A Model-Driven Two-Degree-of-Freedom PID Controller with Manual/Automatic Switching Without Disturbance

Yu Jian1, Wei Lei1, Zhao Xingwang1

NARI Group Corporation (State Grid Electric Power Research Institute), Nanjing, China

Corresponding author’s e-mail: yujian1@sgepri.sgcc.com.cn

Abstract: The model-driven two-degree-of-freedom PID (MD-TDOF-PID) controller is an excellent controller with simple structure and easy parameter setting. However, the MD-TDOF-PID controller has a fatal disadvantage, which is disturbed in the manual/automatic switching in industrial control field applications. This paper designs a model-driven two-degree-of-freedom PID controller with no disturbance in manual/automatic switching. It has all the advantages of this controller and eliminates the shortcomings of disturbance in manual/automatic switching. The controller proved by simulation experiment that the control effect is better than the ordinary PID controller.

1. Introduction

The dominance of PID controllers in industrial process control is unique. Up to now, PID controllers still occupy more than 95% in motion control, aerospace control and other process control applications [1]. In the actual industrial production process, many controlled objects have large inertia, long time-delay, and other characteristics that are difficult to control. At this time, although the traditional PID controller can complete the control task, the control quality is often not satisfactory. In order to improve the control performance of such objects, advanced control strategies such as Smith prediction [2], internal model control [3], and active disturbance rejection control [4] have emerged. The effect is perfect in theory and simulation, but there are still many problems that need to be solved when it is used in the actual production process. First of all, the controller needs to meet the requirements of simple system structure, easy to adjust parameters, good real-time performance etc., and easy for engineering personnel to master; secondly, the actual controlled object often has nonlinear and time degeneration, which requires the controller to have good robustness, When the parameters of the controlled object change greatly, the system can also meet the requirements of the control performance of the production process; finally, the control strategy should be able to achieve manual/automatic switching without disturbance, and manually control the output when necessary. Due to these limitations, many theoretically good control algorithms have not been widely used in production practice. The status quo of industrial production is that many theoretically excellent control algorithms are still difficult to find a foothold in modern industrial control.

MD-TDOF-PID controller has received great attention because of its simple structure and easy parameter tuning. The study of two-degree-of-freedom PID control can help bridge the gap between control theory and engineering practice and improve control quality.

The parameters of the traditional PID controller must be tuned relative to a specific system (determined model, definite system parameters) and can only be fixedly applied to one working condition [5], when the process characteristics or working environment of the controlled object...
changes occur, the controller parameters need to be re-tuned. Moreover, the traditional PID controller can only improve one of the system's set value tracking performance and interference suppression performance when optimizing parameters, so the traditional PID controller is called a one-degree-of-freedom PID control method [6].

In order to overcome the shortcomings of the one-degree-of-freedom PID control theory that cannot take into account the two control requirements of setpoint tracking performance and interference suppression performance, control theorists researched and proposed a two-degree-of-freedom PID control method [7]. Through the combination of traditional PID controller and compensation elements, adjusting the same number of three PID parameters as the original controller can optimize the above two characteristics at the same time.

MD-TDOF-PID controller due to structural factors, the final design cannot achieve manual/automatic switching without disturbance in practical applications with a hand operator, so it has been delayed to be used in the industrial field. Research on how to transform the MD-TDOF-PID controller without changing its working principle so that it can be added to the hand operator and realize manual/automatic switching without disturbance, which can effectively improve the control quality of the production site and increase production efficiency.

2. Structure of model-driven two-degree-of-freedom PID control system

2.1. MD-TDOF-PID control system configuration

The MD-TDOF-PID control system is mainly composed of three parts, namely PD feedback compensator, main controller and set point filter. The main controller can be further decomposed into a gain block, a second order Q filter and a first order model with time delay, which shown in figure 1. \( r, r_y, e, v, u, y \) was setpoint, output from setpoint filter, error, output from main controller, controller output and process variable.

![Figure 1. MD-TDOF-PID control system](image)

2.2. PD feedback compensator \( F(s) \)

The PD feedback compensator is used to stabilize the system to improve the dynamic characteristics of the system, and it can also stabilize the unstable system.

PD feedback compensator including the PD feedback \( F(s) \) make the transfer function of the process to a first order system with time delay [8]. The transfer function of the controlled system from \( v \) to \( y \) is expressed by:

\[
G(s) = \frac{P(s)}{1 + P(s)F(s)} = \frac{Ke^{(-Ls)}}{1 + Ts}
\]

(1)

where \( K, T \) and \( L \) are gain, time constant and dead time of the overall controlled process respectively.

Well-designed PD feedback compensator would get control parameters, gain \( K \) time constant \( T \) and dead time \( L \) properly, which the integral error of MD-TDOF-PID control system will be smaller than that of the originally controlled process.

When \( P(s) \) is identified, the PD feedback can be designed by using many design methods such as the principle pole place allocation method, model match method and optimization method. The PD feedback compensator was designed using model matching method in [9], the PD feedback compensator is designed as:
where $K_f$, $T_f$ and $\gamma$ are constants.

So long time delay process, oscillation process and unstable process can be controlled by MD-TDOF-PID controller.

2.3. Main controller $C(s)$

The main controller consists of three blocks: gain block $K_c$, Q filter $Q(s)$ and ideal model $G(s)$. After $G(s)$ is identified in the form of equation (1). The main controller is designed by adjusting the parameters $\lambda$ and $\alpha$ in Q filter to meet the design specifications. The main controller transfer function is derived as follows.

$$C(s) = K_c \frac{(1 + T_f s)(1 + \alpha T_c s)}{(1 + \lambda T_e s)\alpha}$$

(3)

where $K_c$ is controller gain and $T_c$ is controller time constant.

The open-loop transfer function of system (from $e$ to $y$) is

$$G_1(s) = \frac{1}{K} \frac{(1 + Ts)(1 + \alpha Ts)}{(1 + \lambda Ts)^2} \frac{Ke^{(-Ls)}}{(1 + \alpha Ts)e^{(-Ls)}}$$

(4)

the closed-loop transfer function of system (from $r_y$ to $y$) is derived as

$$G_0 = G_1 / (1 + G_1) = \frac{(1 + \alpha Ts)e^{(-Ls)}}{(1 + \lambda Ts)^2}$$

(5)

the transfer function from $d$ to $y$ is

$$\frac{y}{d} = \frac{G(s)}{1 + G(s)} = \frac{Ke^{(-Ls)}}{1 + \alpha Ts}$$

(6)

The main controller improves the speed response ability of the system. $K_c$ is used to cancel $K$ in $G(s)$ to make sure that $G_0(0) = 0$, thus the steady state position error is zero i.e. $e_p = 0$ for step input signal $(r)$. The term $(1 + Ts)$ is used to cancel the term $(1 + Ts)^{-1}$ in the $G(s)$ by setting $T_c = T$. It is effective in improving the speed response ability of system. In equation (2), the time delay item can be approximated as $e^{(-Ls)} \approx 1/(1 + Ls)$ (in low frequency region), hence one has

$$G(s) \approx \frac{K}{(1 + Ts)(1 + Ls)}$$

(7)
If the slow pole \( s = -\frac{1}{T} \) is removed, \( G(s) \) will become much faster than the previous one. The main controller helps in rejecting the noise \( d \) from entering system. From equation (7), in low frequency region \( s \approx 0 \), one has \( \frac{y}{d} \approx 0 \) which means the noise is rejected from entering system. It is noticed that if the pole is \( s \approx 0 \), one has \( \frac{y}{d} \approx 0 \).

The main controller can allow almost all reference signals to enter the system while suppressing noise.

2.4. Set point filter

The set point filter is used to cancel one zero and one pole in the system and thus to reduce the order of the system from second order to first one.

\[
\frac{y}{r} = \frac{(1 + \lambda Ts)(1 + \alpha Ts)e^{(-Ts)}}{(1 + \alpha Ts)(1 + \lambda Ts)^2} = \frac{e^{(-Ts)}}{1 + \lambda Ts}
\]

(8)

3. Design of improved MD-TDOF-PID controller

3.1. MD-TDOF-PID controller application problem analysis.

MD-TDOF-PID is simple in structure and parameter adjustment, and it is not difficult to implement in industrial control field, but there are still some problems between theory and practice [10]. As the requirement of the industrial control field, the manual control station is an indispensable part. A controller system can not only rely on automatic control, but also can be switched to manual control to deal with various abnormal situations.

It is the basic requirement for the industrial control field controller to be able to switch manually and automatically without disturbance. The MD-TDOF-PID controller based on the structure shown in figure 2 cannot meet the requirements.

According to the industrial control field control principle, the controller output \( u \) in manual state is the manual value \( u_m \) of the manual operation station, the setting value \( r \) is equal to the process variable \( y \), the output \( u \) of the controller in the automatic state is the difference between the output \( v \) of MD-TDOF-PID main controller and the output \( u_f \) of PD feedback device, and the setting value \( r \) is manually set. The range of industrial control field actuator is generally between 0-100%, and the actuator has travel time.

Figure 2. MD-TDOF-PID controller added to manual operation station
For control objects $P(s) = \frac{1.1}{120s + 1} e^{-40s}$, the simulation is carried out after adding the function of the manual controller. The first 1000s of the controller is set as the manual state, and the setting value is 10. After 1000s, the controlled object is basically stable, the manual controller is switched to automatic state, and $r = 10$ is not modified. The response curve is shown in figure 3.

Figure 3. MD-TDOF-PID controller manually switches to automatic response curve

It can be seen from this figure 3 that the deviation of process variables is small at this time, but the deviation between $u_m$ and $u_r$ is very large, and $u_m$ is adjusted slowly, which leads to the fluctuation of process variables and seriously affects the performance of the controller.

3.2. Improved design of MD-TDOF-PID controller

According to the design principle of the controller, the controller output must be adjusted from the back to the front, and every interference factor must be eliminated. The output of MD-TDOF-PID controller consists of two parts, one is the output $v$ of the main controller $G_c(s)$, the other is the output $u_f$ of PD feedback compensator.

In order to achieve the controller manual/automatic switching without disturbance, two schemes can be considered. The first scheme is $u_f = 0$, $v = u_m$ in manual state. At this time, switching to automatic mode can ensure that the output of the controller is equal to $u$ and there is no jump. Second, you can set $u_f + v = u_m$. Considering the adjustability of PD feedback compensator, the first scheme is used in this paper to realize the modularization of each part of the controller as far as possible, so that each part of the controller can achieve manual deviation free from the structure.

The general form of PD feedback compensator designed by MD-TDOF-PID controller is

$$F(s) = K_f \frac{(1+T_f s)}{1+\gamma T_f s},$$

which is a linear link, and the step response can be linearly superimposed in steady state.

After ensuring that the controller has the ability of manual/automatic non-disturbance switching, the modules of the controller are reduced as much as possible. Finally, the structure of MD-TDOF-PID controller is designed as shown in figure 4.
For the control object, the controller is built according to the structure of figure 4, and the function of manual operator is added. The simulation is carried out. The first 1000s of the controller is in manual state, and $u_m$ is set to 10. After 1000s, when the controlled object is basically stable, the manual operator will switch to the automatic state, and set $r = 10$ at 1000s. The response curve is shown in Figure 5. In stable state, the switch of controller is very stable, the output is free of any disturbance.

Figure 5. Improved design of MD-TDOF-PID controller manually switches to automatic response curve

Then we will conduct step response experiments on the improved MD-TDOF-PID controller and traditional PID for the same control object $P(s) = \frac{1.1}{120s + 1} \cdot e^{-40s}$. The comparison result is shown in figure 6.

Figure 6. Comparison of control performance between traditional PID controller and MD-TDOF-PID controller
It can be concluded that the improved MD-TDOF-PID controller can achieve the set point tracking and hand automatic undisturbed switching and has no adverse effect on the control performance. The performance index is obviously better than the traditional PID controller, and the controller does not appear out of control or large deviation in the case of manual/automatic switching disturbance, which indicates that the controller has strong stability. The improved MD-TDOF-PID controller can be used in the industrial control field.

4. Conclusion
This paper mainly aims at the problem that the original structure of MD-TDOF-PID controller cannot be applied to the industrial control field, analyzes the defects of the original structure of the controller, analyzes and simulates the causes and phenomena of the defects of the controller, and then puts forward the solution, analyzes the advantages and disadvantages of the scheme from the principle, and carries out the simulation.

Finally, the structure of the improved MD-TDOF-PID controller is designed, and the practicability of the improved MD-TDOF-PID controller is verified by simulation experiments, which verifies that the improved MD-TDOF-PID controller has the ability to be applied in the industrial control field without weakening its control performance. The improved MD-TDOF-PID controller's control performance is better than the current PID controller, which can effectively improve the control quality of industrial control and enhance work efficiency.

References
[1] Han J. From PID technology to "Auto-disturbance rejection control" technology [J]. Control Engineering, 2002, 03: 13-18.
[2] Yang P, Zhou Z. On the availability of a completely anti-interference Smith predictive control scheme [J]. Chemical Industry Automation and Instrumentation, 2010, 05: 13-15.
[3] Huang Y, Han P, Li Y. Fuzzy adaptive internal model control of main steam temperature system[J]. Proceedings of the Chinese Society of Electrical Engineering, 2008, 23: 93-98.
[4] Zeng H, Li D, Jiang X, Shan W, Xue Y. Auto disturbance rejection PID control for time-delay objects[J]. Journal of Tsinghua University (Natural Science Edition), 2007, 11: 2018-2021.
[5] Zhao X. Research on a high-precision 2-DOF-PID control stability method [D]. Graduate University of Chinese Academy of Sciences (Changchun Institute of Optics, Fine Mechanics and Physics), 2013.
[6] He Z. PID controller parameter tuning method and its application research [D]. Zhejiang University, 2005.
[7] Hiroi K and Yukio T, Two Degrees of Freedom Algorithm, Proceedings of the ISA, 1986, Houston
[8] Yukitomo M, Shigemasa T, Baba Y, et al. A two degrees of freedom PID control system, its features and applications[C]/Control Conference, 2004. 5th Asian. IEEE, 2004, 1: 456-459.
[9] Shigemasa T, Yukitomo M, Kuwata R. A model-driven PID control system and its case studies[C]/Control Applications, 2002. Proceedings of the 2002 International Conference on. IEEE, 2002, 1: 571-576.
[10] Yu X, Liu H, Li J. Design skills and engineering realization of non-disturbed switching function of control system [J]. North China Electric Power Technology, 1996, 04: 25-29.