Cascade Control Systems

BY OMAR AHMAD ALQAHTANI

Abstract— Cascade control is one of the control systems that improve the performance of industrial processes in the event of a disturbance. Which enhances access to high quality products. This paper deals with cascade control system, its field of use, how to choose the appropriate control effects for the secondary controller, methods for tuning these controllers, and how to protect the control system from reset windup.

Index Terms— Industrial controllers, Process Loop, PID controllers, Cascade Control, Controller Mode, Tuning, Reset Windup.

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1 INTRODUCTION

The theory of modern automatic control is one of the most important theories used in the management of technological and production processes. Modern industry is characterized by the steady increase in the productivity of machines and units, as well as the rise in the quality of products and their low cost, as it needs complete safety to avoid any undesirable conditions. The high speeds in production processes and the high requirements for the accuracy of maintaining them have led to the widespread use of automatic control systems Where the automatic control system maintains some of the variable characteristics of the controlled quantities at a certain level or changes them according to a known law without human participation, by means of different types of technical equipment. Control systems are divided into two main systems, Open loop control system, can be defined as a system that affects a specific control process by means of an external control signal (input command) so that the controlled quantity can be expected according to specific physical laws. Therefore, the external factors can make the value of the controlled quantity change or deviate from the required.

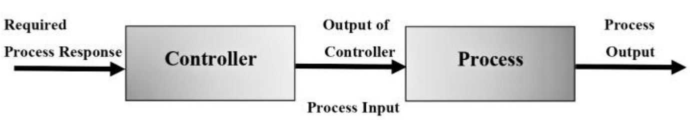

Fig1: Open control system

the closed-loop control system, can be defined as a system characterized by comparing the desert value with the actual value of the controlled quantity, using feedback and comparison element to compare the actual value with the desired value and gives an appropriate output signal that is the difference between the two values and this output is an error or deviation. This error is affected by one of the control effects and produces an output, that affects the final control element until the actual quantity equals the desired value.

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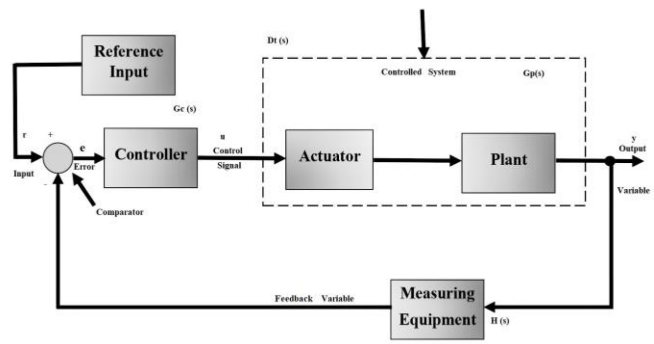

Fig2: Closed control system

1.1 Control variables used in control processes

The important control variables using in control systems are mentioned as following:

- Desired value: It is the value that the operator sets for any process so that the controller works on its basis by not allowing the measured variable to deviate from it.
- The controlled value is the measured or controlled quantity of a process.
- The manipulated variable: is the output of the controller applied to the controlled process.
- The error value: is the difference between the desired value and the measured value.
- Disturbance: is an unwanted signal that affects the value of the controlled quantity and may interfere with the process by combination or through an intermediate point.
- Offset: is the difference between the desired value and the control point at the steady state and it is sometimes called the static error.
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1.2 The main equipment of automatic control system

Any control system consists of controlled process, measurement system, comparator and the controller, the final control element and they are all connected to each other by communication lines.

- The controlled process is the system or process to be controlled, such as the boiler, heating furnace, oil refining units, and water desalination units.
- The measurement system is the basic system for any control system when following the central monitoring system, and it consists of a sense element, a primary measurement kit and a transmitter, a secondary

measurement kit such as a recorder or an indicator. The sensor element and the transmitter are the main elements in the automatic control system and are dedicated to measuring various physical quantities such as pressure, temperature, flow, humidity and other physical quantities.

- The Comparator and controller: the comparator element is mostly part of the controller, the controller receives the measured signal and the desired value set by the operator and compares them by the comparator unit and produces the deflection signal (error signal) which is amplified and affected by the appropriate control effects and then comes out of the controller and affects the final control element (control valve).
- Final control element: It is the element responsible for bringing about the required change in the process to maintain the controlled quantity according to the desired value set by the actuator such as (control valve - motor - cylinder........etc.) and the final control elements are divided according to the type of power into electrical, pneumatic and hydraulic components. The desired requirements are summarized from these elements:
- the power of the actuator must ensure that the controlled member moves at the required speed in all cases.
- The translational or angular displacement of the actuator at the output must correspond to the corresponding displacement of the moving member.
- The characteristics of the actuator must be directly proportional to the input signal.
- The ratio of the kinetic energy of the moving parts to the power of the actuator should be as small as possible.

1.3 Industrial controllers

The controller is the heart of the automatic control system and its main function is to receive the signal of the controlled variable (the output of the technological process or the output of the controlling element) and then compare it with the desired value through the comparison element, which is often found inside the controller and is considered a part of it. The difference between them appears on the output of the comparison element and is called an error. The controller is the part that interacts with the error signal and produces an output proportional to this error or a function in it (proportional, integral, differential…. etc.) and the controller's output signal is the effective force that determines the final position of the control element. The controller contains several control elements and circuits. These elements differ from one product to another according to the design in force, but most organizations contain several main elements, the most important of which are the receiver unit, the comparison unit, the indicator and generator of the control function, and several multifunctional amplifiers. Industrial controllers can be divided into two types: The first is the discontinuous control controllers, such as the two-mode controllers and the three-mode controllers. The second is the controllers with continuous control and depends on the method of calculating the deviation value by the comparator, processing it and then sending it to the final control.

1.3.1 two position controllers (on - off)

The output of the two-mode controller depends on the deviation signal (- or +) and not on the deflection value. The controlled variable (measured) is not fixed at a specific value but oscillates between two values. If the measured variable falls in the region between the two values, there is no change in the controller output. If the measured value exceeds the maximum value, an output decreases the measured value and vice versa.

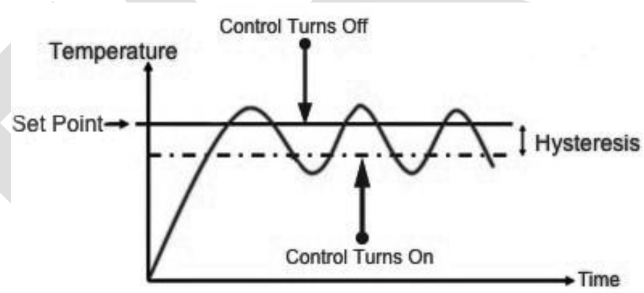

Fig3: two position controllers

The two-position controller is used to control temperatures, oil tanks, water tanks, and in coolants, i.e. the processes that allow this fluctuation.

1.3.2 three – position step controllers

This type of controller is used if the final control element needs three states to operate: "turn left", "turn right" or "stand" such as electric actuators or valves with electric actuators, this controller can produce all the effects it produces continuous controller.

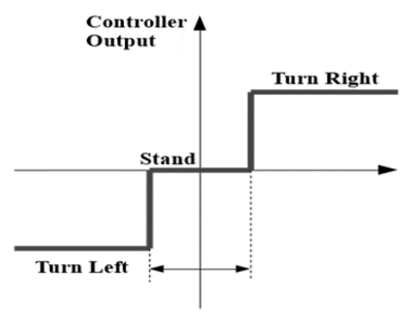

Fig4: three – position step controllers

1.3.3 continuous controllers

In these controllers, the controlled variable is constantly affected by the processed variable (controller output). The controller can be set, so that it gives a fixed output value, so that the controlled variable remains equal to the desired value (setpoint). The controller output changes only if there is a disturbance or change in the value of the deviation (error), No significant changes occur in the value of the controlled variable, which makes the price of these controllers expensive.

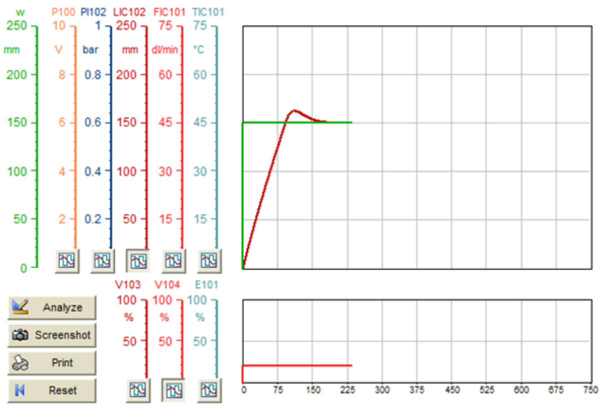

Fig5: continuous controllers

2. Cascade Control System

Cascade control is one of the feedback control systems. in general, it uses for slow processes that are controlled by a relatively fast process. it is effective against disturbances that have a measurable effect, cascading control improves control performance if a disturbance occurs. In this system more than one measurement is used, but only one variable is controlled.
For example, controlling the level of a tank is by controlling the flow. The flow rate and level need to be measured and only the level is controlled. as shown below.

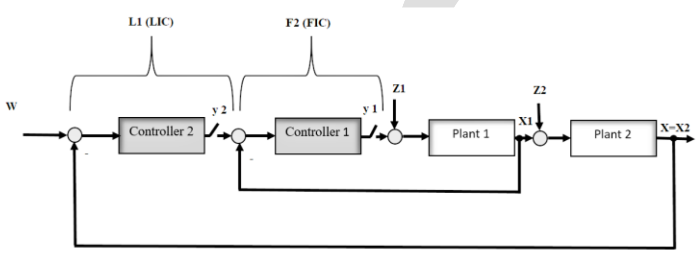

Fig6: cascade control system

There are two control processes, the main is controlling the tank level (plant 2) by controller 2 and the secondary process is controlling the flow of liquid (plant 1) by controller 1. The secondary process, which is the internal process (flow control), is at least three times faster than the external process (level control), and its desired value is the controller output of the main process (y2). disturbance (z1) is corrected immediately, unlike disturbance (z2), which takes time to correct. The flowmeter must also be fast and accurate. cascade control is characterized by improved operating efficiency and disturbance cancellation or reduction. The disadvantages of cascade control are its increased complexity, additional measuring device and control unit and material cost. cascade control does not have the ability to improve the performance of operations that can be controlled, such as fluid levels and gas pressures, or those that do not require stabilization of their value at specific and accurate values, such as averaging level control.

2.1 Controller Modes for Cascade Control Systems.

In a cascade control system, the master controller has the same function as the controller in the simple control system, which is to keep the value of the controlled value equal to the desired value. Therefore, the criteria for selecting controller modes in the main controller is the same as in the single-controller control system. On the other hand, the function of the secondary control system is not the same as the function of the main control and therefore requires other rules. The secondary controller responds as quickly as possible to the change in the desired value with the smallest overshoot and decay ratio and this change is sent to the output of the controller at the maximum speed and is enlarged if possible. The secondary controller output manipulates the final control element and speeds up the response of the main controller output. Therefore, the secondary controller must have a proportional mode and must have a proportional gain of 1.0 or greater within the limits of stability, giving a large and adequate change in the output of the main controller and thus a better response than a single- controller feedback system. The use of the integration and differential effect depends on the type of process we are controlling. It is known that adding the integration effect reduces the proportional gain and adding the differential effect increases the proportional gain. Thus, it can be said that the best for all secondary process is the proportional differential controller, but not in all cases. The integration effect is not required in the secondary process to cancel the bias. It is canceled by the integration effect in the main controller, which sets the desired value of the secondary controller to compensate for the bias. It is a rule in force that the differential effect cannot be used in the main and secondary loop at the same time. It is also a rule, not to use the differential effect in the secondary controller, because tuning six variables in the controllers is a difficult process, as well as not using the differential effect twice in the same loop. To avoid the previous reasons, the following rules can be followed, the first rule, we make the differential time a quarter of the integration time in both controllers and thus only four variables are calculated. two preparational gain and two integral time. The second rule, the differential effect on the secondary controller affects the process variable rather than the error. So, it is not in series with the differential effect on the main controller. The differential effect of the secondary controller is intended to compensate delay of measuring instrument or dead time and allows for a large gain with an overshoot and low decay ratio. When the inner loop is fast and controllable, the secondary controller does not need a differential effect.

2.2 Tuning cascade control system

Tuning of controller in cascading control systems must be carried out from the inner loop to the outer loop and so on. As shown in Figure 6. Each inner loop is set to be more accurate and faster than the outer loop, otherwise the desired value of the inner loop will change more than the controlled value, making the outer loop poorly controlled. Ideally, the value of the secondary variable should quickly follow the desired value whenever possible with low overshoot and oscillation. The best way to set the inner loop is a minimum IAE response for setpoint is suitable for slave loop. After adjusting the inner loop, the outer loop follows any of the controller tuning methods such as quarter-decay ratio response, minimum error integrals or feedback control algorithms. We will study some internal loop processes, for example, such as flow, temperature and pressure. The figure below shows a cascade control system for level by slave flow loop.

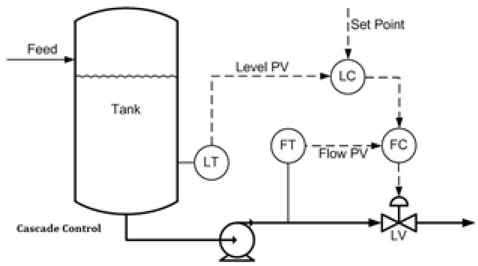

Fig7: cascade control for level tank

The flow signal transmitter compensates for the change in pressure drop across the control valve and absorbs any non-linear performance of the valve. Taking the square root of the pressure difference, the flow and the output of the main controller vary linearly with the flow. The integration proportional controller is used with an integration time equal to the time constant of the valve and a gain greater than one. Increased gain helps to overcome hysteresis or dead band. The figure below shows a cascade control system for temperature by slave temperature loop.

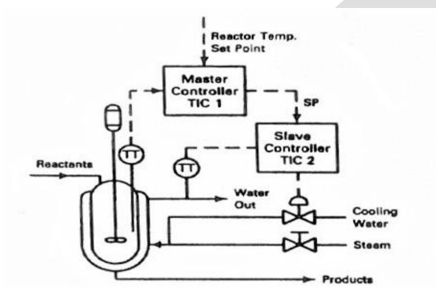

Fig8: cascade control for temperature reactor

There are two difficulties using temperature as a slave measured variable, the response delay of the measuring element and the possibility of a reset windup and they can be dealt with as follows, the delay of the response of the measurement element is compensated by using the differential effect in the secondary controller. The differential time is equal to the sensor time constant and the differential effect affects only the measured variable and does not affect the error signal. To prevent the use of the differential effect respectively in the inner and outer circuit. The figure below shows a cascade control system for temperature by slave pressure loop.

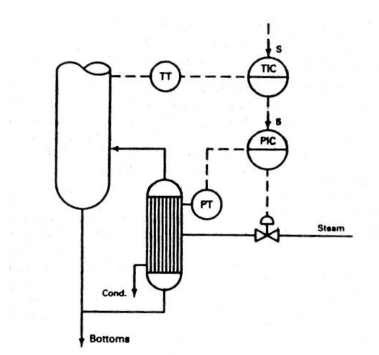

Fig9: cascade control for boiler temperature

The pressure is quick, reliable and easy to measure. The figure above shows the cascade control system for controlling the temperature of a boiler by controlling the pressure of the reboiler. The pressure in the reboiler determines the rate of heat transfer because it controls the temperature of the condensed steam as well as the difference in temperature during the heat transfer area. Compression also has difficulty windup. Also, the pressure can change and go out of the range of the pressure gauge and thus be out of control. If the production rate is low and the boiler temperature is less than one hundred degrees Celsius, the pressure in the steam chest is less than the atmospheric pressure and is outside the measuring range of the pressure gauge unless the pressure gauge is designed to measure positive pressure and negative pressure.in Computer cascade control, When cascade control is carried out in the computer, the inner loop runs at a higher frequency than the outer loop, so the secondary controller responds to the desired value from the main controller before the next change from the main controller arrives. An important consideration in digital feedback algorithms is to consider switching from manual to automatic control, which causes some disturbance. To make a smooth transition to automatic in most cases, the output of the main controller is initialized to measure the variable of the secondary controller when it is switched to automatic.

2.3 Reset windup in cascade control systems

The problem of the reset windup or saturation of the controller output is one of the problems of tuning the controller. But it cannot be overcome by adjusting the controller, but the phenomena of this problem must be dealt with to be able to solve it. tuning of the controller is appropriate if the output of the controller is within the range that allows the change of the controlled variable. If we lose the effect of the output of the controller on the controlled variable, this problem arises. The difference between the controller's output range and the operating range of the control valve is the main cause of the reset windup problem and appears as a large overshoot of the controlled variable. This problem occurs during start-up and shutdown, as well as when a major disturbance occurs during operation. In the cascade control of the jacketed reactor process shown in Fig8. Starting with both controllers in manual operation condition, the cold water valve is closed and the steam valve is manually opened until the temperature reaches the operating temperature we assume it is 55 ºC, the measuring range of the jacket thermometer is from 0 to 120 ºC and condensation The steam is at 110 ºC, which is the value at which the steam valve is closed and the cascade control system is transferred to the automatic control mode. To prevent overshoot, before reaching the temperature of 50 ºC, the main controller output is primed to measure the temperature of the secondary controller which is 110 ºC. At this point the jacket temperature starts to drop and the reactor is at 50 ºC. Meanwhile, the reactor temperature increases slowly due to the reactor temperature. In the period between the temperature 50 ºC to 55 ºC, the control follows the following, the secondary regulator monitors the temperature of the jacket before reaching the desired value of 110 ºC and instructs the cold-water valve to remain closed.

The main controller monitors the temperature below the desired value 55 ºC and gives a command to increase the desired value of the jacket temperature above 110 ºC degrees. Most of the computer control programs determine the output of the secondary controller when it is closed and prevent the main controller from increasing its output and prevent the request to close the cold-water valve when it is already closed and this logic prevents the cascade control system from winding up. Note the gap between the desired value of the secondary controller which freezes at 110 ºC and the measured temperature of the secondary controller. When the reactor temperature exceeds the desired value 55 ºC, the main controller starts to reduce the desired value of the secondary controller to reduce the temperature. However, the cooling valve does not open until the desired value of the secondary controller is less than the measured value, until the gab is overcome. The desired value of the secondary controller changes at a rate controlled by the integration effect of the main controller, which takes a long time to open the coolant valve and overshoots the reactor temperature. These are reset windup phenomena. One of the solutions to this problem is to reformat the output of the main controller to measure the temperature of the jacket if the output of the secondary controller is clamped. And the second solution, using the reset feedback signal in control algorithms, the feedback signal is the measured value of the secondary controller and is expressed as a percentage of the measuring device range. It is used to calculate the output of the main controller (M) by the speed algorithm.

$$M = B + \Delta M$$

where (B) is the reset feedback signal and, in this case, the measured value of the secondary controller, ΔM is the increment in the output of the main controller which is calculated by the speed algorithm. By Using this equation, the desired value of the secondary controller is updated for each treatment of the main controller and thus the possibility of the windup problem disappears, the main controller will be called when any increase or decrease in the measured value of the secondary regulator from its current value and not from the previous desired value. Using the reset feedback approach requires that the secondary loop be processed at a higher frequency than the primary and that the secondary controller has an integration effect. In contrast, any bias in the secondary controller causes a bias in the main controller, especially if the main controller has an integration effect. The third Solution, specify a limit to the desired value of the secondary controller that is consistent with the actual operating limits. In the case of the jacket reactor example these limits are the cold-water temperature and the desired value for the reactor. However, these limits change with normal operation, and are worrisome to have a constant change to keep up with normal operating conditions.

3. Conclusion

1- cascade control is effective against disturbances that have a measurable effect.
2- cascade control uses more than one measurement, but only one variable is controlled, and therefore it is effective and economical in the computer control system as it needs an additional measurement transmitter only.
3- This type of control is valid if the secondary process is at least three times faster than the main process.
4- The disturbance in the secondary loop is corrected immediately, unlike the disturbance in the main loop takes time to be corrected.
5- The successive control does not have the ability to improve the performance of operations that can be controlled, such as the level of liquids and gas pressures, or those that do not require their value to be fixed at specific and accurate values, such as averaging level control.
6- The criteria for selecting controller modes in the main control system are the same as in the control system with a single controller, in contrast to the secondary control system, which requires other rules.
7- tuning controllers in successive control systems must be carried out from the inner loop to the outer loop. The best way to tune the inner loop is a minimum IAE response for a setpoint. The outer loop follows any method for tuning controller such as quarter-decay ratio response, minimum error integrals or feedback control algorithms.
8- When the flow is slave loop, we use the proportional integration controller with an integration time equal to the time constant of the valve and a gain greater than one. Increased gain helps to overcome hysteresis or dead band.
9- When the temperature is slave loop, there are two difficulties, the delay of the response of the measuring element and the possibility of a reset windup, and they can be dealt with, using the differential effect in the secondary controller. The differential effect affects only the measured variable and does not affect the error signal.
10- When the pressure is slave loop, the pressure also has difficulty in windup. Also, the pressure can change and go out of the range of the pressure gauge and thus be out of control.
11- The difference between the controller output range and the operating range of the control valve is considered the main cause of the reset windup problem and appears in the form of a large overshoot of the

controlled variable. This problem occurs during start-up and shutdown, as well as when a major disturbance occurs during operation.

12- Addressing the problem of reset windup by resetting the output of the main controller to measure the internal loop temperature if the secondary controller is clamped. Or by using the reset feedback signal in control algorithms or by setting a limit to the desired value of the secondary controller that is compatible with the actual operating limits.

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