The Study on Temperature Control System Design Using the Improved PLC Technology

LANG Xue-dong
School of Life Sciences, Yunnan University, Kunming, Yunnan 650091, China.

Abstract
This paper proposed the PLC and PID based mix temperature control technology. It adopts PLC ladder figure programming language for programming, thus realizing the automatic control of temperature. The paper improves the quick-response, stability, reliability, control preciseness, providing to with realistic meaning to the industrial control.

Keywords: Temperature Control, PLC, PID, Ladder Figure Programming Language

1. Introduction
Temperature control applicative areas are very broad, which could be as large as industrial production, aerospace or as small as our daily life. Currently, most of the temperature control systems are using computer control technology with a microprocessor core, both improving the degree of automation of the device and the accuracy of the control. PLC enjoyed rapid development in the 1980s to the mid-1990s. In this period, the PLC has been greatly improved and the developed in terms of the ability to handle analog and digital computing, mathematic operation ability and the man-machine interface capabilities. PLC gradually entered the field of process control, and in some applications, it replaced the DCS system’s dominant position in the field of process control. PLC has versatile, easy-to-use features along with wide adaptability, high reliability, strong anti-jamming capability and simple programming [1].

PID control is by far the most common control method. Because of its high reliability, simplicity and algorithm robustness, it can be widely used in process control, especially for establishment of deterministic system of a precise mathematical model. PID control effect depends entirely on the four parameters [2][3], namely the sampling period $T_s$, the proportional coefficient $K_p$, integral coefficient $K_i$ and differential coefficient $K_d$. Thus, the PID parameter setting and optimization are two important topics of research in the field of automatic control. PID in industrial process control applications nearly has a hundred years of history, and during this period, despite the advent of many control algorithms, thanks to the long-term use of the PID algorithm and its own characteristics, coupled with people accumulating a wealth of experience it is widely used in industrial control. In PID algorithm, the key issues lies in the setting and optimization of the three parameters of the P, I, D[4][5].

With the continuous development of science and technology, people have increasingly high requirement for temperature control system, so temperature control system that is highly precise, intelligent and humane is the inevitable trend of development at home and abroad. The introduction, application, development and production of programmable controller begin along with the reform and opening up. Initially, extensive applications of PLC are applied in imported equipment. Next PLC is more widely applied in production equipment and products in a variety of enterprises. At present, China is able to produce small and medium-sized programmable controller. It can be expected that with the deepening of China's modernization process, the PLC in China will have a wider application future[6][7].

PLC technology’s application in temperature monitoring system analyzed and studied of the control system hardware, configuration, schematic design, programming, the establishment of the mathematical model of control object, control algorithm selection and parameter setting, the design of the human-machine interface and so on [8][9][10]. Based on the Mitsubishi FX series PLC controller, temperature sensor transfers the detected the actual oven temperature into voltage signals. Through analog input module it converts the digital signal to the PLC for PID regulation. The PID controller output is converted into high and low signal input control, controlling the zero trigger plate according to certain duty cycle conduction. It controlled energization time of both ends of thermal resistance wire,
achieving closed-loop temperature control.

2. Hardware Composite of PLC Control System

PLC is an industrial control computer, which uses programmable memory to store instructions and to execute logic, sequence, timing, counting, and calculus functions, and input and output via digital or analog, so as to control plant machinery or production processes.

With the rapid development of the microprocessor, computer and digital communication technologies, computer control has been widely used in all industrial fields. Modern society requires the industry to respond quickly to market demand and produce small-volume, multi-species, multi-standard, low-cost and high-quality products. The programmable controller is to respond to this need. Based on a microprocessor, it is a general industrial control device. Programming controller not only can realize logic control over a variety of pre-programmed programs, it also has advantages of being freely programmable, automatic diagnosis, versatility, small size and high reliability. Therefore, the programmable controller is to gradually replace the relay - contactor control system. The composition of the programmable controller includes: PLC CPU module, I / O modules, RAM, power supply module, backplane or rack.

1. CPU

The CPU is the core of the PLC. Its functions conferred by the system program of the PLC receives and stores the user programs and data and it collects state or data sent by on-site input devices in a scanning manner and stores them in a predetermined register. At the same time, diagnosis power source and the work state, PLC internal circuit and syntax error in programming process are also stored there. CPU mainly consists of the operator, controller, register and data links between them. A CPU unit also includes a peripheral chip, bus interface and related circuit. The RAM is mainly used for storing programs and data, which is a PLC indispensable constituent unit. CPU speed and memory capacity are important parameters of the PLC, and they determine the operating speed of the PLC, IO number and software capacity, thus limiting the control scale.

2. I/O Module

The interface of the PLC and the electrical circuit are completed through the portion of the input and output (I / O). I / O integrates modules of the PLC I / O circuits. Its input register reflects the state of the input signal and the output point reflects the output latch state. The input module converts the electric signal into a digital signal into the PLC system; output module is opposite. I / O is divided into a switch input (DI), the switching output (DO), analog input (AI), analog output (AO) module. Common I / O are classified as follows:

Switch: divided by voltage level, including 220VAC, 110VAC, 24VDC; divided by isolation way, including relay isolation and transistor isolation.

Analog: divided by the type of signal, including current-mode (4-20mA, 0-20mA), voltage type (0-10V, 0-5V, -10-10V), etc.; divided by precision, including 12bit, 14bit, 16bit. In addition to the above general IO, there exists special I / O module, such as thermal resistance, thermocouple, pulse module. Determine the number of module specifications according to I / O number. I / O module number can change, but the maximum number of basic configuration is managed by the CPU. In other words, it is limited by maximum floor or rack slot number.

3. Programming

The role of the programmer is to be used for program input, editing, debugging and monitoring. Programmers are generally divided into two types namely, the simple and smart type. Simple programming only works by online programming, and often needs to convert ladder figure into machine language mnemonics so as it could be input. However, smart programming (also known as graphics programmer) not only can realize connected programming, but also can conduct off-line programming. It is easy to operate and yet powerful.

4. Power Supply

PLC power supply is used to provide power supply for integrated circuit of each module for the PLC. At the same time, it also provides input circuit with 24V power supply. Type of power input includes: AC (220VAC 110VAC), DC power supply (24VDC).

Programmable controller's working principle:
PLC’s work pattern refers to cycling sequential scanning. Time spent on scanning each time is known as a scanning cycle or working cycle. Starting from the first step, CPU carries out user’s programs one by one until the user program is completed, and then it returns the first instruction to start a new round of scans. PLC repeats the above cycling scanning in such way.

Overall process of PLC work could be shown by the operational framework of figure 1.

3. **PLC Control System Hardware Design**

From the perspective of system design architecture and hardware design, the paper describes the design procedures of PLC controlling system, PLC hardware configurations, external design and parameters of circuit design and PLC controller setting.

In application design of PLC systems, PLC application system was first designed, namely, according to requirement of controlled object’s function and process, identifying system’s work to be done and required conditions. Then analyze functions of PLC application system, namely through the analysis of systems function, providing the PLC control system structural form, the type of control signal, volume, system sizing, layout. Finally according to conclusion based on the results of the system analysis, determine the specific configuration of model and system of the PLC. To design of PLC control system, one can follow these steps:

1. Familiarize with the controlled object, develop control programs, analyze the process and work characteristics of the controlled object, understand the cooperation of controlled object with machine, electricity, liquid to determine the control requirement of controlled object to the PLC control system.
2. Determine the I / O device according to the control requirements of the system, determine the user input (such as a button, trip switches, selector switches, etc.) and output devices (such as contactors, solenoid valves, signal lights, etc.) thereby determining the PLC I / O points.
3. Select PLC selection includes PLC type, capacity, I/O modules, power supply selection.

4. Assign PLC I/O address and generate the on-site needs according to equipment production, determine the control button, select models, specification and number of switches, contactors, solenoid valves, signal lights and various input and output devices; according to the selected model of PLC, list the input/output device and the PLC input output terminal control table, in order to draw the PLC external I/O wiring figure and to program.

5. Design software and hardware carry out PLC program design; conduct hardware design and on-site construction for control cabinet (table). As program and hardware design can be performed simultaneously, PLC control system design cycle can be greatly shortened and for the relay system, one must first design electrical control circuit before the construction design.

6. The online debugging. Online debugging refers to unified online adjustment for the program that passes through simulation debugging. PLC control system design steps could refer to Figure 2:

**Figure 2. PLC control system design steps**

### 3.2 PLC Model Selection and Hardware Configuration

The selection and configuration of the PLC can be divided into: programmer selection, switch I/O module selection, programming and external equipment selection and selection of communication functions.

#### 3.2.1 PLC Model Selection

The temperature control system adopts Japan Mitsubishi FX2N PLC. FX2N is a small programmable controller, applicable to all walks of life, various occasions in the detection, monitoring and control automation. FX2N Series with its powerful features is able to operate independently, or connected into a network to implement complex control functions. Thus, FX2N series boasts high performance and price ratio. FX2N series refers to small Mitsubishi PLC, which gives full play to its powerful distribution automation systems. The use coverage ranges from a simple alternative relay control to more complex automation control. FX Series refers to PLC unit type, containing the CPU, power supply and fixed input/output. The Q4AR series is a series of Quantum Hot Standby, and the maximum input and output points standing at 8192 points. A series PLC’s maximum input and output points are 2048 points. F series program controller’s maximum input and output points are 256 points.
3.2.2 Electric Heating Controller

The design of the electric heating controller is composed by a trigger circuit and a thyristor. SCR (also known as a thyristor) and its trigger control circuit are used for panel mounting power adjustment unit loaded with power. SCR that plays an important role in the electronic device has been widely used in various types of production sectors and is becoming an indispensible device for automated, efficient device. In the use of the SCR in latest temperature control has become increasingly popular.

The thyristor has two trigger modes, namely, phase-shift trigger and zero trigger. There is electrical contact between the common trigger circuit and the main circuit, which makes the common trigger circuit vulnerable to the impact of fluctuations of the grid voltage and power waveform distortion. Moreover, in order to solve the synchronization problem, the circuit is often further complicated. MOC3061 device produced by MOTOROLA provides good solution to these problems. The photoelectric triac silicon controlled drive of MOC3061 Series is a new kind of optocoupler device, which can be used to control the alternating high-voltage and high-current through direct low voltage and low current. The application of this device to trigger the thyristor boasts such advantages as low price, and simple yet reliable triggering circuit. Next we take MOC3061 to illustrate the working principles and applications this device. The internal structure and main performance parameters of MOC3061: the internal structure and pin configuration of MOC3061 are shown in Figure 3-4; it is capsulated in the way of dual-in-line 6-pin. The main performance parameters: reliable trigger current of $I_{th}$ 5-15mA; maintain $I_{th}$ 100μA; ultra-blocking voltage of 600V; repeated inrush current peak 1A; rated voltage for off-state at $dV/dt$ 100V/μs. The pin configuration of MOC3061 is shown in the following figure: pin 1 and 2 are input ends; pin 4 and 6 are output ends; pin 3 and 5 are suspended in the midair.

![Figure 3. Internal Structure of MOC3061](image)

The thyristor is the relative ideal exchange switch device at present. This design adopts a bidirectional thyristor (SCR) controlling. The control terminal of the PLC outputs a pulse width modulated signal to pin 2 of the conducting control signal terminal of MOC3061. The output terminal is connected to the SCR control electrode, which makes it possible to directly control the thyristor conduction time, thereby controlling the average power of heating. MOC3061 is a photoelectric coupler with zero trigger and it is used to prevent electrical interference, absorb peak interference signal etc. The parallel RC snubber circuit of SCR is vulnerable to sudden changes in the voltage across capacitor C and it can absorb reverse voltage spikes resulting from SCR turnoff. The control circuit can be shown as below:

![Figure 4. Driving and Controlling Circuit](image)

R1 in Figure 2 stands for the current-limiting resistor. Let the input current of the LED be 15mA (MOC3061) R1, then we can calculate in accordance with following formula:
\[ R1 = \frac{(V_{CC} - V_F)}{I_{FT}} \]

Wherein: \( V_F \) is the forward voltage of infrared light-emitting diode and it can take values from 1.2V to 1.4V; \( I_{FT} \) is the trigger current of infrared emitting diode. If the working temperature is below 25°C, the value of \( I_{FT} \) should be appropriately increased. R2 is the triac gate resistor. In the case of relative high SCR sensitivity, the gate resistance is also high. The paralleling of R2 can improve the interference resistance. R3 is the current-limiting resistor of trigger power triac thyristor, the value of which is decided by the voltage spike of alternating grid as well as the allowed repeated current spike of output terminal of the trigger.

### 3.3 Overall System Design Scheme and Electrical Wiring Figure

The controlled object of this system is 1KW electric heating pipe and the control parameter is the heating temperature. The analog output of PLC controls the output of the power regulator; the electric heating controller controls the on and off of the electric heating pipe. The controlled object of PLC is the single-phase heating pipe and the controlled parameter of PLC is the heating temperature. The temperature is determined by the temperature detection module. Then the detected temperature will be transformed into analog quantity of 4 ~ 20mA and then be send to the analog input channel of PLC. In light of the given value and the comparison between \( dF \) and the detected temperature value, the PLC analog output channel will send control signals to the thyristor power regulator so as to achieve the purpose of controlling the temperature. The basic structure of the temperature control system consists of a heating wire, temperature detection module, PLC master system, trigger modules, and thyristor. PLC is the core part of temperature control. The temperature signal of the electric heating wire acquired by the detection module will be processed by signal collecting circuit and A/D and then the analog voltage signal will be converted to digital. Then PLC will process the given temperature and the temperature detected by the system. Through the zero trigger module, it controls the energization time of the heating resistor wire, achieving closed-loop control of temperature. The overall design of the system is as follows:

![Figure 5. PLC control system flowchart](image)

System hardware wiring is shown as:

![Figure 6. PLC external equipment wiring](image)
3.4 PLC Controller Design

3.4.1 Parameter Setting of PID Control

PID controller consists of proportion unit (P), integral unit (I), differential unit (D). Its mathematic expression formula is as follows:

\[
  u(t) = K_c e(t) + \frac{1}{Ti} \int_0^t e(t) \, dt + T_d \frac{d e(t)}{dt}
\]

(1) Impact of proportion coefficient \( K_c \) on system performance:
Increase the proportion coefficient to make the action of the system become sensitive, faster and steady-state error reduced. \( K_c \) is relatively large with increasing number of oscillations and longer adjustment time. If \( K_c \) is too large, the system will tend to be unstable. If \( K_c \) is too small, the system will, in turn, suffer from slow movements. \( K_c \) can choose negative, mainly thanks to the feature that implementing agency and sensors center on controlling the object. If the symbol of \( K_c \) selects inappropriate state of the object (pv value). If such situation occurs, sympol of \( K_c \) should be selected reversely.

(2) Impact of Integral Control \( Ti \) on System Performance:
Integral action undermines the system’s stability. Small \( Ti \) (strong integral action) will lead to unstable system. But it could remove the stable state error and improves the control accuracy of the system.

(3) Impact of Differential Control \( Td \) on System Performance:
Differential action could improve the dynamic features. When \( Td \) becomes relatively large, it has large overshoot and short adjustment time. When \( Td \) becomes relatively small, it also has large overshoot but long adjustment time. Only \( Td \) is proper which could reduce overshoot and adjustment time.

The PID integration software of FX2N Series uses positional PID control algorithm and PID control algorithm discrete cycle uses the following formula:

\[
  u(k) = K_p e(k) + K_i \sum_{i=0}^{k} e(i) + K_d [e(k) - e(k-1)]
\]

Hence, we could get the incremental formula after common conversion:

\[
  \Delta MV = K \{( EV_n - EV_{n-1} + \frac{T}{Ti} EV_n + D_n)\}
\]

Wherein: \( EV_n = \pm (PV_{nf} - SV) \)

\[
  D_n = \frac{Td}{T + \alpha_d Td} \{\mp u(-2PV_{nf} - PV_{nf} + PV_{nf} - 2)\} + \frac{\alpha_d Td}{T + \alpha_d Td} D_{n-1}
\]

\[
  PV_{nf} = PV_n + L (PV_{nf} - PV_n)
\]

PID operation output \( MV_n \):

\[
  MV_n = \sum \Delta MV
\]

Sampling time \( Ts \) is included in the PLC scan cycle; if \( Ts \) is less than the scan cycle, the PID operation errors occur, and execute PID operation regarding \( Ts \) equal to the scan cycle. If this is the case, one should use the PID instruction when timer is interrupted. Input current value could turn filter constant ease and smooth and the differential gain could buffer the dramatic change of output value. In order to make the PID control obtain good result, one needs to obtain the optimum of three constants of
PID, namely $K_p$, $T_1$, $T_0$. The commonly used method refers to the unit step change method.

Because the system is a temperature control system and the temperature has inertia link of delay characteristics, the sampling time is determined in accordance with the design requirements. The present system is sampled 3s. After the above analysis, the temperature control system has been basically decided. Before the system is put into operation, parameter setting has to be done for the controller. The setting can be grouped into two categories, the theoretical calculations setting method and engineer setting method.

Theoretical calculation setting method is based on known mathematical model of the controlled object. According to the selected quality indicators, theoretical calculations (differential equations, and root locus, frequency method, etc.), obtain the optimal setting parameters. Such methods are relatively complex, with heavy workload. In addition, the object mathematic model obtained by using the analysis method or experimental measurement method can only reflect the approximate dynamic features of the process. The setting accuracy result is not very high, and therefore it is not widely in engineering projects.

Through PID control, continuously adjust the heating time of the heater so as to realize the constant temperature control. When the data in the control parameter settings or PID operation has an error, the operation error flag auxiliary relay M8067 turns ON state. With Y0 output, the fault indicator displays.

Below is the law of the action of the electric heater:

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In the feedback control of the software program, the design mainly adopts PID control algorithm. As premature introduction of integral action causes over-saturation, producing excessive overshoot, integral separation PID control algorithm should be applied in order to overcome this disadvantage. While maintaining the role of the integrator, it will also reduce the overshoot, so as to improve the control performance. When the deviation is large, conducts no integration. Only when deviation is less than a predetermined threshold $\xi$, it will carry out integral.

This will not only prevent large amount of control during the large deviation, but also avoid the phenomenon of over-integration. In PLC control system, PID controls instructions to realize the system. Continuous time signal that enters the PLC must turn to digital amount after sampling and the quantization, so they would enter the storage and register. However, in operation and processing in the PLC, either integral or differential, use difference quotient to replace differential quotient to turn the differential equation that describes the continuous PID algorithm to the difference quotient equation that describes the discrete time PID algorithm.

PID subroutine flowchart is shown in Figure 5-2. According to the comparison between the actual value of the detected temperature and the set temperature, obtain the corresponding temperature deviation value $E$; according to comparative judgment of the $E$ and $\xi$, adopt PID algorithm or PD algorithm. Subsequently, carry out algorithm processing, obtaining the control value. PID control identifies the movement direction according to specific instruction unit to execute operation.

The design of system model is one-step inertia lag link and the transmission function is $G(S) = K \cdot e^{-\tau} / TS + 1$.

Decompose $G(S) = G_{\cdot}(S) \cdot G_{+}(S)$

$G_{\cdot}(S) = e^{-\tau}$, $G_{+}(S) = \frac{K}{TS + 1}$ could obtain the PID control parameter:
\[ K_C = \frac{T_1}{K(\alpha + \tau)}, \quad T_1 = T_p + \frac{\tau^2}{2(\alpha + \tau)}, \quad T_D = \frac{\tau^2}{2(\alpha + \tau)} \left( 1 - \frac{\tau}{3T_1} \right) \]

When implementing one-order change signal, record the changing curve. Then, according to the curve, obtain the heat furnace feature parameter. Adopt step change response method to measure value of parameters \( K_p, T_1, T_d \) according to Koen-Kuhn setting formula. The figure below shows the unit step change response of the controlled object.

![Figure 10. Unit step change response of controlled object](image)

4. Conclusion

In the temperature control system, it applies time-sharing call to mobilize the PID operation procedures set in the PLC, realizing PID control algorithm’s mobilization, simplifying procedures, improving programming efficiency and reducing errors. Thus it achieves the purpose of precise temperature control; at the same time, PID operation result decides generation of PWM wave pulse width. It uses timer to generate PWM wave and uses switch to replace analog output, realizing multiple outputs of the PWM and allowing the system to reduce control cost. Practice has proved that the system has fast dynamic response, high control accuracy and strong robustness.

5 References