확장적분 제어개념을 도입한 PI 제어기에 관한 연구

論 文
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Extended Integral Control with the PI Controller

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Abstract - This paper presents an extended integral control with the PI controller by introducing the delay and decaying factors. The extended integral control scheme is developed by substituting the proportional convolution integral control for the PI(Proportional Integral) control. So far, the integral part of PI controller produces a signal that is proportional to the time integral of the input signal to the controller. The steady-state operation points are affected forever by errors in the past due to the input signal containing the information of the error in the past. These phenomena may cause some disturbances for other control purposes related to the given PI control. Introduction of forgetting factors to the error in the past can resolve the disturbance problems. Various forgetting factors are developed using the delay elements, the decaying factors, and the combination of the delay and decaying factors. The proposed various extended integral control schemes can be applicable to the corresponding PI control designs in which the error in the past may badly affect the current steady-state operation points and may cause some disturbances for other control purposes.

Key Words : Extended Integral Control, PI Control, Proportional Convolution Integral, Delay Element, Decaying Factor

1. Introduction

The PID(Proportional Integral Derivative) controller has received a great deal of attentions in the process control areas because of its simplicity, robustness, and successful practical applications.[1,2] Its commercial applications are easily found in the process industries. In order to fulfill some industrial control requirements, various efforts of modifying PID controllers and tuning of PID controllers have been directed to find an enhanced control performance for the various process models[3,4,5,6,7,8]. Among other controls, the PI control technique has an advantage to reduce the steady-state error to zero by feeding the errors in the past forward to the plant.

However, in some control problems, due to the effects of the unnecessary errors in the past, the PI control scheme makes some disturbances in other control purposes. For example, in the LFC (Load Frequency Control) system of power systems, the integration of the error in the past remains forever affecting the steady state operation point after the system state has settled down. These phenomena may disturb other control purposes such as AGC(Automatic Generation Control).

In order to overcome these difficulties, an extended integral control with the PI controller is developed by substituting the proportional convolution integral controls for the PI controls. The feeding signal to the PI controller in the plant contains the information of the error in the past by the integration of the error. In the proposed scheme, the key idea is reducing the effects of the error in the past using the forgetting factors which are made by substituting the delays or the decaying factors for the integral term of PI controller. Delay makes the input signal include the integral of the errors only for the essential time periods. With introduction of the decaying factor, the past error terms are forgotten exponentially. Both of the delay and the decaying factor can be employed to some control models. These extended integral controls which are like types of convolution integral controls, can be implemented in circuits or some microprocessors. The main objective of the proposed scheme is minimizing the disturbances for other control purposes using the forgetting factors which can reject or reduce the effects of the unnecessary errors in the past. The results of the simulation to an application are obtained by Runge-Kutta method and described in section 2.3. The proposed extended integral scheme can enhance the design of PI controller after investigation of a targeted control systems.

2. Main Discourse

2.1 PI Control Involving Convolution Integration

The PI(Proportional Integral) controller is widely used

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to improve steady-state error in several control problems such as chemical engineering process problems, LFC problem of power systems, automatic steering of ships and so on[4,5]. Generally, the implementation of PI controller consists of feeding the proportional error plus the integral of the error forward to the plant. As shown in Fig.1, the general form of PI controller consists of proportional part(K) and integral part($H(s)=K_I/s$)

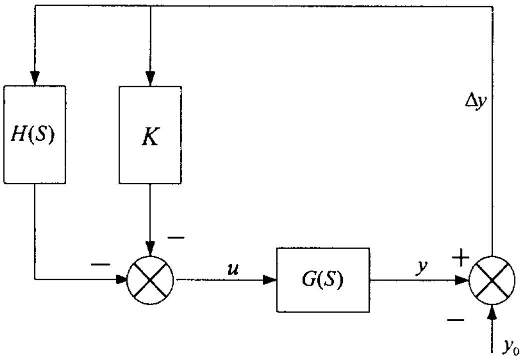


Fig. 1 Block diagram of the general PI controller

The PI control technique perfectly reduces steady-state error to zero. However, in some control problems, some disturbance results from the PI control are obstacles to other control purposes. Due to the feeding signal to the plant containing the unessential information of the errors in the past, the integration of the errors in the past affect badly and continuously the current steady-state operation points. For example, in LFC system of power systems, the integration of the errors in the past remains forever affecting the steady state operation points after the system state has settled down. In other words, the PI control causes some disturbances for AGC since the unessential information in the past badly affects the current steady state operation points. For another example, in the speed control system for a steel rolling mill, the load on rolls changes depending on the engaged bar in rolls. It is obvious that the information of the change in speed resulted from the load disturbance in the past, should be ignored in the current steady state operation points. To do ignoring unnecessary information in the past, the convolution integration concept is proposed by substituting the convolution integral for a general integral term, $H(s)$.

When the integral gain K_I is set to a unit value, the well-known integral block is represented by $H(s)=1/s$ and its transfer function in the time domain is as follows:

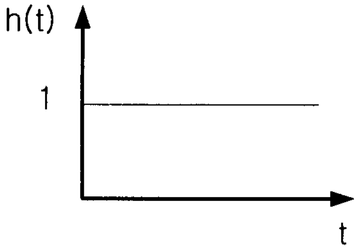


Fig. 2 The representation of the integral block in the time domain

The feeding signal to the plant becomes

Feeding Signal =

$$U(S) = K\Delta Y(s) + H(s)\Delta Y(s)$$
$$u(t) = K\Delta y(t) + h(t) * \Delta y(t) \tag{1}$$

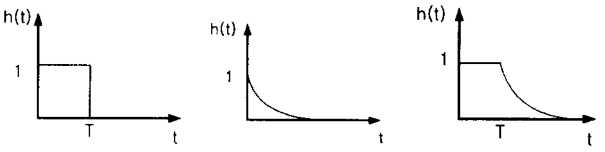
In the time domain, Eq.(1) says that the feeding signal is in proportion to the current errors plus the integration of the errors from the past(the initial time) to the current time. In order to reduce or reject the unnecessary information in the past, the integration term in the feeding signal is modified by introducing the convolution integral concept. In the convolution integral control scheme, the impulse response $h(t)$ should be properly chosen to get rid of the error information in the past.

2.2 Extended Integral Control

The extended integral control with the PI controller is developed by substituting the proportional convolution integral controls for the PI control. The extended integral control is one of types of convolution integral controls. In the proposed scheme, the key idea is reducing the effects of the error in the past using the forgetting factors which is made by substituting the delays or the decaying factors for the integral term of PI controller. The impulse response $h(t)$, the inverse Laplace transform of $H(s)$, is chosen among the following various convolution integral types:

$$\begin{aligned} &\text{a) } u(t)-u(t-T)\\ &\text{b) } e^{-\lambda t}u(t) \qquad (2)\\ &\text{c) } [u(t)-u(t-T)]+e^{-\lambda(t-T)}u(t-T) \end{aligned}$$

The various convolution integral types are described in the following graphical representations:



(a) delay (b) decay (c) combination of delay and decay

Fig. 3 The representation of the convolution integral block in the time domain

Let us investigate the improved input signal except the proportional error. The improved input signal is made by the convolution of the error, $\Delta y(t)$, and one of the above three functions in Fig. 3. The integral function and the above three functions are described in the time domain and the frequency domain as shown in Table 1.

The best choice for the three convolution integral schemes can be made after investigating the characteristics of a targeted control system. The various convolution schemes of Table 1 can be built in physical devices such as circuits or some micro-processors with the advancements of electronic circuits and signal processing technology.

Table 1 Realizable transfer function

$h(t)$	$H(S)$
$u(t)$	$\frac{1}{s}$
$u(t)-u(t-T)$	$\frac{1}{s}(1-e^{-sT})$
$e^{-\lambda t}u(t)$	$\frac{1}{s+\lambda}$
$[u(t)-u(t-T)]$ $+e^{-\lambda(t-T)}u(t-T)$	$\frac{1}{s}(1-e^{-sT})$ $+e^{-sT}\frac{1}{s+\lambda}$

The improved input signal except the proportional error is given by

Input Signal =

$$L^{-1}\{H(s)\Delta Y(s)\}=h(t)*\Delta y(t)=\int_{0_-}^{t}\Delta y(t-\tau)h(\tau)d\tau \qquad (3)$$

The Eq. (3) implies that the input signal forward to plant is made by the convolution of the error and the function $h(t)$. In the case of $h(t)=u(t)-u(t-T)$ where T is the time delay, input signal includes the integration of the error for the essential time periods(T). Due to the time delay T, the input signal is not affected the error $\Delta y(t)$ after time period T. On the other hand, the errors of the unnecessary time periods (The information for T time periods previous to the current time) are rejected from the input signal. When h(t) is selected as $e^{-\lambda t}u(t)$, the past error terms are forgetting exponentially by the decaying factor(λ). As the above both cases are combined, sum of the delay and the decaying factor can be considered as the impulse response to produce an improved input signal to the plant. That is $h(t)=u(t)-u(t-T)+e^{-\lambda(t-T)}u(t-T)$. The proposed various convolution integral controls are applicable to some control problems in which effects of the error in the past disturb the other control purposes.

2.3 Applications

The proposed extended integral control can be applied in the process control area such as a chemical process and a steel rolling process etc.

In power systems, the proposed extended integral control can be used in LFC instead of PI control. It is well known that the conventional PI LFC scheme does not yield adequate control performance with consideration of the non-linearities of speed governor such as rate limits on valve position and Generation Rate Constraints(GRC). However, the proposed controller can be provide improved performance for system with non-linearities. In this simulation, the performance of proposed controller will be checked over a small range of operation conditions. The PI controller in the LFC is adopted to simulate the extended integral control. Its block diagram is shown in Fig. 4.

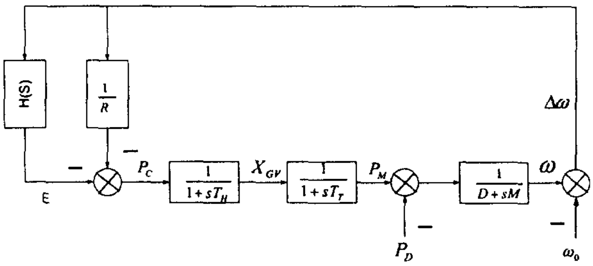


Fig. 4 Block diagram of the PI controller in the LFC of Power Systems

The tested system is a typical mechanical-hydraulic speed-governing system which consists of a speed governor, a steam turbine, and a PI controller. Typical parameters for mechanical-hydraulic systems are given in Table 2[9].

Table 2 Typical parameters of Mechanical Hydaulic Speed Governor

Parameter	Value
Inertia Constant H	6.175s
Damping Factor D_{pu}	0.15pu
Frequency f_0	60Hz
Decaying Factor λ	0.5
Governor Time Constant T_H	0.1s
Turbine Time Constant T_T	0.3s
Speed Regulation R	0.05

Note) $M=H/\pi f_0$, $D=D_{pu}/2\pi f_0$

In order to examine delay(T), decaying factor(λ) and the combination of delay and decaying factor, the simulation has been conducted for each transfer function.

<u>Case I</u>

The simulation has been conducted for the conventional proportional control scheme, i.e.

$$H(s)=0 \qquad (4)$$

<u>Case II</u>

The extended integral control scheme adopts the delay function as its block of $H(s)$.

$$H(s)=\frac{1}{s}(1-e^{-sT}) \qquad (5)$$

<u>Case III</u>

The extended integral control scheme adopts the decay function as its block of $H(s)$.

$$H(s)=\frac{1}{s+\lambda} \qquad (6)$$

<u>Case IV</u>

The extended integral control scheme adopts the combination of the delay and the decay function as its block of $H(s)$.

$$H(s) = \frac{1}{s}(1-e^{-sT})+e^{-sT}\frac{1}{s+\lambda} \tag{7}$$

Case V

The simulation has been conducted for the conventional PI control scheme, i.e.

$$H(s) = \frac{1}{s} \tag{8}$$

The proposed control scheme is tested for two cases of load change. Disturbances of interest are chosen to be step load changes of 0.01pu or 0.05pu, i.e.

$$\text{i) } P_D = -0.01pu \text{ or} \tag{9}$$
$$\text{ii) } P_D = -0.05pu$$

The results of simulation are obtained by Runge-Kutta method and summarized in Table 3. Fig. 5 depicts frequency responses for each control case.

Table 3 Numerical results of simulation

Controller	Transient overshoot (%)	Steady-state error when $P_D=-0.05pu$
Case I	0.01332	0.040
Case II	0.04832	0.016
Case III	0.05666	0.011
Case IV	0.05332	0.013
Case V	0.07500	0.0

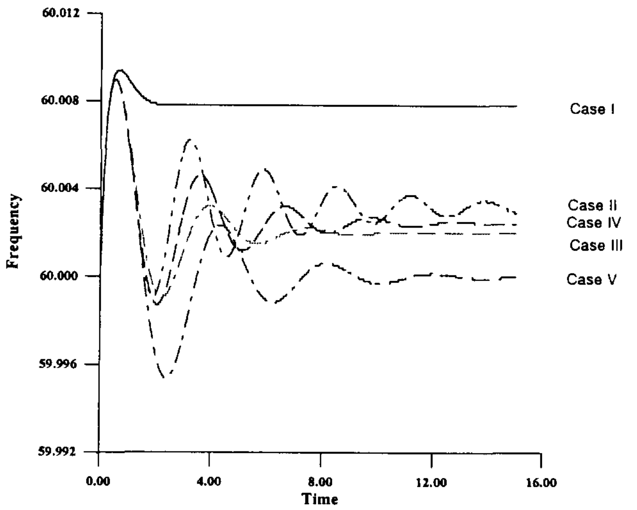
As shown in Fig. 5, the PI control technique which means Case V perfectly reduces the steady-state error to zero. However, from a viewpoint of overshoot, Case III has produced better performance than any other cases. As shown in Table 3, the frequency response by Case III is much less oscillatory at the expense of steady-state error.

In LFC system of power systems, it is well known that the PI controller makes the frequency droop to be zero. That is, the PI controller produces a control signal which makes the frequency deviation to be zero as follows:

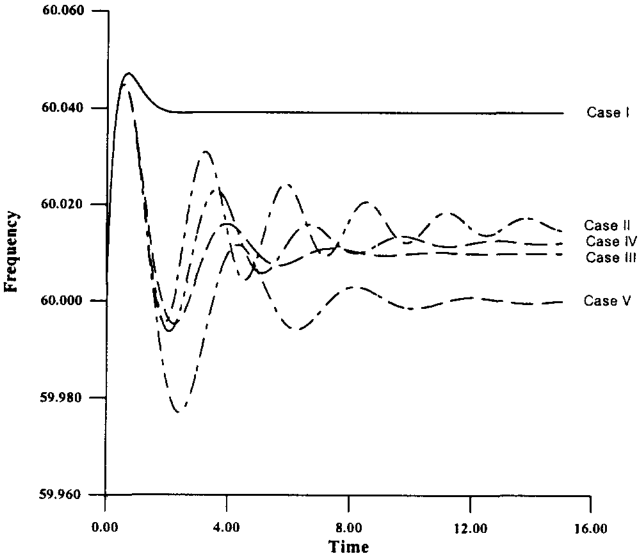
$$\delta_i = \int_0^t \Delta\omega_i \, dt + \delta_{oi} \tag{10}$$

However, since the initial time for integration of the frequency deviation error is difficult to be set same for all generators. In other words, the determination of δ_{oi} in Eq.(10) is difficult to be same. Therefore, all generators are not controlled by the PI controller. In practice, one of all generators is controlled by the PI controller and the others are controlled by the proportional controller.

On the other hand, the extended integral controller does not need the same initial time, so that it can be applied to any generator simultaneously. Consequently, the extended integral control scheme can produce better control performance than the proportional control scheme. As shown in Fig.5, Case III, which is one of the extended integral control scheme, provided better performance than Case I, which is the proportional control scheme.



a) $P_D = -0.01$



b) $P_D = -0.05$

Fig. 5 Frequency responses of five cases when disturbance $P_D=-0.01$ and $P_D=-0.05$

In the extended integral control concept, it is obvious that the past error should be ignored in the integral of error forward to the plant after enough time has passed. It is enough to consider the recent information to get the required engineering performance in the LFC. In order to get rid of the effects of the past error on the current steady state, the extended integral scheme is proposed with its acceptable accuracy and fast settling time. Disturbances of AGC resulted from effects of the errors in past can be remarkably reduced. One may expect that the extended integral control scheme using the combination of the delay and decaying factor would provide the better performance of the frequency response than Case II and Case III. Unexpectedly, the combined convolution integral scheme, the case IV, is not enhanced in the accuracy of the steady-state error and settling time compared with the case III since the delay term causes the oscillation. Investigation of the reasons of the oscillation caused from the delay remains for the further researches.

3. Conclusion

This paper presents an extended integral control with the PI controller by introducing the various forgetting factors which are the delay element, the decaying factors, and the combination of the delay and decaying factors. The extended integral control schemes are developed by substituting the proportional convolution integral controls for the PI control. In the conventional PI control, the steady-state operation points are affected forever by the errors in the past due to the input signal containing the information of the errors in the past. These phenomena may cause some disturbances for other control purposes. The proposed various extended integral control scheme can be applicable to the corresponding PI control designs in which the error in the past may badly affect to the current steady-state operation points and may cause some disturbances for other control purposes. The test results for the LFC of the power systems explain the reason why the proposed various extended integral controls can resolve the obstacles for other control purposes by introducing of forgetting factors of the errors in the past.

Further research should be done to select an optimal forgetting factor which affects greatly the controller performance under GRC.

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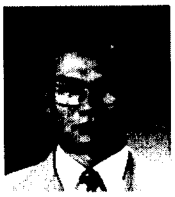

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