

PI Control Technology Principal Analysis and Simulation

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Abstract. As the requirements for control accuracy and speed increase, proportional-integral (PI) control systems can better achieve stable control. Proportional-integral (PI) control is widely used in modern industry because it has the characteristics of block speed and high accuracy. However, the performance of proportional control systems with different parameters varies greatly in different usage scenarios, and the behavior of PI control systems can be observed and adjusted in advance through computer simulation and modeling. This process can be optimized in advance by observing the response performance of the PI control system, thus reducing the development time and helping to improve the development efficiency in actual engineering. This paper explains the basic principle of PI control from the basic mathematical principle, and simulates the specific behavior of PI control system under different regulation parameters and shows the zero-pole distribution and step response of PI controller under different states and analyzes the application of PI control system in real engineering.

Keywords: PI controller, pole-zero map, step response, computer simulation.

1. Introduction

As the sensitivity and accuracy of control systems are improved, proportional-integral (PI) control techniques are increasingly used. Proportional-integral controllers are characterized by simple algorithms, good robustness and high reliability; however, they often have nonlinearity and event uncertainty in the actual process.

In order to better design PI control system, this paper will introduce its simulation principle and analyze the application in real engineering. This paper gives a detailed introduction to the basic principles of PI control, explaining the operations performed on the signal in the proportional and integral links and the transfer function of the PI control system in the frequency domain. The implementation method and circuit diagram in practical applications are also given. By analyzing the transfer function in the frequency domain and the needs of the practical situation, the article analyzes and simulates the zero, pole and root locus diagrams as well as the step response in MATLAB for different values of the transfer function. Finally, the article analyzed PI control in three practical applications: permanent magnet synchronous motor, home inverter refrigerator temperature control and temperature control in data centers. By observing the performance of the adjusted parameters, it is possible to obtain the proportionality factor used to set the error between the current value and the desired value, and the integration factor to control the oscillation effect between the output and the input.

The computer can make a reasonable simulation of PI control system, which will reduce the design and development cycle of PI control system in engineering, and at the same time can verify the performance of PI control system in advance [1].

2. PI control circuit basic principle and analysis

2.1. Basic model and working principle of the circuit of PI control

Proportional-integral (PI) controllers are another name for proportional integral controllers. It is a sort of controller made up of integral and proportional control actions. As a result, it is called a PI controller.

Although improved controllers have been proposed by control theory to handle production items with hysteresis, PID controllers, which have three parts—a proportional (P) component, an integral (I), and a differential (D) part—remain the majority of controllers currently utilized in industry. The D component cannot truly enhance control performance for long lag production objects, and the test signal differential prediction is currently inaccurate. As a result, only the PI controller without the prediction element is used when the PID controller is applied to the lag problem [2].

Electrical systems often utilize PI controllers because of their straightforward implementation and structure. They are widely employed in direct current (DC) applications as well as in alternating current (AC) applications in conjunction with coordinate transformations to control constant or slowly variable quantities. A PI controller can be pictured as follows figure 1 when it is implemented in parallel form.

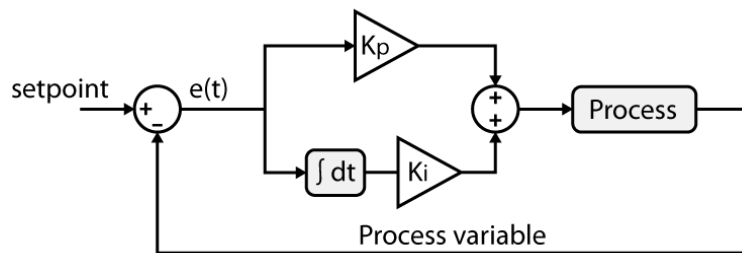


Fig.1 PI control schematic [2]

The formula is shown in (1)

$$m(t) = K_p e(t) + K_i \int e(t) \tag{1}$$

where $e(t)$ and $m(t)$ are the input and output of the circuit respectively, K_p is the proportionality factor and K_i is the integration factor.

2.1.1 Working principle

Given the Laplace transform of the equation (1), it could be derived to:

$$m(t) = K_p E(s) + K_i \frac{E(s)}{s} \tag{2}$$

Taking the common term out, it will be:

$$M(s) = E(s) \left[K_p + \frac{K_p}{s} \right] \tag{3}$$

$$\frac{M(s)}{E(s)} = K_p \left[1 + \frac{1}{T_i s} \right] \tag{4}$$

$$T_i = \frac{K_p}{K_i} \tag{5}$$

Therefore, the circuit of the PI controller can be simplified as shown in the following figure 2.

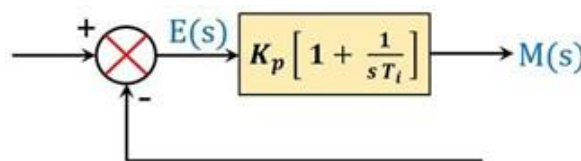


Fig.2 PI control system after simplification (Photo/Picture credit: Original)

2.1.2 Basic model of the circuit of PI control

As can be seen from the implementation steps of the schematic, PI control consists of an adder, a proportional amplifier, and an integrator and a proportional amplifier in series in the implementation process. Different control parameters may correspond to different application processes, but the circuit image can be constructed as follows in figure 3.

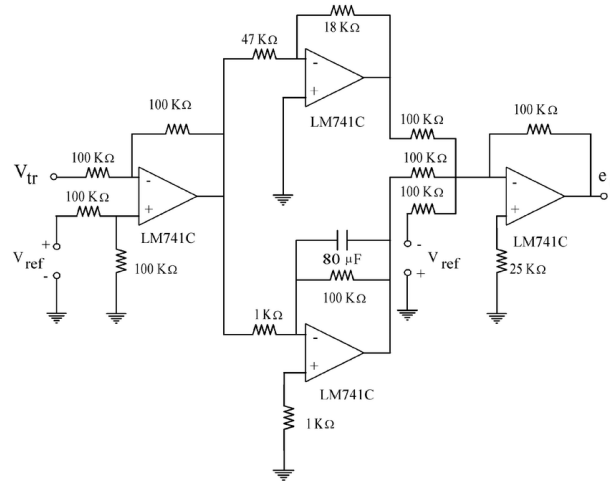


Fig.3 Circuit of PI control (Photo/Picture credit: Original)

Since phase reversal occurs during the amplification process, it is necessary to compensate for the phase reversal at the input front end. In addition, for the integral circuit, in practice, the presence of input detuning voltage and input bias current will result in a continuous current flow through the feedback capacitor, causing the voltage on the capacitor to increase or decrease cumulatively, eventually reaching the maximum output voltage. To avoid this phenomenon, a larger resistor is usually connected in parallel with the capacitor [3]. Finally, the proportional and integral controls are summed and output using an adder.

In many control systems, a feedback system is used to keep the system balanced after the PI control circuit. This article will not be discussed here.

2.2. Digital control PI algorithm

In comparison to a continuous-time PI controller, discrete-time closed-loop controller has a faster time reaction and rising time. Although we must assess the stability of any digital controller over a continuous time, we use the digital signals as an input to the computer after utilizing the z-transform to change the system into a digital control system [4].

We already know that the transfer equation is:

$$\frac{M(s)}{E(s)} = K_p \left[1 + \frac{1}{T_i s} \right] \tag{6}$$

In digital control systems, discrete signals are usually used for control. There are several methods for discretizing frequency domain transmissions.

This is the equation for Forward Euler:

$$C(z) = K_p + K_i T_s \frac{1}{z-1} \tag{7}$$

This is the equation for Backward Euler:

$$C(z) = K_p + K_i T_s \frac{z}{z-1} \tag{8}$$

This is the equation for Tustin/Trapezoidal:

$$C(z) = K_p + K_i T_s \frac{z+1}{z-1} \quad (9)$$

Let the sampling period be T , and use the backward difference method for the integral link to perform the Z-transform in the discrete domain, it could be

$$Z = \frac{Z-1}{TZ} \quad (10)$$

and the PI controller transfer function in Z domain is:

$$G_c(z) = K_p + K_i T_z \frac{z}{z-1} = \frac{(K_p + K_i T)z - K_p}{z-1} \quad (11)$$

Let $a = K_p + K_i T$, $b = K_p$, the equation (11) could be written as:

$$G_c(z) = \frac{az-b}{z-1} \quad (12)$$

Equation (12) can be used in the simulation of digital control to express the transfer function of the PI controller, and a sequence of zero-order retainers should be used to discretize the transfer function of the control object to produce the expression in the z-domain [5].

3. Simulation of PI Control Circuit

3.1. MATLAB model simulation

Designing a PI controller using the analog design method means determining the coefficients K_p and K_i . A common design approach is to first design the D(s) for analog PI control, and then derive the corresponding D(z) after the differential transformation live bilinear transformation [6]. Second, to ensure the integrity and executability of the system design, it is usually necessary to observe the overall zero and pole distributions after the design is completed and make minor adjustments to obtain the best results.

In general, the locations of the zeros and poles are determined according to the performance index requirements of the system, and then the controller parameters are determined in the order of proportional first and then proportional integral.

3.1.1 Software and parameter setting

In this paper, we use MATLAB to conduct simulation experiments on PI control systems. MATLAB can perform matrix operations, plot functions and data, implement algorithms, create user interfaces, and connect programs in other programming languages, etc. It is mainly used in the fields of engineering computing, control design, signal processing and communication, image processing, signal detection, etc.

Effective usage of their software is essential for the use of modeling and simulation approaches. Compared with other simulation software, MATLAB can use matrix and other tools instead of loops to improve the speed of simulation [7]. In addition, MATLAB also uses a variety of signal processing toolkits that can be easily utilized by simulation and test developers.

According to the transfer function of PI control, set the poles of the transfer function to 0, and change different values of the zero point to observe the effect of PI control system respectively. The simulation will analyze the system feedback from the perspective of zero-point pole as well as step response.

3.1.2 Modeling process

The transfer function of the PI control:

$$\frac{M(s)}{E(s)} = K_p + \frac{K_I}{s} \tag{13}$$

It is especially important to maintain system stability under a multitude of constraints. In a practical control system, it is often desired to obtain a stable control system through PI control. In the complex frequency domain, a closed-loop system is stable when the poles of the closed-loop transfer function are in the left half-plane of the S-plane [8]. Therefore, in the process of PI control system design, the location of the poles in the complex plane needs to be tested. In this simulation, it is assumed that the poles are located at the position of real axis -20 . In this simulation, different K_p parameters were set to observe the different performance of the PI control system which is shown in figure 4.

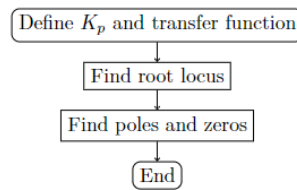


Fig.4 Root locus, poles, and zeros simulation in MATLAB (Photo/Picture credit: Original)

For closed-loop control systems, observing the zero and pole distributions of the system requires simulation in the closed transfer function.

$$z = \frac{PC}{1 + PC} \tag{14}$$

The step is shown in figure 5.

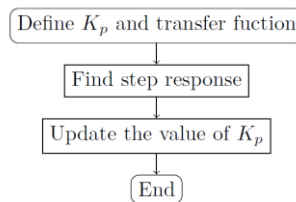


Fig.5 Step response simulation in MATLAB (Photo/Picture credit: Original)

By adapting the parameters of K_p , the different performance of the step response of the system is observed. Similarly, the step response of the system also needs to be simulated in the closed-loop transfer function.

3.1.3 Analysis of results

The simulation results of the zero-pole distribution for this PI control system are shown in figure 6 below.

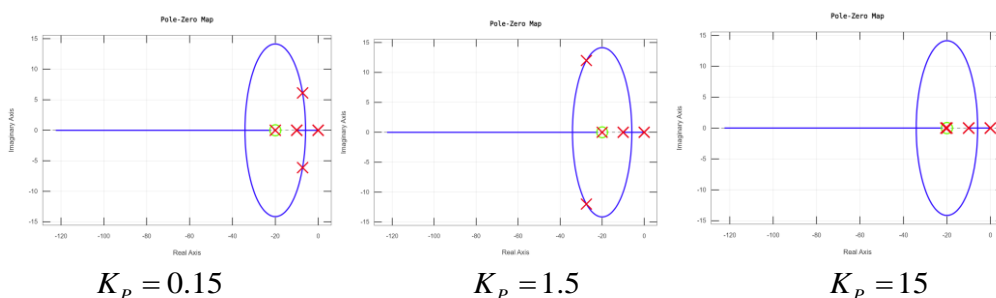


Fig.6 Root locus, poles, and zeros simulation results in MATLAB (Photo/Picture credit: Original)

It is demonstrated that the poles can be calculated in the discrete-time case by resolving a nonlinear recursion with time-varying coefficients. The poles can be determined in the continuous-time case by resolving a nonlinear differential equation with time-varying coefficients [9]. The green circle in the figure indicates the distribution of zero points, the red fork indicates the distribution of poles, and the blue line indicates the distribution of root trajectories. At the present given parameters, the system has five poles, with three real poles located at 0, -10 and -20, in addition to two conjugate poles. Since the transfer functions of this system are all real coefficient transfer functions, the poles are always on the real axis or show a conjugate distribution when the pole-zero plot is observed. The trajectory of the pole moves gradually closer to the position of -20 along the root trajectory diagram. In fact, the conjugate form is maintained throughout the movement of the pole and finally almost coincides with the pole where -20 is located. The step response of the PI control system is shown in the following figure 7.

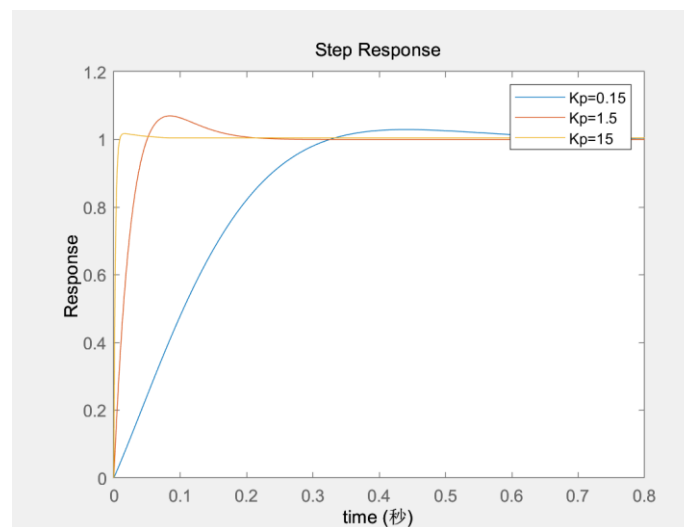


Fig.7 Step response simulation results in MATLAB (Photo/Picture credit: Original)

It is observed that different K_p values lead to different step response times of the system due to different integration units, and the response time of the system shortens as the K_p value rises. Although different K_p values were used in the simulation, they were all able to reach the standard value of the input after a long enough time.

4. Analysis of PI control in a Practical Scenario

PI control has an important role in industry and control. According to the needs of different fields need to test the effectiveness and stability of PI control systems, in addition to the need to design different PI controllers to meet the actual needs according to the use of scenarios and actual conditions.

4.1. PI control on permanent magnet synchronous motor

Improvement of the system dynamics is limited since the standard current PI controller in the permanent magnetic servo system is built using the zero-pole cancellation method [10]. In order to resolve the issue, the classic PI controller for current loop problem was first examined using the transfer function, and only then was the compound PI controller based on the state equation designed. It was made clear by comparing the transfer functions of the two systems that the compound PI controller is more effective at rejecting disturbances than the conventional one, and the matching constraint condition was provided [10].

Finally, step response and tracking sinusoidal reference experiments were demonstrated to demonstrate the viability of the suggested approach. The experiment's findings indicate that the system using a compound PI controller has the advantages of a smaller tracking error and a quicker

step response, which improves the system's tracking performance and disturbance rejection ability when using a compound PI controller and validates the effectiveness of the suggested approach.

4.2. PI control in the application of home inverter refrigerator temperature control

To find more appropriate control parameters, simulate the PI controller. Setting the ambient temperature as well as the control temperatures for the refrigerator and freezer compartments allows the refrigerator to track its internal temperature. The findings demonstrate that the controller has improved control level and accuracy, serving as a benchmark for PI control and simulation of gas-liquid two-phase flow temperature of home inverter refrigerators [11]. In this link need to judge the refrigerator (including freezer and refrigerator) temperature changes, compression speed changes and evaporator and condenser fan relative humidity comprehensive control of the compressor working speed.

It is noteworthy that a small oscillation in the refrigerator temperature occurred when the refrigerator reached the desired temperature. This oscillation occurred more significantly in the observation of the compressor speed. This is related to the inability of the PI controller to eliminate the integral effect, but the amplitude of the overshoot oscillation is very small and the control system quickly eliminates the oscillation effect and gradually converges to the desired temperature, which is important for the high precision of the refrigerator temperature [11]. This has an important role in the high precision control of the refrigerator temperature and the saving of electrical energy.

4.3. PI control in the application of temperature control in data centers

The aim of this study is to achieve the maintenance of target air inlet temperature of data center server racks by simulating PI control. Existing models have shown high effectiveness in predicting data center air temperature distribution, but complex methods require long computation time and make it difficult to control parameters in real time [12]. In addition, the lack of communication between inputs and outputs leads to delays in data acquisition and change execution.

Data is collected by using OSIsoft's PI system and regression and conditional statements are applied in MATLAB to generate a new optimal return air temperature setpoint [12]. The new setpoint was then written back to the PI system to override the building management system via MODBUS communication. The model developed in this study provides an effective benchmark for maintaining the target intake air temperature of the server rack using real-time control techniques. By simulating PI control, can achieve accurate control of data center temperature and improve data center performance and reliability.

5. Conclusion

Through actual simulations of the PI (Proportional-Integral) control system, this research uncovers the potential for achieving effective control of different performance aspects by adjusting specific control parameters. By harnessing simulation technology, engineers can attain more accurate and rapid control over the targeted system. In practical engineering applications, complex system structures are commonplace, and the implementation of PI control technology ensures the stable operation of each individual system, thereby enhancing overall system performance.

Looking towards future advancements, the integration of intelligent systems and intelligent control will enable PI control to efficiently carry out control tasks in engineering systems. With the incorporation of intelligent algorithms and adaptive mechanisms, PI control will become even more efficient, providing optimized control strategies to tackle challenges in complex industrial scenarios. This exciting progress will unlock new possibilities for engineering control systems, facilitating enhanced performance, improved productivity, and increased efficiency in diverse fields of application.

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