Hybrid Fuzzy Controllers for Non-Minimum Phase Systems

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Abstract—The class of non-minimum phase systems modeled by transfer functions with “unstable” zeros is considered as a controlled plant in control systems. The stabilization and control of this class of systems is difficult stabilizing because of the unusual behavior in both time and frequency domains. The paper shows that fuzzy control is a successful control solution for this class of systems. With this regard, the paper proposes two hybrid fuzzy controllers of Takagi-Sugeno type that cope with the class of second-order non-minimum phase systems with a “right half plane zero”.

I. INTRODUCTION

The controlled plant (CP) taken into consideration belongs to the class of second order non-minimum phase systems (NPSs) with two negative real poles and one positive zero having the main transfer function (t.f.) in form of:

\[ H_{CP}(s) = \frac{y(s)}{u(s)} = k_{CP} \frac{1 - sT_1}{(1 + sT_2)(\alpha_3 + sT_3)} \quad (a), \]

\[ H_{CP}(s) = \frac{y(s)}{u(s)} = k_{CP} \frac{1 - sT_1}{(1 + sT_2)(\alpha_3 + sT_3)(1 + sT_4)} \quad (b). \]

For the t.f. (1) (a), an equivalent informational structure is presented in Fig. 1, having: \( u \) – the control signal, \( v \) – the disturbance input, \( y \) – the controlled output. The values of the variable positive parameters \( k_{CP}, T_1, T_2, \alpha_3, T_3, T_4 \) depend on the operating point. The variation in plant parameters can be included in \( k_{CP} \) and \( \alpha_3 \); the corresponding aspects must be treated separately regarding the application.

\[ H_{\Delta \text{output}}(s) = \frac{\Delta \alpha_3(s)}{\Delta u_s(s)} = k_{\Delta \alpha_3} \frac{1 - sT_1}{(1 + sT_2)(\alpha_3 + sT_3)}, \]

\[ H_{\Delta \text{output}}(s) = -k_{\Delta \alpha_3} \frac{1 - sT_1}{(1 + sT_2)(\alpha_3 + sT_3)}, \]

\[ H_{\Delta \text{input}}(s) = \frac{\Delta \alpha_3(s)}{\Delta m_{\text{load}}(s)} = -k_{\Delta \text{input}} \frac{1 + sT_2}{(1 + sT_2)(\alpha_3 + sT_3)}, \]

where: \( T_2 \) and \( T_3 \) are the electrical and the mechanical time constants for the DC-m, \( T_2 \) – the excitation circuit’s time constant; all parameters in (2) are easy calculable from Fig. 2, the DC-m parameters are well-known (see, for example, [6]). Using Fig. 2, detailed input-output and state space models can be easily established.

Two remarkable cases in power engineering are:

- For speed control of hydro-power-generators (SISO case); Fig. 1 is similar to the second-order “right half plane zero” system proposed as benchmark system in [7].

- For boiler control (the MIMO case), the model to be used for CS testing must take into account the coupling between the individual boiler subsystems; and the plant model contains a non-minimum type interconnecting t.f. [8]–[10].
In many cases the non-minimum phase results from a proper approximation of dead-time component in the plant structure (for example a first or a second order Padé approximation). One of the properties of this class of NPSs is that in the first part of system response, there exists a tendency of variation in an opposite direction to the direction of control signal variation. This leads to the appearance of the down-shoot that can produce incidents in CS operation. Another significant property is in the fact that the open-loop Bode phase plot is rapidly decreasing for increasing values of the frequency. These peculiar behaviors make the control of these systems a difficult but challenging problem. Therefore it can be considered as a reason for the development of advanced Takagi-Sugeno fuzzy controllers [11].

The goal of controller development, for controlling the CP from Fig. 1, is to ensure as good as possible dynamic as well as steady-state CS performance. Therefore, the paper proposes two hybrid PI-neuro-fuzzy controllers (PI-NFCs) based on the on-line adaptation of a PI-fuzzy controller (PI-FC). The numerical application presented in this paper corresponds to the well-accepted approximation [12] to the speed control of a hydro-electric turbine-generator system; the approximation can be also accepted for speed control of the DC-m driving systems (Fig. 2).

The paper is organized as follows. An overview on the standard version of Takagi-Sugeno PI-fuzzy controllers is presented in Section II. Aspects concerning adjusting the speed by weakening excitation field are discussed in Section III. Section IV treats the case of a hybrid fuzzy controller structure and development considerations. Section V analyzes two case studies of non-minimum phase plants; simulation results and performance-comparison are included to validate the control solutions. The conclusions are highlighted in Section VI.

II. STANDARD VERSIONS OF TAKAGI-SUGENO PI-FUZZY CONTROLLERS

The standard versions of Takagi-Sugeno PI-fuzzy controllers are of two types depending on the way of including the dynamics in the structure of the fuzzy controller: the PI-FC with integration on controller output (PI-FC-OI), and the PI-FC with integration on controller input (PI-FC-II). According to Fig. 3 [3], the PI-FC-OI considered here is characterized by including the dynamics in terms of differentiating the control error $e_k$ and integrating the increment of control signal $\Delta u_k$:

$$
e_k = r_k - y_k, \quad \Delta u_k = u_k - u_{k-1},$$

with $r$ – the reference input and $k$ – the index of the current sampling interval.

The strictly speaking fuzzy controller without dynamics from Fig. 3 (FC) is characterized by the following features (exemplified for a smaller number of linguistic terms): the fuzzification is performed by means of the membership functions from Fig. 4 pointing out the PI-FC tuning parameters, $\{B_s, B_u\}$; it uses the max and min operators in the inference engine assisted by the rule base presented in Table I, and employs the weighted average method for defuzzification.

![Fig. 3. PI-fuzzy controller with output integration.](image)

![Fig. 4. Membership functions of PI-fuzzy controller.](image)

<table>
<thead>
<tr>
<th>$\Delta u_k$</th>
<th>$e_k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>$\Delta u_k$</td>
</tr>
<tr>
<td>ZE</td>
<td>$\Delta u_k$</td>
</tr>
<tr>
<td>P</td>
<td>$\alpha \Delta u_k$</td>
</tr>
</tbody>
</table>

This rule base ensures a quasi-PI behavior of the PI-FC. An additional parameter $\alpha$, $\alpha \in (0, 1]$, was introduced for the sake of performance enhancement by alleviating the overshoot and down-shoot in situations when $e_k$ and $\Delta e_k$ have the same sign. Otherwise the rule base of Table 1 can be reduced to only one rule.

The development of the standard PI-FC is done in terms of the following steps:

- Determine by a classical design method the parameters $\{k_C, T_i\}$ of the conventional PI controller (to be replaced by the PI-FC) with the t.f.:

$$H_c(s) = \frac{k_c}{sT_i}(1+sT_i). \quad (4)$$

- Choose the sampling period $h$, discretize and obtain the parameters $\{K_p, K_i\}$ of the quasi-continuous digital PI controller:

$$\Delta u_k = K_p \Delta e_k + K_i e_k, \quad (5)$$

with $\Delta e_k = e_k - e_{k-1}$ – the increment of control error.

- Apply the modal equivalence principle resulting in:

$$B_{su} = (K_i/K_p)B_s, \quad (6)$$

where, in the case of Tustin’s discretization method:
After the development of the fuzzy controller, the desired nonlinear behavior can be ensured by the proper modifications of the membership functions.

The PI-FC-II considered here is characterized by including the dynamics in terms of integrating the control error \( e_k \) (\( e_k \) represents the integral of \( e_t \) in Fig. 5). The parameters of the PI-FC-II are \( \{ B_e, B_n \} \) instead of the parameters \( \{ B_e, B_{n_e} \} \) from the case of the PI-FC-OI, and its development is based on (7), similar to (5):

\[
B_{el} = \left( \frac{K_p}{K_i} \right) B_e. \tag{8}
\]

For both fuzzy controllers the parameter \( B_e \) is usually chosen by heuristic rules in accordance with the experience of the CS specialist. This is the reason why \( B_e \) appears as an input to the PI-FC-OI (Fig. 3), and the same situation is encountered for the PI-FC-II (Fig. 5).

The aim of the paper is to obtain CS performance enhancement by the development of a PI-NFC which performs the on-line adaptation of both standard PI-fuzzy controllers by tuning the parameter \( B_e \) in terms of a model reference adaptive controller (MRAC) structure.

III. SPEED CONTROL SYSTEMS BY WEAKENING EXCITATION FIELD

In order to extend the control range into the high speeds field, it is necessary to weaken the excitation flux, the angular speed can thus be increased to maximum allowed levels by switching and mechanical considerations. The control is done as shown in Fig. 6, at constant torque up to nominal speed \( \Omega_N \) and at constant power in the speeds range corresponding to the weakened flux.

Up to the nominal speed, the control is done through induction with a unidirectional converter, after which the control switches to excitation, its winding being powered by a thyristor converter. The converter can be unidirectional; in this case contactors are necessary to change the excitation polarity during the braking-reversing periods (Fig. 7).

The solution presented in Fig. 7 leads to a simpler converter on the force side but a more complicated one on the control signal side by introducing an additional dead time in the reversing process necessary for the switching of the way contactors.

IV. HYBRID FUZZY CONTROLLERS

The structures of fuzzy CSs containing the two proposed hybrid fuzzy controllers are hierarchical ones; the structure of the two hybrid PI-NFCs is shown in Fig. 8, with the adaptation block and its operating logic described briefly as follows. \( B_e \) replaces \( B_e \) in Fig. 5 in order to point out that \( B_e \) is permanently updated, not constant as in the case of the standard versions of FCs.

For the accepted NPS the following reference model (RM) having the transfer function (in continuous time) can fulfill the desired CS performance:

\[
H_{RM}(s) = \frac{1}{(1 + sT_1)(1 + sT_{imp})^2}. \tag{9}
\]

where the CS performance can be specified / imposed by a proper choice of the time constant \( T_{imp} \) (the increase of \( T_{imp} \) with respect to \( T_1 \) determines the alleviation of the downshoot).

Discretizing (9) by Tustin’s method results in the discrete equation of RM (\( y_{M,k} \) – the output of RM):

\[
y_{M,k} = d_1y_{M,k-1} - d_2y_{M,k-2} - c_0f_k + c_1f_{k-1} + c_2f_{k-2}, \tag{10}
\]

where:

\[
K_p = k_c[1 - h / (2T_i)], \quad K_i = k_c h / T_i. \tag{7}
\]
where for weight updating is used in the tuning of of the shapes (scaling) of the output membership functions. results in [13], [14], but dealing with the on-line adaptation system.

...from the input weight of the neuron, $\eta$, $\lambda \in [0,1]$ stand for the learning rate and the momentum factors, respectively, and (13) is used in order to obtain the output $B_{s,k}$ from the input $e_k$ (the activation function is absent because it is accepted to be a linear one and included in the single neuron):

$B_{s,k} = q_k e_k$.

The development of the two hybrid PI-NFCs is done in an unified way, and it is based on: expressing the partial derivative of the cost function in terms of a chain of partial derivatives, approximating for the considered class of plants (slow ones) the partial derivative with two other controllers: a PI controller (PI-C) designed in the frequency domain, and two PI-fuzzy controllers (PIFC-OI and FC-II) with a constant $\alpha_s = 1$, $T_i = 2.2$ s, $T_2 = 1.1$ s and $T_3 = 6.8$ s for testing and validating the proposed solutions of hybrid fuzzy controllers. The assessment of CS performance is done by performing a comparison with the cases of controlling the same plant with two other controllers: a PI controller (PI-C) designed in the frequency domain, and two PI-fuzzy controllers (PIFC-OI and PI-FC-II) with a constant $B_{s,g} = B_{0.5}$. The comparison is done by the analysis of CS performance defined in the unit step responses with respect to the reference input $r$ (of type illustrated in Fig. 9) and to the disturbance input $v$ (of type illustrated in Fig. 10). The main controller parameters are: $k_C = 1.1$, $T_i = 6.8$ s, $T_{imp} = 5$ s, $h = 0.05$ s.

![Fig. 9. Definition of performance indices in unit step response with respect to $r$.](image)

Table III and Table IV illustrate CS performances with respect to a step reference $w$ and to a step disturbance $v$, respectively. The presented results, synthesized in the tables, prove that:

<table>
<thead>
<tr>
<th>$g_{s,k}$</th>
<th>$g_{s,k-1}$</th>
<th>N</th>
<th>ZE</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_1^i$</td>
<td>$\rho_2^i$</td>
<td>$\rho_3^i$</td>
<td>$\rho_4^i$</td>
<td>$\rho_5^i$</td>
</tr>
<tr>
<td>$\rho_1^i =</td>
<td>\rho_{s,k-1}</td>
<td>$</td>
<td>$\rho_2^i =</td>
<td>\rho_{s,k-1} + \gamma</td>
</tr>
</tbody>
</table>

The presented rule base ensures a quasi-equivalence of the AB, with the dependence in the following conditions:

$\rho_1 = |\rho_{s,k-1}|$, $\rho_2 = |\rho_{s,k-1} + \gamma|$, $\rho_3 = |\rho_{s,k-1} - \gamma|$. (15)

The development of AB is done by the proper choice of the parameters $\{B_{s,g}, B_{s,g}\}$ according to the experience of the specialist in control systems.

V. CASE STUDIES

The first case study considers the plant from Fig. 1, with the numerical values the parameters adapted to a hydro-power-generator on the river Danube: $k_{CP} = \alpha_s = 1$, $T_i = 2.2$ s, $T_2 = 1.1$ s and $T_3 = 6.8$ s for testing and validating the proposed solutions of hybrid fuzzy controllers. The presented rule base ensures a quasi-equivalence of the AB, with the dependence in the following conditions:

$\rho_1 = |\rho_{s,k-1}|$, $\rho_2 = |\rho_{s,k-1} + \gamma|$, $\rho_3 = |\rho_{s,k-1} - \gamma|$. (15)

The development of AB is done by the proper choice of the parameters $\{B_{s,g}, B_{s,g}\}$ according to the experience of the specialist in control systems.
Fig. 10. Definition of performance indices in unit step response with respect to $v$.

TABLE III.
PERFORMANCE WITH RESPECT TO REFERENCE INPUT

<table>
<thead>
<tr>
<th>Controller type</th>
<th>CS performance</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>$t_1$ [s]</td>
</tr>
<tr>
<td>PI-C</td>
<td>2.7</td>
</tr>
<tr>
<td>PI-FC-OI</td>
<td>2.7</td>
</tr>
<tr>
<td>PI-FC-II</td>
<td>1.2</td>
</tr>
<tr>
<td>PI-NFC-OI</td>
<td>4.3</td>
</tr>
<tr>
<td>PI-NFC-II</td>
<td>3</td>
</tr>
</tbody>
</table>

TABLE IV.
PERFORMANCE WITH RESPECT TO DISTURBANCE INPUT

<table>
<thead>
<tr>
<th>Controller type</th>
<th>CS performance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$t_M$ [s]</td>
</tr>
<tr>
<td>PI-C</td>
<td>5.5</td>
</tr>
<tr>
<td>PI-FC-OI</td>
<td>4.9</td>
</tr>
<tr>
<td>PI-FC-II</td>
<td>6.5</td>
</tr>
<tr>
<td>PI-NFC-OI</td>
<td>4.8</td>
</tr>
<tr>
<td>PI-NFC-II</td>
<td>7.2</td>
</tr>
</tbody>
</table>

- With respect to the modification of $r$: the PI-NFC-OI ensures much better CS performance (excluding the values of $t_1$ and $t_0$).
- With respect to modification of disturbance input $v$: the PI-NFC-OI ensures not so good CS performance because the RM block represents in fact a reference filter.
- The PI-NFC-II ensures not so good CS performance with respect to both the reference input $w$ and the disturbance input $v$.
- For the PI-NFCs the results are similar to those obtained for Mamdani fuzzy controllers [15].

The second case study is related to the field controlled DC-m electrical drive application. Two control loops are introduced (Fig. 7):
- 1: the speed loop with $u_f = k_2 u_C$ (in its classical version), acting in the normal operating regime.
- 2: the speed control loop by weakening the excitation field (the field-controlled regime).

These two loops cannot work simultaneously, switching to loop 2 removes the loop 1 from the control structure with angular speed (as if loop 1 is in open circuit). In the following the results obtained after adjusting the speed by weakening the excitation field will be presented. The main simulation results are synthesized in Figs. 11 and 12. Fig. 11 (a) illustrates the angular speed versus time and Fig. 11 (b) details the output around the portion between 1 and 19 seconds sustaining that PI-NFC ensures better behavior.

- Fig. 12 (a) illustrates the control error (excitation field) versus time and Fig. 12 (b) details the portion between 1 and 22 seconds sustaining again that PI-NFC ensures better behavior compared to PI-FC-OI, PI-FC-II and to PI-C.

Fig. 11 and 12 present a part of the results. The same controllers were considered for the loop 1 but the results are not presented here for the sake of simplicity. However different results can be obtained if other plants are controlled such as those presented in [16]–[22].

VI. CONCLUSION

The paper has presented two structures of hybrid fuzzy controllers that cope with the second-order “right half plane zero” systems belonging to a class of non-minimum phase systems. The two controllers are based on the online tuning of the free parameter of the standard PI-fuzzy controllers by introducing a single neuron with a simplified back-propagation learning algorithm.
The digital simulation results presented in Section V for two case studies validate the proposed solutions and recommend the proposed hybrid fuzzy controller solution for use in controlling the considered class of plants. These results correspond with well accepted approximation to the speed control of hydro-power-generator, and they prove that one of the proposed controllers offers very good CS performance in comparison with a classical PI controller and with the standard PI-fuzzy controllers.

More convenient results can be obtained for a larger number of linguistic terms (five for the inputs and seven for the output) resulting in better CS performance. Future research will be focused on the improvement of CS performance using different controller structures.

ACKNOWLEDGMENT

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REFERENCES


Fig. 12. Control error (excitation field) versus time (a), details of control error (excitation field) versus time (b).