particle swarm optimization algorithm is proposed. In the proposed algorithm, the particle swarm optimization algorithm has combined with a nested local search, which runs at each step of the algorithm. The local search part is also included two sub-sectors: the part of local search on the chosen particles, and the part of local search on the chosen particles among the pre-selected particles. Therefore, at each stage the best particles are selected and so more accurate and better updates are achieved. Simulation results show the superb performance of the designed optimal adaptive fuzzy controller to control boiler system in spite of uncertainties.

INTRODUCTION

Boiler is a device used to produce steam and is one of the major components of power systems. Power system performance is affected by pressure, temperature, and flow rate of steam. Although steam production varies during the operation of power system, but boiler output variables such as vapor pressure, temperature, and water level in reservoir should remain at their optimal values. So it is expected from a boiler system to set water level of reservoir and to provide desired steam pressure of it, and output power. However, physical limitations of stimuli such as limitation in input signal domain and also saturation phenomenon in fuel control valves and steam water, when keying rate rises [1,2], should also be considered in generating of control signals. There are two different configurations for production. The first compound in which a single boiler-turbine exists, steam is produce by a boiler and it is fed by a turbine and in the second compound, steam is produce by several boilers and the steam is directed to a collector and then is distributed among several turbines. Industrial factories usually use this type of composition. Since boiler has fast response to charge changes in power of network, so the composition of the second type is preferred [3]. Boiler is a complex nonlinear model and several models have been proposed for boiler system [4-6]. Also various methods are presented for designing of controllers for boiler system, which can mentioned to feedback linearization method [1,2], adaptive control [7], linear quadratic Gaussian (LQG) [8] and also intelligent control methods [9-12]. The problem that should be investigated in these studies is that parametric uncertainties associated with dynamical model have not been considered. In addition to achieving a proper performance in a boiler, it is necessary for controller to have capability to deal with these uncertainties. A control system is robust, if does not sensitive to difference between performed model in designing of controller and an actual model. These differences can be interpreted as uncertainties. This lack of sensitivity there is also implicitly in structure and method of obtaining adaptive law, in the case of adaptive fuzzy controller. A linear time invariant (LTI) model of boiler system is considered in this study. Input variables are mass flow rate of entering water and fuel mass flow rate, while output variables are water level of reservoir, pressure and temperature of reservoir. In this study, uncertainties are modeled as an accumulative term.
Optimization is a process that is used to improve responses. Optimization is talking about finding the best answer to a problem. The term “best” implies that there are more than one answer to the considered question, which of course all the answers have not same values. Optimization consists of two maximum and minimum elements. At a time we say an element is minimum (or maximum) that the values obtained for it, are satisfied for a series of conditions. Optimization process is a repetitious process which continues until the termination conditions is established. The termination conditions can be the number of loop repetition or achieving to the desired response [13]. In this article, a new memetic optimization algorithm with a part of nested local search based on particle swarm optimization algorithm will introduced. In the proposed algorithm, one- fifth of particles with the best responses are chosen as the selected particles using a selection strategy, and the update operation is applied among them. Then half of the chosen particles are re-selected and the update operation is performed among them. The performance of the two steps of update operation leads to increment of convergence and improvement of the algorithm response. The results of simulation and studies have shown well and favorable performance of the proposed algorithm.

In the following of the article, a linear time invariant (LTI) model of boiler system is studied. Then an adaptive fuzzy controller design method is proposed. The proposed memetic algorithm is introduced in the next section and finally the obtained results from investigation and designing of optimal controller to control the boiler system are presented.

1. Linear time invariant (LTI) model of boiler:

In the model examined in this study, water flows in pipes, and heat applies around the pipes. Function of this kind of boiler is shown in Figure (1) [14].

![Boiler Operation Procedure](image)

**Fig. 1:** The boiler operation procedure.

Input variables $u_1$, $u_2$ and $u_3$ are respectively as follows: mass flow rate of input water, mass flow rate of fuel and mass flow rate of spray. Output variables $y_1$, $y_2$ and $y_3$ are also respectively as follows: reservoir water level, reservoir pressure and steam temperature. A boiler actual model is used to control the output variables. This model is proposed by [15]. The model uses a complex collector system for distribution of steam, which consists of four collectors in pressures of 0.372, 1.068, 4.24 and 6.036. Collector receives steam flows from three boilers (UB), (CO) and (OTSG’s). Then the steam is supplied through the collector system with several steam turbines to produce electricity. If the boiler system is functioning properly, despite changing in the level of consumer demand steam, the steam pressure must remain constant at the level of 6.036. Also, to prevent excessive heating of the reservoir components and to prevent from overflowing in steam flow lines, the amount of water inside the reservoir should remain constant. On the other hand, steam temperature should be remained at optimal levels to be prevented from entering the mixed steam with water inside the turbines. By using of SYNSIM of input-output data relate to production boiler system and by using of system identification tools in MATLAB, a linear invariant time model for boiler is obtained as follows.

$$
\begin{bmatrix}
    y_1 \\
    y_2 \\
    y_3
\end{bmatrix} =
\begin{bmatrix}
    0.9416 & 0.0062 & 0.0001 \\
    -0.0395 & 10^{-9} & 0 \\
    -0.0091 & 0.0001 & 0
\end{bmatrix}
\begin{bmatrix}
    u_1 \\
    u_2 \\
    u_3
\end{bmatrix}
$$

With regard to the items listed in the study of [14], a third order model fits the input-output data with reasonable accuracy. After investigation of zeros and dominant poles in the transfer functions (1) and also according to the obtained results by [15], the level of reservoir water, $y_1$, mainly is influenced by the mass flow rate of input water, $u_1$. Similarly, the reservoir pressure, $y_2$, and the steam temperature, $y_3$, are mainly influenced by the fuel mass flow rate, $u_2$. Also it can show that the effect of mass flow rate of attemperator spray, $u_3$, is negligible in the output variables [15]. Therefore, the transfer function between $y_1$ and $u_1$ is approximated by the
following equation. For responding to stairs and slop inputs, this equation operates with reasonable accuracy like actual model.

\[ G_1(z) = \frac{Y(z)}{U(z)} = \frac{k_a}{s^2 + a_1 s + b_1} \]  

Similarly, transfer functions related to other inputs-outputs are obtained as follows:

\[ G_2(z) = \frac{Y(z)}{U(z)} = \frac{k_b}{s^2 + a_2 s + b_2} \]  

\[ G_3(z) = \frac{Y(z)}{U(z)} = \frac{k_c}{s^2 + a_3 s + b_3} \]  

Table (1) shows the values of the used parameters in the above equations.

<table>
<thead>
<tr>
<th></th>
<th>( G_1 )</th>
<th>( G_2 )</th>
<th>( G_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_1 )</td>
<td>( 4.7 \times 10^{-2} )</td>
<td>( b_1 )</td>
<td>( 4.5 \times 10^{-2} )</td>
</tr>
<tr>
<td>( a_2 )</td>
<td>( 7 \times 10^{-4} )</td>
<td>( b_2 )</td>
<td>( 6.5 \times 10^{-4} )</td>
</tr>
<tr>
<td>( a_3 )</td>
<td>( 3.4 \times 10^{-6} )</td>
<td>( b_3 )</td>
<td>( 3 \times 10^{-6} )</td>
</tr>
<tr>
<td>( k_a )</td>
<td>( 1.2 \times 10^{-4} )</td>
<td>( k_b )</td>
<td>( 2.5 \times 10^{-8} )</td>
</tr>
</tbody>
</table>

**Adaptive fuzzy control by direct method:**

To control the system due to the uncertainties and unknown terms of system, fuzzy control is used that itself is a robust controller. There are different parameters in fuzzy controller to adjust the controller. Among adjustable parameters can be mentioned to membership functions, scaling coefficient, interface algorithms, fuzzification and defuzzing. In this study, the adaptive fuzzy controller method which is not dependent on initial value of parameters is used to adjust parameters. Given the following system

\[ x^{(n)} = f(x) + bu(x) \]  

Where \( f(x) \) and \( b \) are unknown and \( b \) is constant. In direct adaptive fuzzy control law is proposed as follows.

\[ u(X) = \hat{Y}^T \xi(X) \]  

The \( \hat{Y} \) vector is containing of unknown parameters related to centers of output fuzzy groups in the fuzzy system, \( u = \hat{Y} \xi(X) \). In fact \( u \) control is a fuzzy system. By applying of the control law, closed-loop system is obtained as follows:

\[ x^{(n)} = f(x) + b\hat{Y}^T \xi(X) \]  

Now it is assumed that the vector is such that

\[ X_d - X = \varepsilon \]  

Where \( \varepsilon = [e_1, ..., e_n]^T \) is the error vector and \( e_i = x_i - x_i^{(i-1)} \). \( K = [k_1, ..., k_n] \) are also the constant parameters vector in the controller designing. All \( K \) components must be positive in order that dynamic error to be stable in equation (8) after adjustment of \( \hat{Y} \). Due to the general approximation rule of fuzzy systems, there is such \( \hat{Y} \). Also state vector as an input of the control system is as follows:

\[ X = (x_1, x_2, ..., x_n) = x^{(n-1)} \]  

By difference of equations (7) and (8), the following equation is obtained.

\[ X_d^{(n)} - x^{(n)} + KE = b(\hat{Y}^T - \hat{Y}) \xi(X) \]  

The \( \hat{Y} \) vector is in fact the approximation of \( Y \), that the aim is to obtain an relation for its adjustment. If \( \hat{Y} \) is properly adjusted, the right side of equation (10) becomes zero and the dynamic of error becomes stable and so tracking is realized. To adjust \( \hat{Y} \), a Lyapunov function is determined and by Lyapunov function stability method, the adaptive law for adjustment of \( \hat{Y} \) is obtained. The selected lyapunov function which involving dynamics error, are taken into account as follows:

\[ V = \frac{1}{\gamma} \hat{Y}^T P \dot{E} + \frac{1}{\gamma} (\hat{Y}^T - \hat{Y})^T (\hat{Y} - \hat{Y}) ; \gamma > 0 \]  

Where \( \gamma > \dot{\varepsilon} \) is a constant number and \( P \) is a symmetric positive definite matrix. To maintain stability, \( \dot{\varepsilon} \) should adjust so that \( \dot{\varepsilon} < 0 \). In this case, and according to the Lyapunov function stability \( \varepsilon \rightarrow 0 \) will be established. By derivative of equation (11) the following equation is obtained.

\[ \dot{V} = \frac{1}{\gamma} \hat{Y}^T P \dot{E} + \frac{1}{2} \hat{Y}^T \dot{P} \dot{E} - \frac{1}{2} \hat{Y}^T (\dot{Y} - \dot{\hat{Y}}) - \frac{1}{2\gamma} (\hat{Y}^T - \hat{Y})^T (\hat{Y} - \hat{Y}) \]  

\[ x^{(n)} - x^{(n)} + k_n (x^{(n-1)} - x^{(n-1)}) + \cdots + k_1 (x_d - x) = b(\hat{Y}^T - \hat{Y}) \xi(X) \]  

(12)
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And state-space model for error is
\[
\begin{align*}
\{ & 
\begin{bmatrix}
e_1 \\
e_2 \\
\vdots \\
e_{n-1} \\
e_n
\end{bmatrix} = \begin{bmatrix}
0 \\
0 \\
\vdots \\
0 \\
-\kappa
\end{bmatrix} \xi(x) + 

\begin{bmatrix}
b \\
\vdots \\
\vdots \\
\vdots \\
b
\end{bmatrix} \left( \begin{bmatrix}
Y_f \\
\vdots \\
\vdots \\
\vdots \\
Y_f
\end{bmatrix} - \begin{bmatrix}
\hat{Y}_f \\
\vdots \\
\vdots \\
\vdots \\
\hat{Y}_f
\end{bmatrix} \right) + 

\begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\vdots \\
\sigma_n
\end{bmatrix} \\
\end{align*}
\]

The matrix form of the equation (13) is as follows.
\[
\begin{align*}
\dot{e} &= AE + BU; \quad B = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}; \quad U = (Y_f - \hat{Y}_f) \xi(x) \\
A &= \begin{bmatrix} 0 & 1 & \cdots & 0 \\ 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ -k_1 & -k_2 & \cdots & -k_n \end{bmatrix} ; \quad B = \begin{bmatrix} 0 \\ 0 \end{bmatrix}
\end{align*}
\]

By insertion of equation (14) in (13), we obtain the following equation
\[
\begin{align*}
\dot{V} &= \frac{1}{2} (B^T A T + U^T B^T) PE + \frac{1}{2} E^T P (A E + B U) - \frac{1}{2} \frac{1}{\gamma} (Y_f - \hat{Y}_f) \dot{Y}_f \\
&= \frac{1}{2} E^T (A^T P + P A) E + E^T P B U - \frac{1}{2} \frac{1}{\gamma} (Y_f - \hat{Y}_f) \dot{Y}_f
\end{align*}
\]

Assume that the positive definite and symmetric matrix \( P \) is such that \( A^T P + P A = \Omega \) for arbitrary positive definite and symmetric matrix \( Q \) is established. Thus, by insertion in (15), the equation (16) is obtained:
\[
\begin{align*}
\dot{V} &= -\frac{1}{2} E^T Q E + E^T P B (Y_f - \hat{Y}_f) \dot{Y}_f
\end{align*}
\]

In order that \( \dot{V} \leq 0 \), the equation \( (Y_f - \hat{Y}_f) (E^T P B \xi(x) - \frac{1}{\gamma} \dot{Y}_f) = 0 \) must be established. Thus the matching equation for \( \dot{Y}_f \) is as follows.
\[
\dot{Y}_f = \gamma E^T P B \xi(x) \to \dot{Y}_f = \int_0^t \gamma E^T P B \xi(x) dt + \hat{Y}_f(0)
\]

The proposed memetic algorithm:

In recent years a new algorithm has been developed for solving complex optimization problems, which is named memetic algorithm. Compared to the other evolutionary optimization algorithms, this algorithm has better and more accurate responding [12]. Complicated problems are those problems that global search algorithms do not perform well for findings of optimal responses. The memetic algorithms are those kinds of evolutionary algorithms that have been combined with one part of local search, to improve responding. The memetic algorithms have very good performance to solve many optimization problems such as, combinatorial optimization [13], optimization of variable functions and multipurpose optimization [14]. In various studies, methods for combination of evolutionary algorithms with local search have been allocated different names to themselves, such as the hybrid genetic algorithm, baldwinian evolutionary algorithm and Lamarckian evolutionary algorithm. Moscato used the term memetic algorithm for covering all algorithms based on the evolutionary search that are combined with a local search algorithm. In this article, a new memetic optimization algorithm is proposed with a part of nested local search optimization based on the particle swarm optimization algorithm. In this algorithm, first, one-fifth of particles with the best responses are chosen as the selected particles, and then the updating function is performed on them. After that half of the selected particles are reselected and updating function is performed on them. Therefore, at each step of the implementation of the local search algorithm, the rate and position of the selected particles will be updated with the equations (18) and (19). Applying two steps of updating cause increases of convergence and improve of algorithm responses.

\[
x_{i,j}(t+1) = x_{i,j}(t) + v_{i,j}(t+1)
\]

\[
v_{i,j}(t+1) = v_{i,j}(t) + c_1 r_{i,j} [y_{i,j}(t) - x_{i,j}(t)] + c_2 r_{2,j} [\dot{y}_{i,j}(t) - x_{i,j}(t)]
\]

In this article, 50 particles are used, that in the each step, 10 particles are selected as the first chosen particles (with a better cost function) for applying the local search. Then 5 particles (with better cost function) were selected among them as the second chosen particles and then the update operation is performed on them. Pseudo-code of the proposed memetic algorithm will be as follows:

1. Identifying and initialization of position and velocity of particles.
2. Obtaining the cost function for each particle and identifying the best particles (with the smallest value of the cost function).
3. Selection of the first chosen particles and applying a local search among them (updating velocity and hence their position by using the equations (18) and (19)).
4. Selection of the second chosen particles and applying a local search on them (updating velocity and hence their position by using the equations (18) and (19)).
5. As long as the stopping conditions have not been established:
6. Investigation of the cost functions of the particles and selection of the best particle (with the best cost function).
7. Updating the velocity and the position of all particles and obtaining their cost function.
8. Selection of the first chosen particles and applying a local search on them (updating velocity and hence their position by using the equations (18) and (19)).
9. Selection of the second chosen particles and applying a local search on them (updating velocity and hence their position by using the equations (18) and (19)).
10. Investigation of cost function of the particles and selection of the best particles (with the best cost function).
11. End of the algorithm.

Simulation results:
The following control law for all three transfer function is considered separately in the boiler system.

\[ u = V^T \xi(X) \] (20)

It is necessary that the equations (2, 3 and 4) to be written in time domain in order that the state variables to be available for \( \xi(x) \) definition. Since the transfer function is calculated zero at the initial conditions, thus:

\[ y_3^{(3)}(t) + a_1 y_1(t) + a_2 y_2(t) + a_3 y_3(t) = k_4 u_4(t) \] (21)
\[ y_3^{(3)}(t) + b_1 y_1(t) + b_2 y_2(t) + b_3 y_3(t) = k_5 u_5(t) \] (22)
\[ y_3^{(3)}(t) + c_1 y_1(t) + c_2 y_2(t) + c_3 y_3(t) = k_6 u_6(t) \] (23)

For the control law, a fuzzy system is selected with single fuzzifier, mean defuzzifier of centers and implications of Mamdani multiplication. To determine fuzzy system, input and output variables should be defined at first. About the equation (19) subsystem, \( u_i \) is as output of fuzzy system and its inputs are \( y_1, y_2, \) and \( y_3 \). Input membership functions are considered as follows for each input.

\[ \mu_{A_1}(x_i) = \frac{1}{1 + e^{-z_i(x_i - \bar{x}_i)^2}} \] (24)
\[ \mu_{A_2}(x_i) = e^{-z_i(x_i - \bar{x}_i)} \] (25)
\[ \mu_{A_3}(x_i) = \frac{1}{1 + e^{-z_i(x_i - \bar{x}_i)^2}} \] (26)

In the above equations, \( x_i \) is \( i^{th} \) of the input fuzzy system that can be \( y_1, y_2, \) and/or \( y_3 \). And \( i = 1, 2, \) and 3. The fuzzy system equation is as following.

\[ f(x) = \sum_{i=1}^{m} \prod_{l=1}^{n} \mu_{A_l}(x_l) \] (27)
\[ \xi_l = \sum_{i=1}^{n} \prod_{l=1}^{m} \mu_{A_l}(x_l), \] (28)

In which \( \mu_{A_l}(x_l) \) represents the membership function of the input variable, \( x_i \), in the \( l^{th} \) law and \( \xi_l \) is the center of membership function of the output in the \( i^{th} \) law. The number of laws is considered \( m=9 \). Disturbances have also been modeled as an accumulative term and subsystems equations associated with disturbances are as follows.

\[ y_3^{(3)}(t) + a_1 y_1(t) + a_2 y_2(t) + a_3 y_3(t) - rand = k_4 u_4(t) \] (29)
\[ y_3^{(3)}(t) + b_1 y_1(t) + b_2 y_2(t) + b_3 y_3(t) - rand = k_5 u_5(t) \] (30)
\[ y_3^{(3)}(t) + c_1 y_1(t) + c_2 y_2(t) + c_3 y_3(t) - rand = k_6 u_6(t) \] (31)

In which “rand” produces a random value of desired value in the range \( \pm200 \% \). The following parameters are used for simulation.

\[ \begin{bmatrix} \dot{e}_1 \\ \dot{e}_2 \\ \dot{e}_3 \end{bmatrix} = \begin{bmatrix} e_2 \\ e_3 \end{bmatrix} + K \xi(X) \]
\[ A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -k_3 & -k_2 & -k_1 \end{bmatrix} \]
\[ k_1 = 1, \quad k_2 = 1, \quad k_3 = 2 \]
\[ Q = \begin{bmatrix} 4 & 3 & 0.5 \\ 3.5 & 3.5 & 2 \end{bmatrix}, \quad r = 50 \]

Selection of \( k_i \) is important and impressive in determining of \( P \). As it can be seen \( P \) is obtained positive definite symmetric.

As can be seen in Figure 2, despite the large amplitude of disturbances, which are twice of the desired value, the adaptive fuzzy control has done well the adjustment operations and reservoir water level is adjusted on the desired value. The process of reservoir water level, \( \xi \), is adjusted in Figure 3.
Fig. 2: Reservoir water level adjustment on desired value $y_{1d} = 1$.

Fig. 3: Adjustment of vector $\tilde{y}_f$ components.

As can be seen in the above Figure, the $\tilde{y}_f$ is adjusted with relatively good speed and each of its component is converged to a constant value. Although there are three inputs in the mentioned fuzzy system, but it just covers nine laws of the space. While, at least 27 laws should be considered to completely cover the rules. However, the fuzzy system well done the adjustment of water level reservoir and also the effect of uncertainties is largely and acceptably neutralized.

Fig. 4: Adjustment of steam temperature on desired value $y_{2d} = 415^\circ C$.

Fig. 5: Adjustment of reservoir pressure on desired value $y_{3d} = 6.035 \text{ MPa}$ associated with matching process $\tilde{Y}_f$.

As can be seen in simulation results, despite the relatively high disturbances, by applying of control by direct adaptive fuzzy method, control objectives have been met, and steam temperature and reservoir pressure will also be adjusted on desired value. The objective function parameters and equation is as follows:
Figure 6 and 7 demonstrate the estimation error and the procedure of minimizing the objective function in different iterations, respectively.

By noticing figure 7 we conclude that, as the number of iterations increase, the convergence of estimation error to zero increases. Supposing the only parameter to optimize, \( \sigma \), the optimum least square estimation error obtains in \( \sigma = 3.08 \).

**Conclusions and Recommendations:**

A linear time invariant (LTI) model of boiler relates to the fourth refinery of South Pars Gas Complex, was investigated in this study. Direct adaptive fuzzy controller was used to control and adjust the level of water in reservoir, steam temperature and reservoir pressure. Simulation result showed proper performance of adaptive fuzzy controller. This process can be continued in the field of selection of the fuzzy laws numbers with the aim of performance improving of the controller and also investigations can be performed in using of evolutionary optimization algorithms to determine optimal control parameters such as \( K = [k_1, k_2, k_3]^T \) vector and positive constant, \( \gamma \).

**REFERENCES**


