Anti-windup design for internal model control based on the optimal compensator

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Abstract: This paper addresses an anti-windup analytical design method based on the optimal compensator, by adding a parameter α to the sub-controllers to optimize the compensator with a design procedure formulated as a constrained optimization problem, which depend on new particle swarm optimization (NPSO) algorithm, applicable to SISO and MIMO systems with time delay/coupling plants. The proposed anti-windup design provides the minimum integral of squared error (ISE). Illustrative examples are given to show the effectiveness and merits of the Anti-windup IMC design based on the optimal compensator.

Key Words: Nonlinear system, Internal model control (IMC), constraints, anti-windup, optimization, multivariable system

1 INTRODUCTION

Most real world control systems are nonlinear systems that have constraints [1][2]. One of the constraints is physical limitations—steering wheels can only be turned between a certain degree, compressors and pumps can only provide finite press, motors have limited range of speed, valves have maximum opening, pressure and temperature limits are typically appear in process control. In addition, actuator saturation causes another constraint—some valves can only be operated between fully closed and fully open like a valve that controls the coolant's flow rate to a reactor. And we call the constraints above input limitation. Another constraint is plant substitutions—the switch between operating modes that has its own liner controller to satisfy its performance requirement [3][4].

Controller windup is a result of limitations and substitutions—the actual plant input does not match the controller output, which causes the states of the controller wrong updates, and as a result large overshoots of the output, significant performance deterioration [5], and even instability of the control system may happen [6].

Considerable effort has been expended to develop the control strategies to solve the constraints of the systems over the past several decades.

One of the strategies is model predictive control (MPC), which is known to handle problems appeared in multivariable or multi-input multi-out (MIMO) systems with control input saturations [7][8]. However, robust design techniques of MPC have a series of drawbacks: (i) computational burden of the controller may increase seriously; and (ii) it may result in solutions that are so conservative or even infeasible thus cannot be applied [9].

An alternative strategy is anti-windup (AW) design for Internal Model Control (IMC). A general framework that unifies anti-windup bumpless transfer (AWBT) schemes is proposed with a two-step design procedure: (i) design a linear controller neglecting nonlinearities of the control input; (ii) and then add AWBT compensation to maintain a performance with the maximum extent even if constrains presence [4]. In 1994, an IMC-based AWBT scheme, applicable to MIMO systems, is proposed with a two-step design procedure: (i) design the optimal IMC controller ignoring constrains; and (ii) breakdown the IMC controller into two sub-controllers based on the factorization to compose the anti-windup (AW) configuration [10]

Anti-windup compensators are the most important for AW-IMC. It intended to provide a graceful closed-loop performance degradation and global stability in the presence of actuator saturation [11]. In the past several decades, the researches of AW-compensator design has achieved significantly with various compensation design techniques dealing with different AW problems being proposed. Earlier AW-compensators were designed heuristically based on experience and simulations [12]. Then systematic approaches have been presented, in 1999, the reference and command governor scheme has been propose [13]; The compensation designed based on H_∞ optimal control which is developed in 2002 [14]; The compensation designed techniques based on the linear matrix inequality (LMI) were proposed and developed in recent years [15][16]. It is impossible to list all techniques but for more comprehensive overviews of modern AW techniques can be found in Ref. [17].

Though the AW-compensator design techniques developed so much in recent years, there are still some drawbacks that need to be modified: the compensator may not be the optimal compensator, the calculations do not carry over directly to the case of a nonlinear plant [10]; computational burden of the controller may increase. These problems motivate us to develop an optimal compensator.

In this paper, we addresses an anti-windup analytical design method based on the optimal compensator by adding a parameter α to the sub-controllers to optimize the compensator with a design procedure. The design procedure is formulated as a constrained optimization problem, which depends on new particle swarm optimization (NPSO) [18]. The proposed anti-windup design can provide the minimum integral of squared error (ISE), applicable to SISO/ MIMO systems and the plants with time delay/ coupling. Illustrative examples are given to show the effectiveness and merits of the Anti-windup IMC design based on the optimal compensator.

This paper is organized as follows. In Section 2 we recall some preliminary results on IMC. In Section 3, a brief summary of the

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optimal compensator for IMC is provided, also the issue about how to design a compensator and to guarantee the result optimal as well has been proposed. And then we design the compensator by adding the parameter α which can be optimized by NPSO algorithm, applicable to SISO and MIMO systems with the time delay/coupling plants. In Section 4, the performance of the proposed design is illustrated through three simulation examples involving ill-conditioned plants with excellent ITAE and ISE indicators. At last, some conclusions are summarized in Section 5.

2 PRELIMINARY RESULTS

The structure of classical IMC is introduced in Figure 1 [19], where $G(s)$, $G_p(s)$, $Q(s)$ denote the process to be controlled, the process model, the IMC controller; r, d and y are the set-point, external disturbance of the system and output, respectively. The form of IMC controller can be designed as formula (1).

$$Q(s) = G_{m-}^{-1}(s) f(s) \tag{1}$$

Where $G_{m-}^{-1}(s)$ is the static and minimum phase part of the model, filter f(s) is generally chosen as $f(s) = 1/(\lambda s+1)^n$, where n is large sufficiently to ensure the controller proper, λ is the only filter time constant [20].

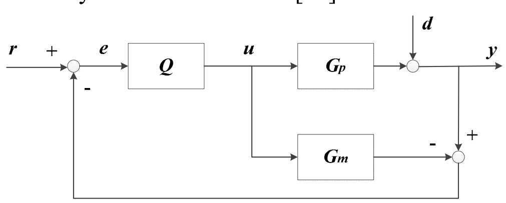

Fig 1. the standard IMC structure

3 OPTIMAL COMPENSATOR FOR IMC

3.1 Problem statement

As shown in Fig 2, there exists a class of saturating systems where the actual process input is $v(t) = sat(u(t))$, and we will assume that the system is stable and linear. Here, the input signal u is limited as formula (2).

$$u_i^{\min} \le u_i(t) \le u_i^{\max} \quad , \ i = 1,\cdots,m \tag{2}$$

And saturation function sat(.) is defines as formula (3).

$$sat(u(t)) = \begin{bmatrix} sat(u_1(t)) \\ \vdots \\ sat(u_m(t)) \end{bmatrix} \tag{3}$$

Where

$$sat(u_i(t)) = \begin{cases} u_i^{\max} & u_i > u_i^{\max} \\ u_i & u_i^{\min} \le u_i \le u_i^{\max} \\ u_i^{\min} & u_i \le u_i^{\min} \end{cases} \tag{4}$$

denotes the input saturation nonlinearity related to each of the input $u_i(t)$.

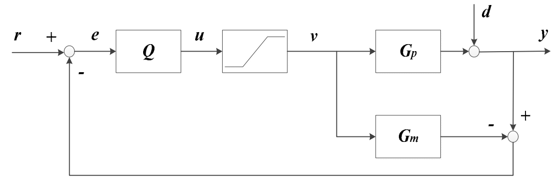

Fig 2. the constrained IMC system

Define the output of constrained system is y, the unconstrained system is y'. Then the design procedure is considered as an optimization problem, which can be stated as formula (5).

$$\min \| y(t) - y'(t) \| \tag{5}$$

3.2 Anti-windup design

For convenience of AW-IMC design, this article takes general expansion to describe the SISO system which can be stated as:

$$G_p(s) = \frac{b_m s^m + b_{m-1} s^{m-1} + \ldots + b_1 s + b_0}{a_n s^n + a_{n-1} s^{n-1} + \ldots + a_1 s + a_0} e^{-\tau s} \tag{6}$$

Where b_i (i=0, 1, ……, m) and a_j (j=1,2,……, n) are coefficient, with $m < n$. $\tau \ge 0$ is the transmission delay.

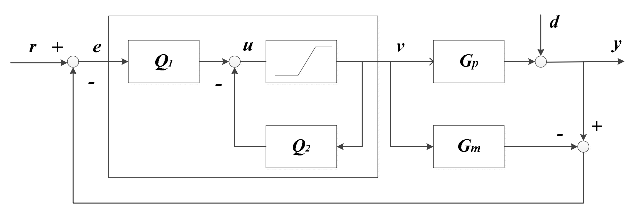

Fig 3. the modified IMC anti-windup structure

According to the above description, the main task is the design of Q_1 and Q_2 In Ref. [10],

$$Q = (1+Q_2)^{-1} Q_1 \tag{7}$$

$$Q_1 = HG_p' Q \tag{8}$$

$$Q_2 = HG_p' - 1 \tag{9}$$

where H is a compensator, G_p' is the minimum phase part of the process, Q is the traditional IMC controller. However, it doesn't mention how to design the H, and it can't guarantee the result is optimal. So in the following part, this paper will get the final result based on the design of optimal.

3.2.1 For first order system with time delay

Assume the process is expressed as:

$$G_p(s) = \frac{k}{Ts+1} e^{-\tau s} \tag{10}$$

Where k is the process gain, T is the time constant, and τ is the time delay. The compensator is designed as:

$$H(s) = \frac{T}{k} s + \alpha \tag{11}$$

The AW IMC controllers are expressed as:

$$Q_1(s)=H(s)G_p'(s)Q(s)=\frac{\frac{T}{k}s+\alpha}{\lambda s+1} \quad (12)$$

$$Q_2(s)=H(s)G_p'(s)-1=\frac{\alpha k-1}{Ts+1} \quad (13)$$

The design of H consists two parts, and the one order factor is get from the ratio of T and k. Thus, there exists only two parameters that can influence the response result. λ is designed by traditional IMC rules, a is the only parameter that can be optimize. NPSO algorithm also can be replaced by other optimize algorithms.

3.2.2 For two order systems with time delay including the normal form acquired by reduction from high order systems

Assume the process is expressed as:

$$G_p(s)=\frac{T_1 s+c_1}{T_2 s^2+T_3 s+c_2}e^{-\tau s} \quad (14)$$

The compensator is designed as:

$$H(s)=\frac{T_2}{T_1}s+\alpha \quad (15)$$

The design of H for two order system is similar to the first order system which is the ratio of T_2 and T_1, in other words, the highest coefficient of denominator and numerator. Also a is the only parameter can be optimized using NPSO algorithm which also could be replaced by other optimize algorithms.

The AW IMC controller can be deduced as:

$$Q_1(s)=H(s)G_{p-}(s)Q(s)=\frac{\frac{T_2}{T_1}s+\alpha}{\lambda s+1} \quad (16)$$

$$Q_2(s)=H(s)G_{p-}(s)-1=\frac{(T_2c_1/T_1+\alpha T_1-T_3)s+\alpha c_1-c_2}{T_2s^2+T_3s+c_2} \quad (17)$$

3.2.3 For MIMO systems

Here consider square system, for example：

$$G_p=\begin{bmatrix} G_{p11} & G_{p12} \\ G_{p21} & G_{p22}\end{bmatrix} \quad (18)$$

For MIMO systems, we first need to do the decoupling work. Feed-forward redeem decoupling scheme is usually used in multivariable systems control because it’s relatively simple and easy to implement.

In this scheme, the two outputs are:

$$Y_1(s)=U_1G_{c11}(s)G_{p11}(s)+U_2G_{c22}(s)[G_{d12}(s)G_{p11}(s)+G_{p12}(s)] \quad (19)$$

$$Y_2(s)=U_2G_{c22}(s)G_{p22}(s)+U_1G_{c11}(s)[G_{d21}(s)G_{p22}(s)+G_{p21}(s)] \quad (20)$$

So the ideal of decoupling is $Y_1(s)$ only affected by $U_1(s)$, $Y_2(s)$ only affected by $U_2(s)$.

$G_d(s)$ is the feed-forward redeem decoupler:

$$G_d(s)=\begin{bmatrix} 1 & G_{d12}(s)=-\frac{G_{p12}(s)}{G_{p11}(s)} \\ G_{d21}(s)=-\frac{G_{p11}(s)}{G_{p22}(s)} & 1\end{bmatrix} \quad (21)$$

the improved feed-forward redeem decoupler:

$$G_d(s)=\begin{bmatrix} e^{-[\tau(G_{p11})-\tau_1]s} & -\frac{G_{p12}(s)}{G_{p11}(s)}e^{-[\tau(G_{p22})-\tau_2]s} \\ -\frac{G_{p21}(s)}{G_{p22}(s)}e^{-[\tau(G_{p11})-\tau_1]s} & e^{-[\tau(G_{p22})-\tau_2]s}\end{bmatrix} \quad (22)$$

$N(s)$ is the generalized controlled plant, decoupling from the decoupler:

$$N(s)=G_p(s)G_d(s) \quad (23)$$

the IMC controller is designed as:

$$G_{IMC}=N_-^{-1}F=\begin{bmatrix} G_{IMC11} & G_{IMC12} \\ G_{IMC21} & G_{IMC22}\end{bmatrix} \quad (24)$$

$$F(s)=\begin{bmatrix} f_1(s) & \\ & f_2(s)\end{bmatrix},\ f_i(s)=\frac{1}{(\lambda_i s+1)^n} \quad (25)$$

After the feed-forward redeem decoupling, Y_1 is controlled only by U_1, Y_2 is controlled only by U_2, thus the controller can just take the main diagonal elements.

$$G_{IMC-diag}=\begin{bmatrix} G_{IMC11} & \\ & G_{IMC22}\end{bmatrix} \quad (26)$$

The compensator

$$H=\begin{bmatrix} H_{11} & \\ & H_{22}\end{bmatrix} \quad (27)$$

where H_{11} corresponding G_{p11}, H_{22} corresponding G_{p22}, thus, the design can refer to the SISO systems.

$$Q_1=HG_{p-}G_{IMC-diag} \quad (28)$$

$$Q_2=HG_{p-}-I \quad (29)$$

Above all the systems, the optimal process contains two parameters which are λ and α. Here λ is designed by traditional IMC rules. α is the optimal compensator parameter obtained by NPSO algorithm.

4 SIMULATION STUDY

4.1 Example 1. First order systems with time delay

We use an example to apply the proposed IMC based anti-windup scheme. A comparison of traditional IMC, windup IMC and the proposed Anti-windup IMC has showed in following figures. Consider a process as:

$$G(s)=\frac{1}{3s+1}e^{-2s} \quad (30)$$

Take $\lambda=1$, then the conventional IMC controller is as:

$$Q(s)=G_{p-}^{-1}f(s)=\frac{3s+1}{s+1} \quad (31)$$

the compensator $H(s)=3s+\alpha$, then factorize the $Q(s)$:

$$Q_1 = \frac{3s+\alpha}{s+1},\ Q_2 = \frac{\alpha-1}{3s+1} \tag{32}$$

Firstly, we discussed the standard conditions. The total simulation time is 50s. Added the unit-step signal respectively at 0s, added amplitude of disturbance 1 at 25s. Take the controller constrains u, $-0.5<u<1.2$. The optimal value of $\alpha = 8.7001$ is obtained through the NPSO algorithm.

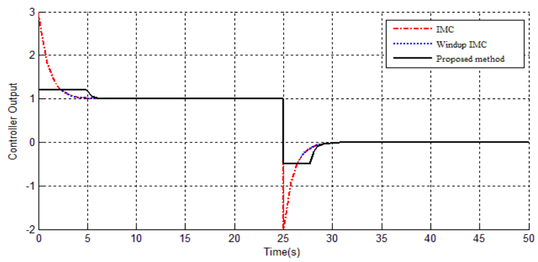

Fig 4. the output of controller for model match

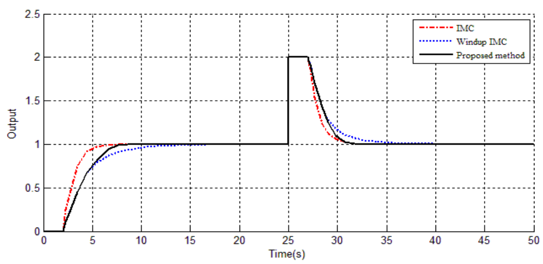

Fig 5. The response of system output for model match

Table1. The comparison of performance index for model match

		y-y'	
	a	ITAE	ISE
IMC	-	-	-
windup-IMC	-	47.7112	0.4866
proposed method	8.7001	30.1640	0.4095
		y-r	
IMC	-	86.4490	5.0653
windup-IMC	-	134.0972	6.3424
proposed method	8.7001	116.5027	6.2541

Then we consider the model perturbation, T is added by 20% (change to 3.6), the time delay is reduced by 20% (change to 1.6). The optimal value of $\alpha = 2.6989$ is obtained through the NPSO algorithm. The controlled plant $G_p(s)$ is as:

$$G_p(s) = \frac{1}{3.6s+1}e^{-1.6s} \tag{33}$$

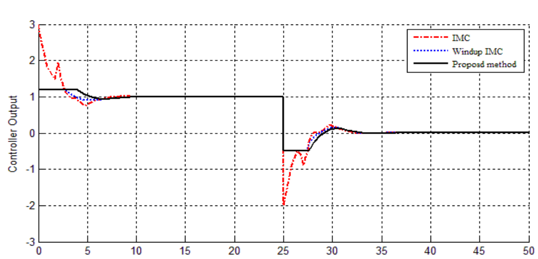

Fig 6. The output of controller for model mismatch

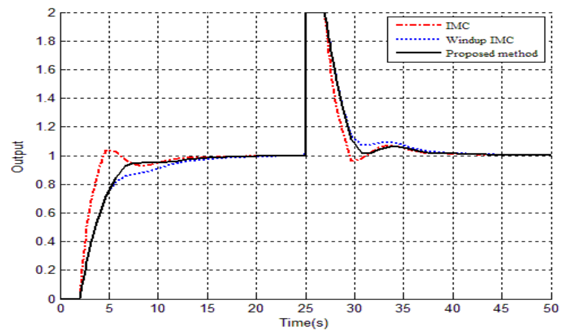

Fig 7.The response of system output for model mismatch

Table2. The comparison of performance index for model mismatch

		y-y'	
	a	ITAE	ISE
IMC	-	-	-
windup-IMC	-	34.5337	0.4285
proposed method	2.6989	23.4745	0.3726
		y-r	
IMC	-	100.0663	5.0620
windup-IMC	-	131.1166	6.0787
proposed method	2.6989	117.4700	5.9806

Through the figures 4-7 and the tables above, it can be seen obviously through the comparison of the ITAE and ISE value, that the proposed anti-windup IMC method has the optimal tracing performance index both on y-y' and y-r.

4.2 Example 2. High order systems with time delay

For high order systems, it can be changed into second order systems through order reduction. We use a second order system as an example.

$$G_p(s) = \frac{2s+1}{5s^2+10.5s+1}e^{-2s} \tag{34}$$

We take a filter $f(s)=1/(2s+1)$, the traditional IMC controller is designed as:

$$Q(s) = \frac{5s^2+10.5s+1}{4s^2+4s+1} \tag{35}$$

The compensator is designed as:

$$H(s) = 2.5s + a \tag{36}$$

The controller $Q(s)$ is factorized into:

$$Q_1(s) = \frac{2.5s+a}{2s+1},\ Q_2(s) = \frac{(2a-8)s+a-1}{5s^2+10.5s+1} \tag{37}$$

Same as example 1, we studied the outputs for model match first. The simulation time is 100s, and we added the unit-step signal respectively at 0s, add amplitude of disturbance 1 at 50s. Take the controller constrains u, $-0.5<u<1.2$. Through the NPSO algorithm, the optimal value of $\alpha = 8.4986$.

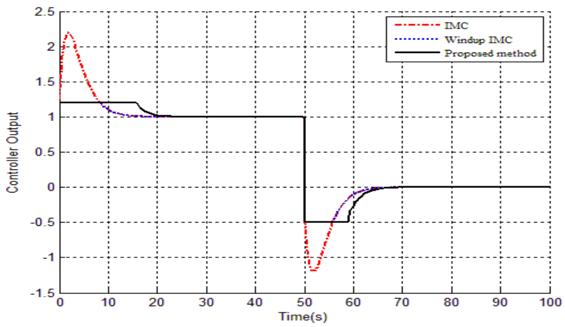

Fig 8. The output of controller for model match

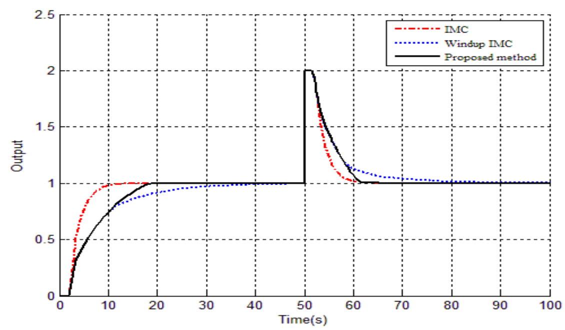

Fig 9.The response of system output for model match

Table3. The comparison of performance index for model match

		y-y'	
	a	ITAE	ISE
IMC	-	-	-
windup-IMC	-	190.8850	1.1257
proposed method	8.4986	85.1512	0.9335
		y-r	
IMC	-	163.7832	4.0135
windup-IMC	-	354.1882	6.2696
proposed method	8.4986	248.9083	6.0851

It can be seen obviously that the proposed Anti-windup IMC method has the optimal tracing performance and a faster response.

Then we take a consideration of model mismatch with $G_p(s)$:

$$G_P(s) = \frac{2s+1}{4s^2+12.6s+1}e^{-0.8s} \tag{38}$$

controller constraints u: $-0.5<u<1.2$, a=7.8998 by NPSO.

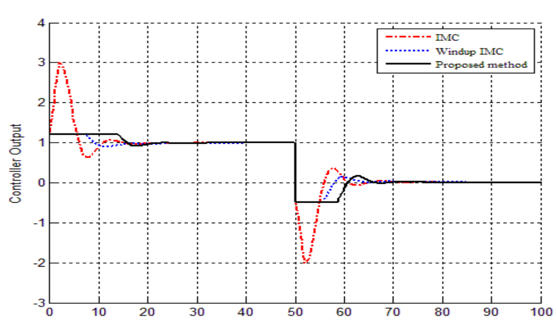

Fig 10. The output of controller for model mismatch

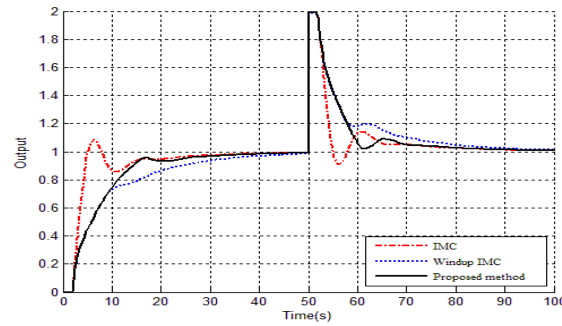

Fig 11.The response of system output for model mismatch

Table4. The comparison of performance index for model mismatch

		y-y'	
	a	ITAE	ISE
IMC	-	-	-
windup-IMC	-	173.3118	0.8554
proposed method	7.8998	74.8679	0.6733
		y-r	
IMC	-	316.5917	4.1895
windup-IMC	-	489.0707	6.6594
proposed method	7.8998	386.7638	6.1788

Through the figure 8-11,and the table 3,4, the proposed method is proved to be effective to develop the control performance of the system, applicable to high order systems.

4.3 Example 3. MIMO systems with constrains

The TOTO VL process is considered in this example, expressed as:

$$G_p(s) = \begin{bmatrix} \frac{-2.2}{7s+1}e^{-s} & \frac{1.3}{7s+1}e^{-0.3s} \\ \frac{-2.8}{9.5s+1}e^{-1.8s} & \frac{4.3}{9.2s+1}e^{-0.35s} \end{bmatrix} \tag{39}$$

the decoupler is designed as:

$$G_d(s) = \begin{bmatrix} 1 & 0.59 \\ G_{d21}(s) = \frac{-2.8(9.2s+1)}{4.3(9.5s+1)}e^{-1.45s} & e^{-0.7s} \end{bmatrix} \tag{40}$$

the generalized controlled plant is as:

$$N(s) = \begin{bmatrix} \frac{s+0.1032}{-5.072s^2-1.258s-0.07627}e^{-3.7914} & \\ & \frac{s+0.1032}{3.41s^2+0.7297s+0.03902}e^{-3.1414} \end{bmatrix} \tag{41}$$

Considering the robust and the performance of the systems, we take the filter matrix as:

$$F(s)=\begin{bmatrix}\frac{1}{s+1} & \\ & \frac{1}{1.8s+1}\end{bmatrix} \quad (42)$$

The traditional IMC controller is:

$$G_{IMC}(s)=\begin{bmatrix}\frac{-5.072s^2-1.258s-0.07627}{s^2+1.103s+0.1032} & \\ & \frac{3.41s^2+0.7297s+0.03902}{1.8s^2+1.186s+0.1032}\end{bmatrix} \quad (43)$$

The compensator matrix is:

$$H(s)=\begin{bmatrix}\frac{7}{-2.2}s+a_1 & \\ & \frac{9.2}{4.3}s+a_2\end{bmatrix} \quad (44)$$

Through the NPSO algorithm a_1=-3.5011, a_2=0.8976, the controller is factorized into:

$$Q_1(s)=\begin{bmatrix}\frac{-35.5s^3-44.31s^2-9.343s-0.5339}{7s^3+8.723s^2+1.826s+0.1032} & \frac{-14.08s^3-17.1s^2-3.175s-0.162}{12.6s^3+10.1s^2+1.908s+0.1032} \\ \frac{-22.02s^4+2.889s^3+32.12s^2+7.663s+0.4568}{6.888s^4+17.82s^3+12.99s^2+2.159s+0.1032} & \frac{31.37s^3+38.09s^2+7.072s+0.359}{16.56s^3+12.71s^2+2.135s+0.1032}\end{bmatrix}$$

$$Q_2(s)=\begin{bmatrix}\frac{6}{7s+1} & \frac{-4.13-4.13}{7s+1} \\ \frac{-5.99s-5.99}{7s+1} & \frac{8.2}{9.2s+1}\end{bmatrix} \quad (45)$$

We study the outputs for model match first. The simulation time is 50s, added amplitude of disturbance 0.1 at the 25s. Take the controller constrains -1<u_1<1, -1<u_2<0.5.

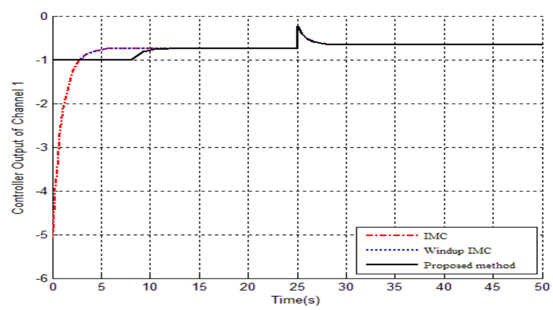

Fig 12. The channel 1 output of controller for model match

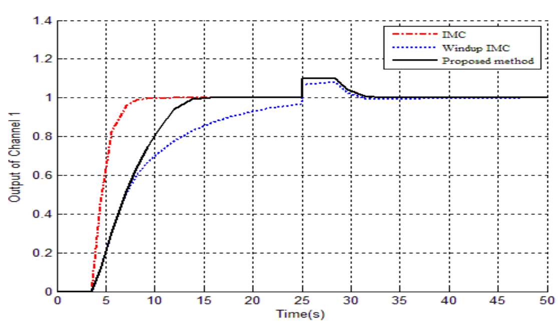

Fig 13.The channel 1 response of system output for model match

Table5 The channel 1 comparison of performance index for model match.

		y_1-y_1'	
	a_1	ITAE	ISE
IMC	-	-	-
windup-IMC	-	32.5476	1.3844
proposed method	-3.5011	15.3205	1.0900
		y_1-r	
IMC	-	16.2966	2.4771
windup-IMC	-	48.8244	2.8039
proposed method	-3.5011	30.7821	1.0077

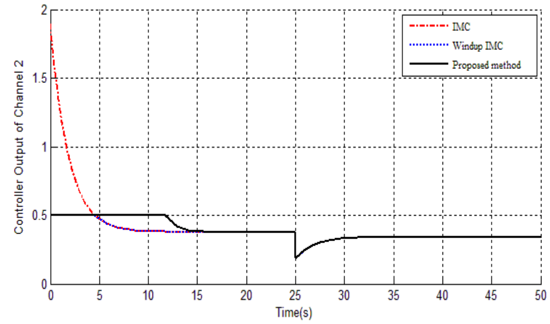

Fig 14.The channel 2 output of controller for model match

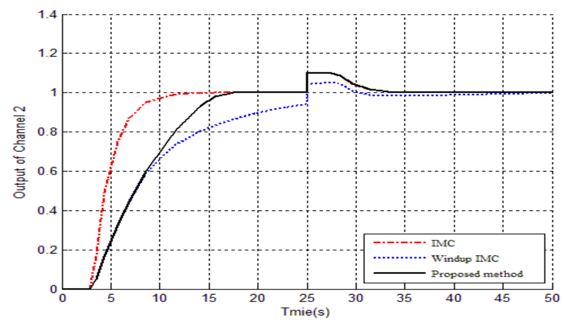

Fig 15.The channel 2 response of system output for model match

Table6 The channel 2 comparison of performance index for model match.

		y_2-y_2'	
	a_2	ITAE	ISE
IMC	-	-	-
windup-IMC	-	34.1111	1.1497
proposed method	0.8976	42.2278	0.9672
		y_2-r	
IMC	-	29.3203	0.8355
windup-IMC	-	74.9300	2.8850
proposed method	0.8976	60.4105	2.6090

The model perturbation：

$$Q_p(s)=\begin{bmatrix}\frac{-2.2e^{-1.2s}}{8s+1} & \frac{1.3e^{-0.36s}}{8.4s+1} \\ \frac{-2.8e^{-2.16s}}{11.4ss+1} & \frac{4.3e^{-0.42s}}{11.04s+1}\end{bmatrix} \quad (46)$$

Take the controller constrains $-1<u_1<1$, $-1<u_2<0.5$. Through the NPSO, a_1= -4.0103, a_2=2.1401.

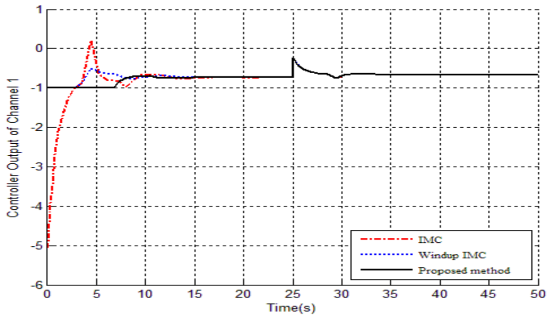

Fig 16. The channel 1 output of controller for model mismatch

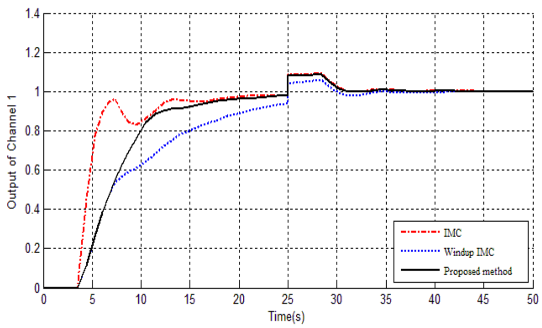

Fig 17. The channel 1 response of system output for model mismatch

Table7 The channel 1 comparison of performance index for model mismatch.

		y_1-y_1'	
	a_1	ITAE	ISE
IMC	-	-	-
windup-IMC	-	36.1036	0.6841
proposed method	-4.0103	24.8627	0.6841
		y_1-r	
IMC	-	39.9411	1.1803
windup-IMC	-	73.5587	3.1116
proposed method	-4.0103	60.5403	2.5573

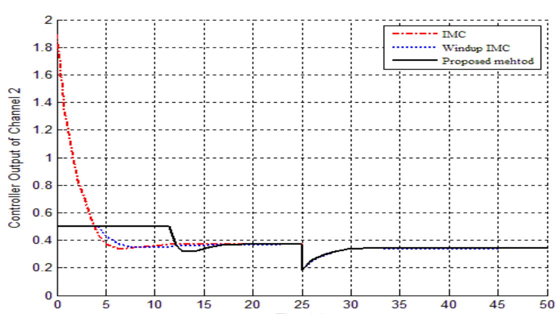

Fig 18. The channel 2 output of controller for model mismatch

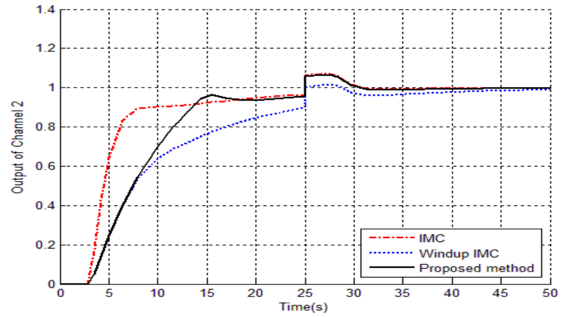

Fig 18. The channel 2 response of system output for model mismatch

Table8 The channel 2 comparison of performance index for model mismatch.

		y_2-y_2'	
	a_2	ITAE	ISE
IMC	-	-	-
windup-IMC	-	48.8829	0.8729
proposed method	2.1401	54.5008	0.6730
		y_2-r	
IMC	-	63.1284	1.1217
windup-IMC	-	103.9092	3.1983
proposed method	-4.0103	32.6999	2.5767

Through the figures and tables above, the proposed method is proved to be effective to develop the control performance of the system, applicable MIMO systems.

5 CONCLUSION

An anti-windup design for internal model control based on the optimal compensator has been presented. The key element in this method is adding a parameter α to the sub-controllers to optimize the compensator with a design procedure, using NPSO algorithm. Compared with the classical AW-IMC structure, the method presented in this paper shows a better tracking performance, a faster dynamic response and ensure the robustness of the systems as well, which can be illustrated through three simulation examples involving ill-conditioned plants with excellent ITAE and ISE indicators. The proposed methods is applicable to SISO and MIMO systems with the time-delay and coupling plants which provide us new thoughts in industrial production.

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