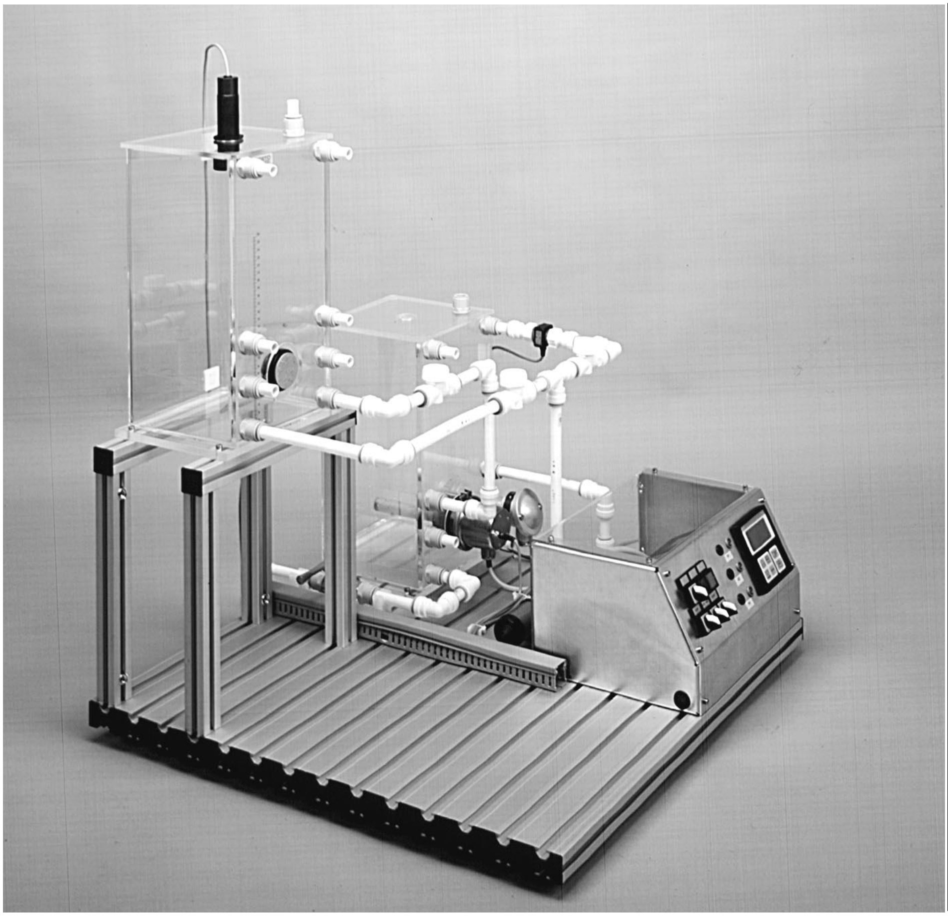
Learning System for Automation and Communications

Process Control System

Control of temperature, flow
and filling level

Workbook



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Authors: H. Bischoff*, D. Hofmann*, E. v. Terzi
Editor: F. Ebel

* Technische Universität Dresden
Institut für Automatisierungstechnik
D-01062 Dresden

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Preface

The Festo Didactic Learning System for Automation and Communications is designed to meet various training needs and professional requirements and consists of the following training packages:

- Basic packages provide basic knowledge covering a wide range of technologies.
- Technology packages deal with the important topics of open and closed loop control technology.
- Function packages explain the basic function of automated systems.
- Application packages facilitate vocational and further training in line with industrial practice.

The authors have produced this book in order to present to you the main training contents relating to the automation of continuous processes in a practice-related form intended for vocational and further training. To this end, the extensive experience available at Festo Didactic and at the Department of Automation Technology at the Dresden University of Technology has been gathered and combined in the form of this workbook.

The authors, Dr. Eng. H. Bischoff and Dr. Eng. D. Hofmann, both hold posts at the Department of Automation Technology at the Dresden University of Technology and are responsible for student training in the areas of project designing of automation systems, comprehensive practical training in process automation and the design of closed control loops and binary control systems.

The authors feel that this workbook will provide a meaningful contribution towards application-related vocational and further training, and hope that those who have studied the book will have gained some useful knowledge.

All readers are invited to contribute with tips, criticisms and suggestions for the further improvement of this book.

July 1997 The authors

Layout of the workbook

The workbook is made up as follows:

Section A – Course

Section B – Fundamentals

Section C – Solutions

Section D – Appendix

Section A – Course is designed to teach project design and closed control loop synthesis with the help of practical exercises.

Section B – Fundamentals contains general technical knowledge as an addition to the training contents of the practical exercises in Section A. It provides an explanation of the essential technical terminology and establishes the theoretical correlations with the help of examples.

Section C – Solutions represents the results of the practical exercises and provides brief explanations.

Section D – Appendix contains the software for the ProVis process visualisation.

Notes regarding safety and procedure

Notes regarding safety

The following advice should be followed in the interest of your own safety:

General

Trainees must not work on the station unless supervised by a qualified instructor.

- Please observe the specifications given in the data sheets for the individual components, and in particular all advice regarding safety!

Electrics

- Electrical connections are to be wired up or disconnected only when power is disconnected!
- The heater is operated using 230 V AC. Please observe the current safety regulations during commissioning!
(DIN VDE 0113 [EN 60204])

Mechanics

- Mount all components on the plate.
- The maximum operating temperature of the containers of + 65 °C must not be exceeded.
- Do not operate the heater, unless the heating element is fully immersed in the fluid.

Notes regarding procedure

- Prior to commissioning of the system, check all electrical connections and piping.
- Do not fill the containers with contaminated fluids as this may block the proportional valve and damage the pump seals.

Part A

Exercises and Worksheets

Title

Overview of project design process

Introduction and motivation

Those carrying out project design work on automation systems should be skilled and have a comprehensive, general knowledge of at least the main elements.

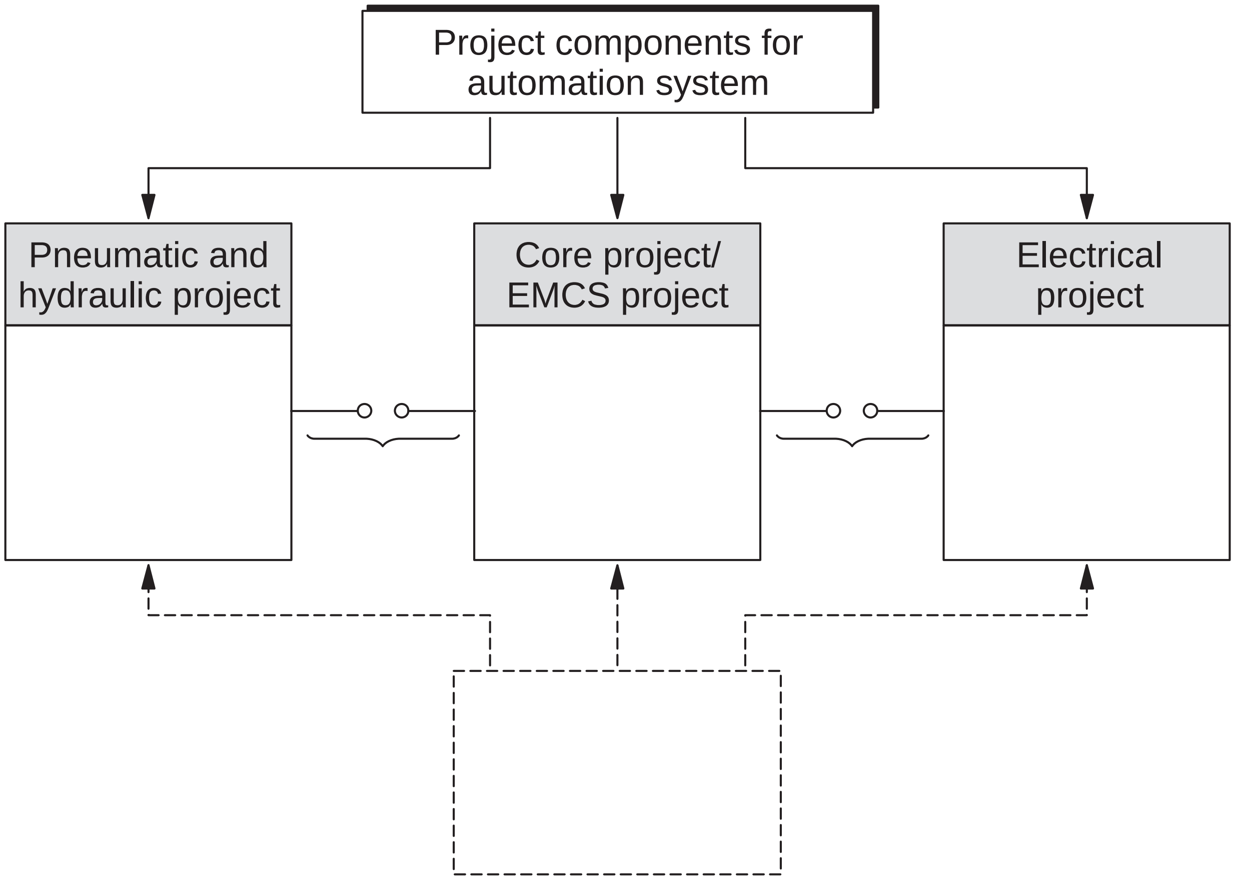
Part exercise 1-1

Name (in brief) the key areas involved in core project design!

- ______________________________
- ______________________________
- ______________________________
- ______________________________
- ______________________________
- ______________________________

Part exercise 1-2

Explain in principle, the procedure for the linking of the core, electrical and pneumatic projects.



Title

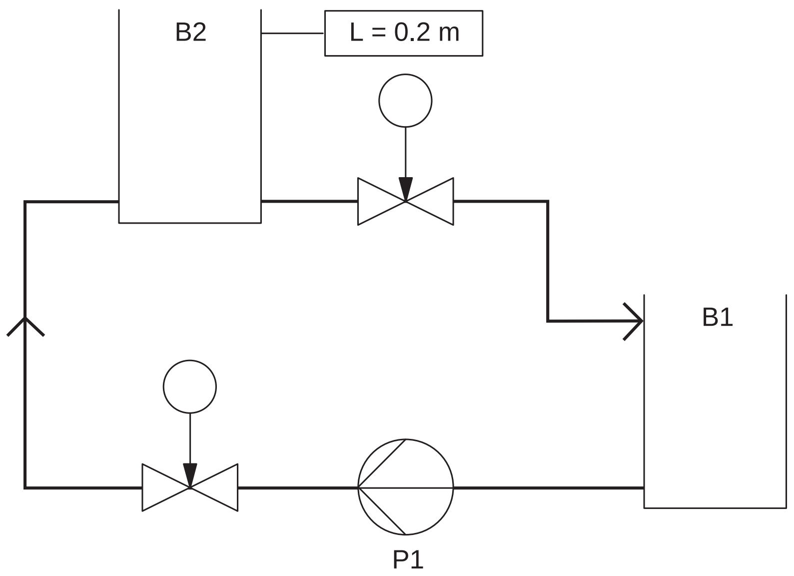
Core project design – Fundamental methodology for the project design of automation systems

Introduction and motivation

One important part exercise of the project design work is the development of the piping and installation (PI) flow diagram. As a rule, this is based on a process flow diagram, also taking into consideration any relevant comments.

Part exercise 2-1

Draft the PI flow diagram for the specified process flow diagram (Requirements: Control of filling level in container 2 [B2]; monitoring of filling levels in containers B2 and B1).

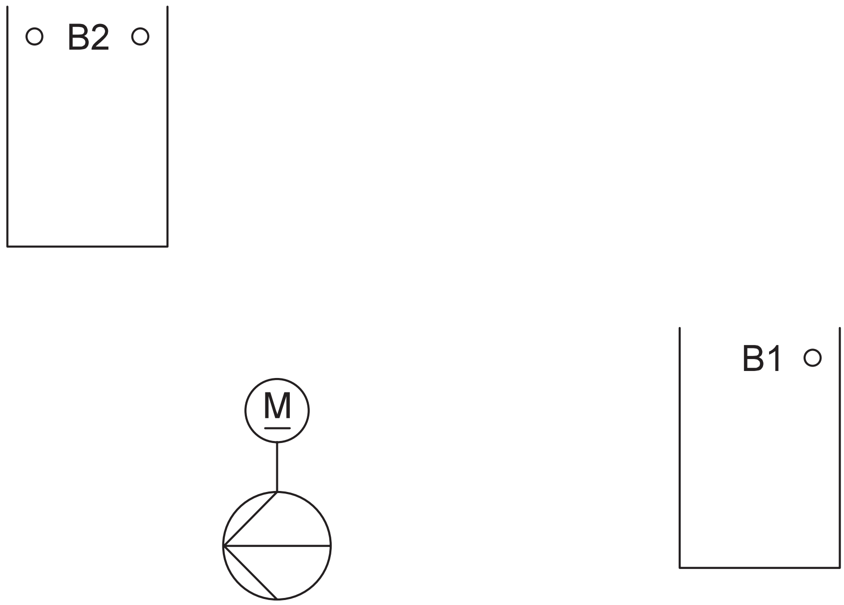


Filling level control – Process flow diagram

A2 – 2

Exercise 2

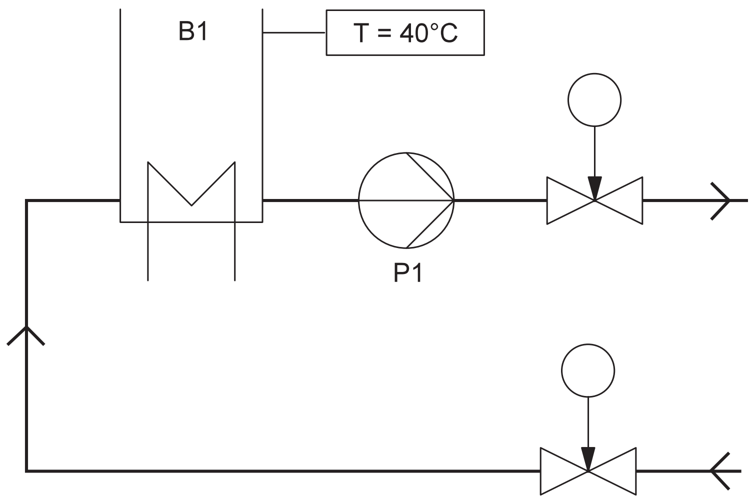
Complete the PI flow diagram.



Filling level control system – PI flow diagram

Part exercise 2-2

Draft the PI flow diagram for the specified process flow diagram (Requirements: Control of temperature in container B1; monitoring of filling level and temperature in container B1).



Temperature control system – Process flow diagram

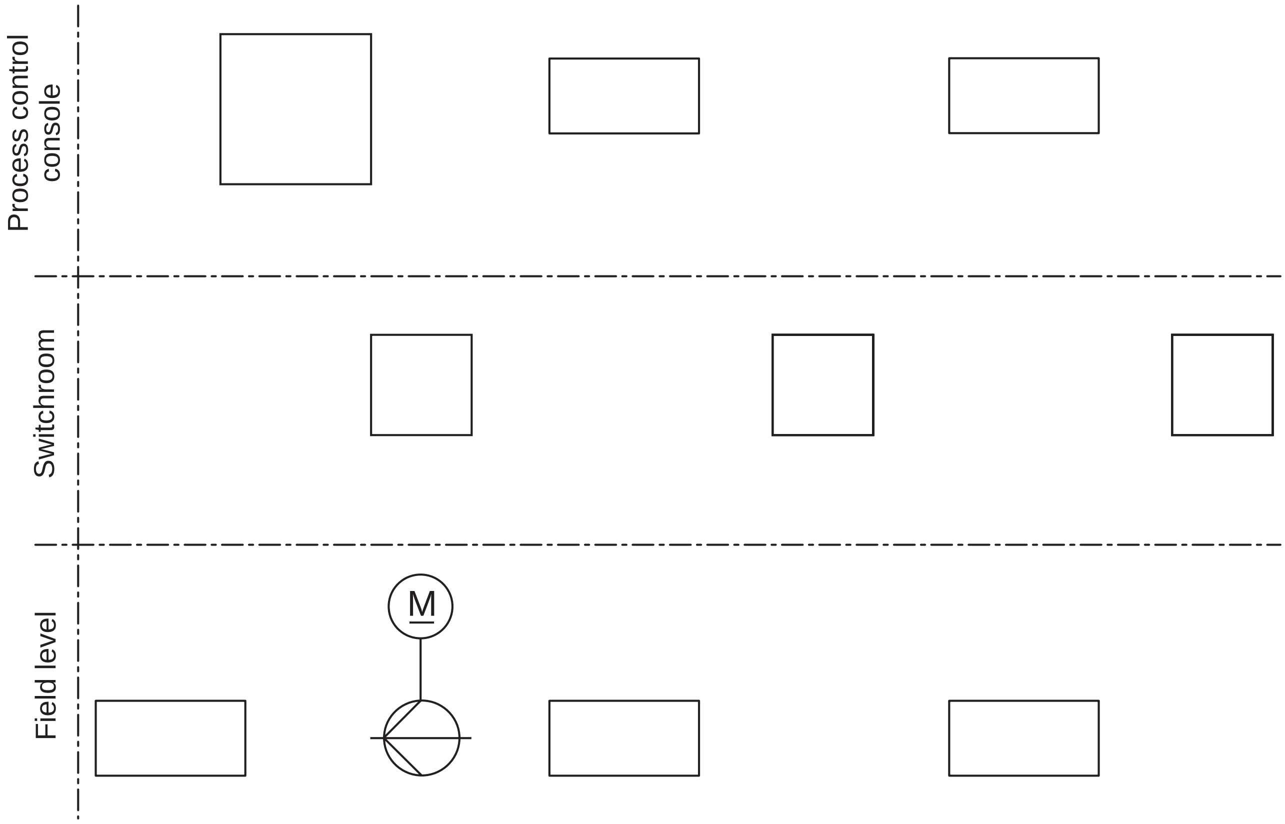
Complete the PI flow diagram.

Temperature control system – PI flow diagram

Part exercise 2-3

Draft the preliminary EMCS (Electronic Measuring Control System) block diagrams for the EMCS points of the PI flow diagram created in part exercise 2-1 (see solution, part exercise 2-1).

Complete the preliminary EMCS block diagrams.

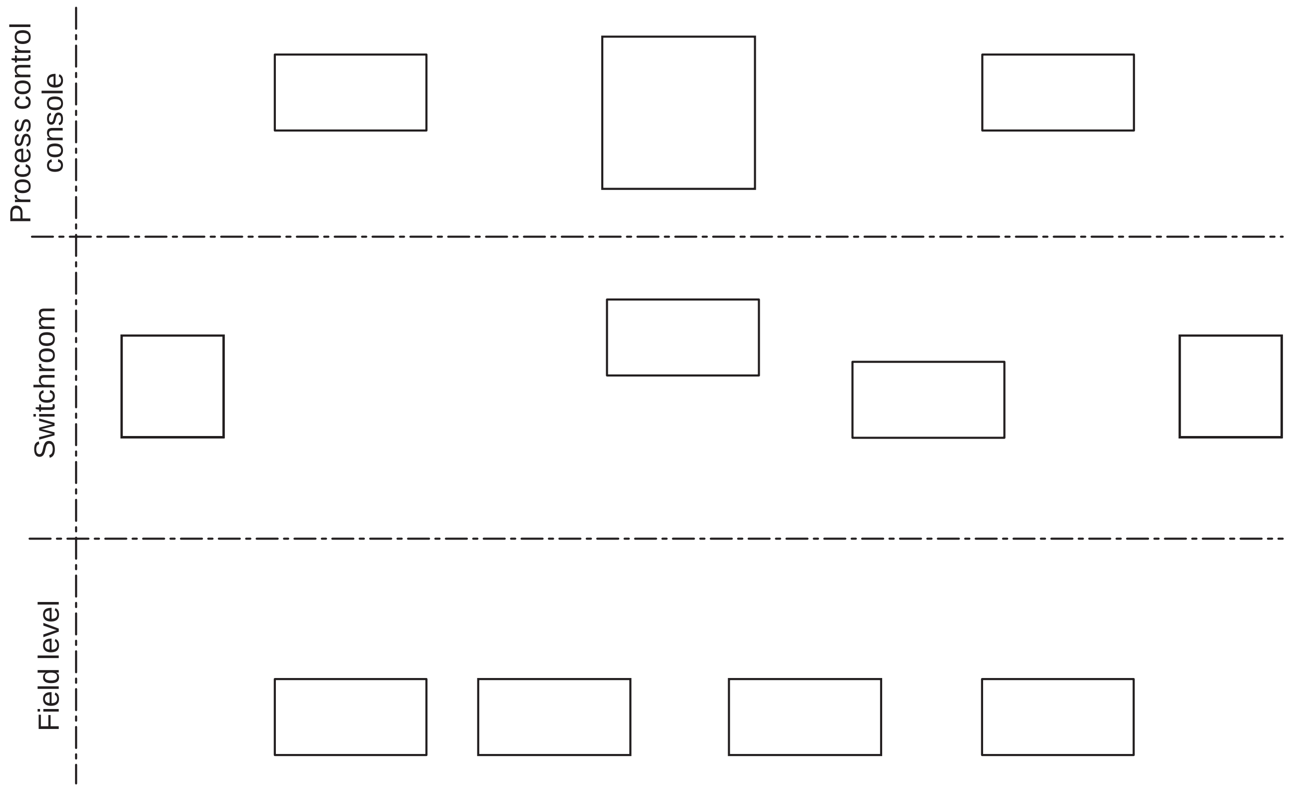


Filling evel control system – EMCS block diagram – in draft form

Part exercise 2-4

Draft the preliminary EMCS block diagrams for the EMCS points of the PI flow diagram created in part exercise 2-2 (see solution, part exercise 2-2).

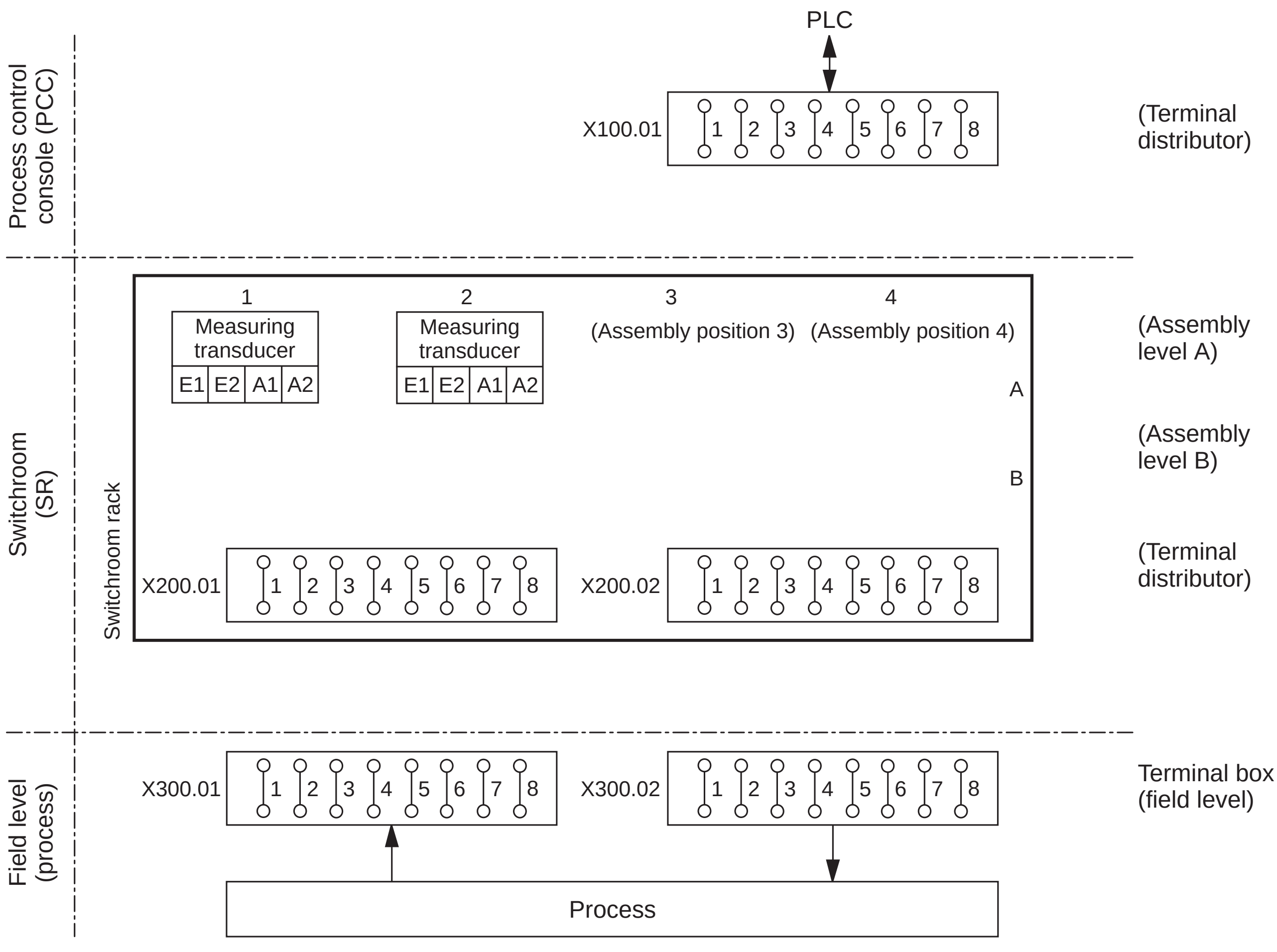
Complete the preliminary EMCS block diagram.



Temperature control system – EMCS block diagram – in draft form

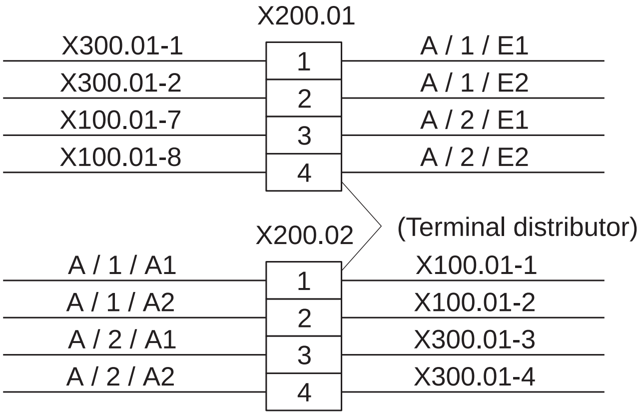
Part exercise 2-5

With the help of the project configuration (process control console, switchroom and field level), draw up two examples of wiring (e. g. simple allocation of the switchroom terminal distributors X200.01 and X200.02), whereby the terminal boxes/field level (X300, ...), the assembly levels A and B (switchroom rack) and the terminal distributor X100.01 (process control console) are to be used as additional components.



Wiring routing (Part 1) – Project configuration

Wiring routing (Part 2) – Terminal distributor allocation



Title

Closed control loop synthesis and design of binary control systems

Introduction and motivation

The objective of the practical exercise is the commissioning of a filling level control loop, i.e. the main points to be addressed by the student are

- Investigation of experimental areas,
- Establishing of static behaviour of the controlled system,
- Determining the dynamic behaviour of the controlled system,
- Controller configuration and parameterisation and
- Controller test

Part exercise 3-1

- Investigate the method of operation of the filling level control loop (closed control loop in manual operation, type of action of sensors and actuators).
- Develop a strategy for computer-aided measured-value acquisition.
- Determine the static characteristic curve of the ultrasonic sensor, i.e. the correlation between filling level and the respective current or voltage signal.
  Note: Record a sufficient number of interpolation points.

Part exercise 3-2

- Determine the static behaviour of the filling level control system. Note: Record the corresponding controlled variable for each correcting variable in the steady-state condition.
- Represent the results in a diagram in the form of a static characteristic.
- Evaluate the static characteristics determined (e. g. linear/non-linear) and compare the results with those determined in the theoretical process analysis.
- Define the operating point for the dynamic analysis (identification) of the controlled system.

Part exercise 3-3

- Determine the dynamic behaviour of the control system (identification) for the selected operating point.
  Note: Carry out step-change experiments around the selected operating point; observe the form of static characteristic curve to define the step change height. Also, try to record the correcting variable in parallel with the controlled variable.
- Determine the characteristic values (proportional coefficient, time delay, transient time) of the controlled system, using the inflectional tangent method.
  Note: If necessary, also establish an average of the measured values. Use a sampling interval of 0.2 to 0.5 s for the data acquisition.

Part exercise 3-4

- Determine a favourable controller configuration for the controlled system behaviour.
- Parameterise the controller according to the Chien, Hrones and Reswick method.
- Set the controller parameters on the compact controller (Bürkert controller).
  Note: Please note that with the Bürkert compact industrial controller Type 1110, the scale range also enters into the proportional coefficient K_R.

Part exercise 3-5

- Examine the control characteristics of the closed control loop around the operating point (triggering of setpoint step-change).
- Evaluate the results obtained according to the following criteria:
  - How are the dynamics of the correcting variable to be evaluated?
  - Does the controlled variable achieve the new setpoint value after a finite time?
  - Is it necessary to correct the set controller parameter?

Title

Process protection measures

Introduction and motivation

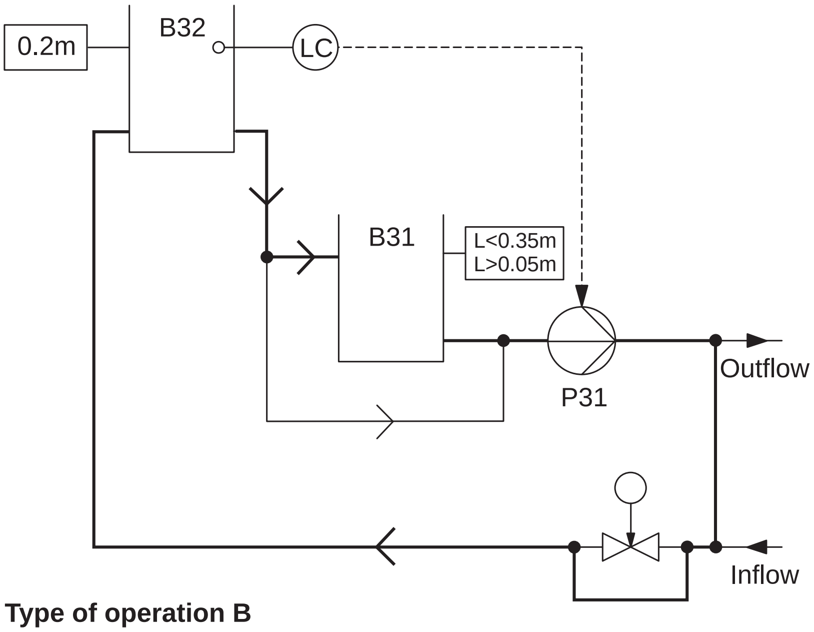
One important task of project design work is the definition ("establishing") of the necessary EMCS (Electronic Measuring Control System) points. To do this, the extent and functional requirement of the EMCS points are to be determined on the basis of a specified process flow diagram and corresponding exercise definitions.

This task can only be accomplished on the basis of experience (heuristics) and must therefore be sufficiently evolved using suitable examples.

Part exercise 4-1

Draft the PI flow diagram for the process flow diagram provided (fig. 4-1 Flow method A / Flow method B), integrating the EMCS functions for control, monitoring, structure variation and process protection into the process flow diagram in an adequate form.

Type of operation A



Type of operation B

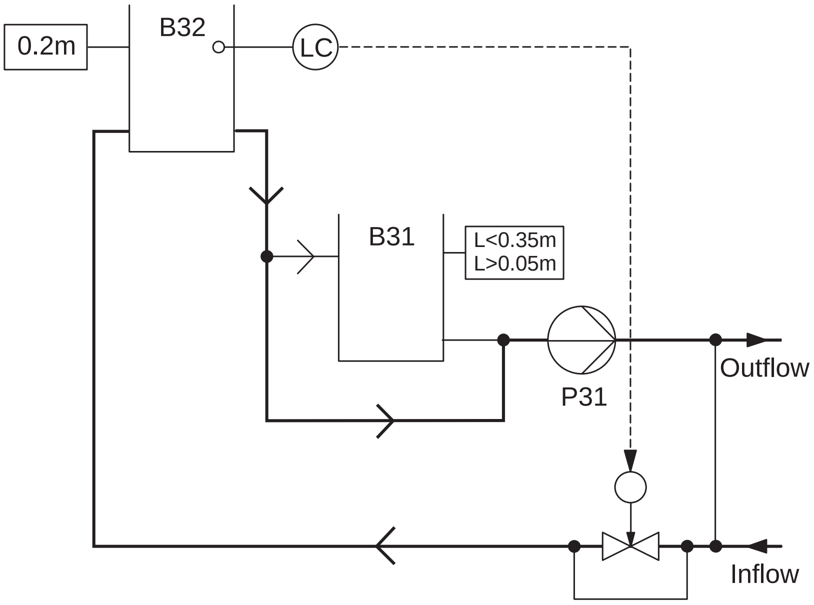


Fig. 4-1:
Process flow diagram for filling level control

Complete the PI flow diagram.

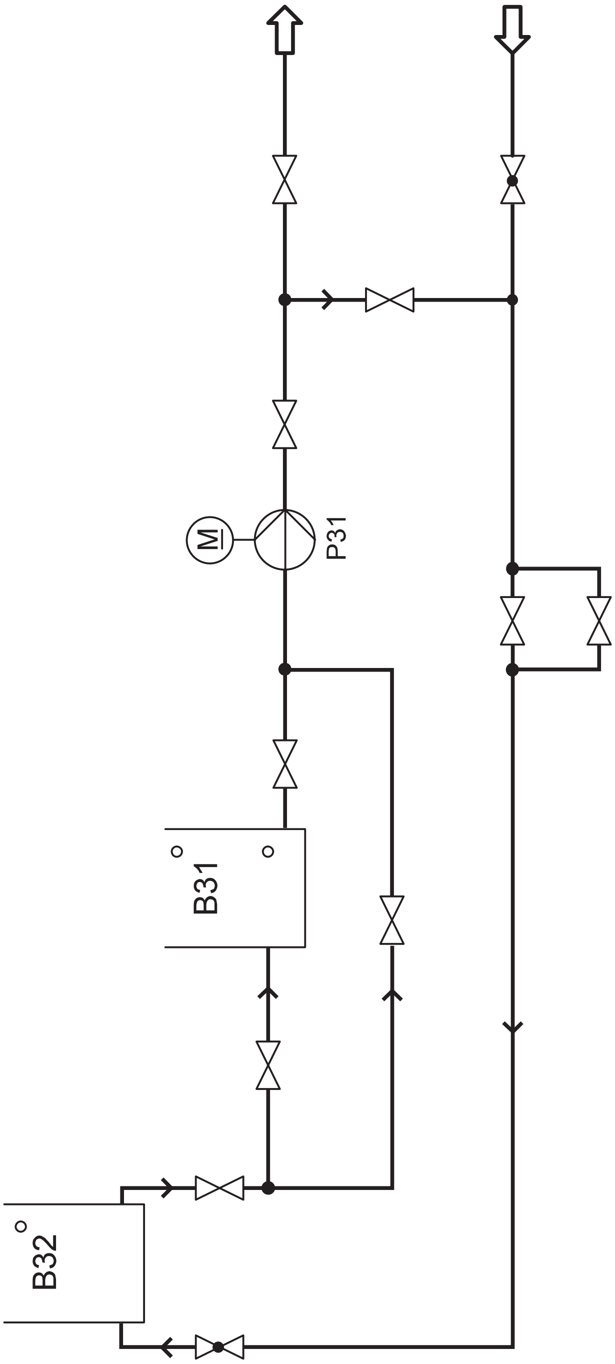


Fig. 4-2:
PI flow diagram for filling level control (Open and closed loop control and process protection)

Part exercise 4-2

Compile the EMCS points drawn up in part exercise 4-1 in a table (EMCS points table), providing an explanation of the function of the individual EMCS points.

EMCS point	**Function**	**Closed loop control**	**Open loop control**	**Process protection**

Table: For functioning of EMCS points of PI flow diagram – Filling level control

Title

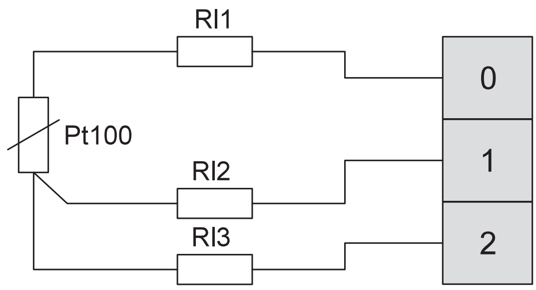
Connection of Pt100 temperature sensors

Introduction and motivation

Pt100 temperature sensors are widely used in many parts of a system and can be connected in a variety of different ways.

Part exercise 5-1

- Determine the effects of the supply lines using 3-wire connection



– if Rl1 = Rl2 = Rl3, or
– with different Rl's.

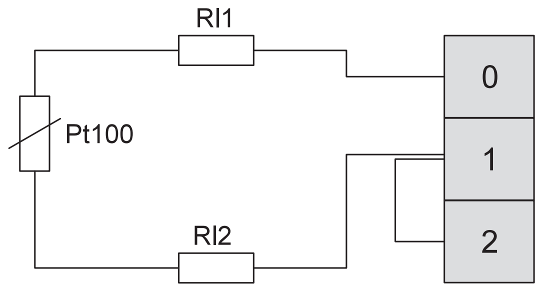
	Rl1= Rl2= Rl3 with short supply line	Rl1= Rl2= Rl3 with long supply line	Rl1 increased	Rl2 increased	Rl3 increased
Temperature displayed	°C	°C	°C	°C	°C

- Discuss the result.

Note
Conduct the measurements in quick succession at a constant water temperature.

Part exercise 5-2

- Determine the effects of the supply lines using two-wire connection.



– if Rl1 = Rl2, or
– with different Rl's.

	Rl1= Rl2 with short supply line	Rl1= Rl2 with long supply line	Rl1 increased	Rl2 increased
Temperature displayed	°C	°C	°C	°C

- Discuss the result.

Note
Conduct the measurements in quick succession at a constant water temperature.

Title

Closed loop control technology

Introduction and motivation

Technical controllers are component parts of automation systems, whose main task is that of process stabilisation. Different methods are used in practice to set the control parameters.

Exercise 6

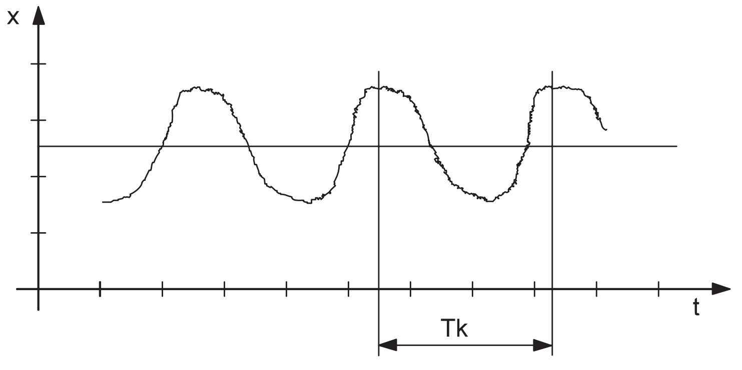
- Setting of control parameters to Ziegler/Nichols
  - Determine the operating point:
    Set the controller to 'Manual' and determine the possible control range by means of changing the correcting variable. Select the operating point so that the controller has sufficient "reserve" in both modulation directions, (e. g. in the centre of the control range).

Correcting variable	Actual value
Y = 0%	X1 =
Y = 100%	X2 =

Selected operating point (X1 + X2) / 2:

W =

  - Configure the controller as a P controller: To do this, set T_n at the highest possible value (9999.) and T_v at 0.
  - Determine the critical amplification K_r (stability limit, closed control loop is in the process of carrying out continuous oscillation), by analysing small setpoint step-changes around the operating point after each newly set amplification. This determines the critical amplification factor K_{KR} and the period of oscillation T_k of this continuous oscillation.



Kp	closed control loop oscillates	closed control loop does not oscillate
10	Lower Kp	Increase Kp

– Note:
The flow and filling level control systems have been selected in such a way that the oscillating process can be observed without any auxiliary equipment (just eyes and ears).

Controlled system parameter	
K_{KR}	
T_K	

– The control parameters K_p, T_n, and T_v are determined according to controller type with the help of the table.

Controller type	K_p	Tn	T_v
P	0.5 K_{KR}	–	–
PI	0.4 K_{KR}	0.85 • T_n	–
PID	0.6 K_{KR}	0.50 • T_K	0,12 • T_K

Selected parameters:

Controller type	K_p	Tn	T_v
P			
PI			
PID			

- Verify the determined control parameter of a PI controller by carrying out a setpoint step-change from approx. 20 % to 60 % of the modulation range.
- What is the closed control loop behaviour if you increase (e. g. double) T_n?
- What is the closed control loop behaviour if you increase the amplification (e. g. by 30 %)?
- In addition, also carry out the setpoint step-changes.

Part B

Fundamentals

Chapter 1 Fundamentals of closed-loop control technology

Chapter 2 Projecting of automated systems

Chapter 1

Fundamentals of closed-loop control technology

This chapter outlines the differences between closed-loop and open-loop control and gives an introduction to closed-loop control technology. The control loop is explained, enabling you to carry out the following:

Recognize closed-loop control systems

- Analyze a control loop
- Understand the interaction of the individual systems
- Set a controller
- Evaluate control response

1.1 What is closed-loop control technology?

Variables such as pressure, temperature or flow-rate often have to be set on large machines or systems. This setting should not change when faults occur. Such tasks are undertaken by a closed-loop controller.

Control engineering deals with all problems that occur in this connection.

The controlled variable is first measured and an electrical signal is created to allow an independent closed-loop controller to control the variable.

The measured value in the controller must then be compared with the desired value or the desired-value curve. The result of this comparison determines any action that needs to be taken.

Finally a suitable location must be found in the system where the controlled variable can be influenced (for example the actuator of a heating system). This requires knowledge of how the system behaves.

Closed-loop control technology attempts to be generic – that is, to be applicable to various technologies. Most text books describe this with the aid of higher mathematics. This chapter describes the fundamentals of closed-loop control technology with minimum use of mathematics.

Reference variable

In closed-loop control the task is to keep the controlled variable at the desired value or to follow the desired-value curve. This desired value is known as the reference variable.

Controlled variable

This problem occurs in many systems and machines in various technologies. The variable that is subject to control is called the controlled variable. Examples of controlled variables are:

Pressure in a pneumatic accumulator

- Pressure of a hydraulic press
- Temperature in a galvanizing bath
- Flow-rate of coolant in a heat exchanger
- Concentration of a chemical in a mixing vessel
- Feed speed of a machine tool with electrical drive

Manipulated variable

The controlled variable in any system can be influenced. This influence allows the controlled variable to be changed to match the reference variable (desired value). The variable influenced in this way is called the manipulated variable. Examples of manipulated variable are:

Position of the venting control valve of a air reservoir

- Position of a pneumatic pressure-control valve
- Voltage applied to the electrical heater of a galvanizing bath
- Position of the control valve in the coolant feed line
- Position of a valve in a chemical feed line
- Voltage on the armature of a DC motor

Controlled system

There are complex relationships between the manipulated variable and the controlled variable. These relationships result from the physical interdependence of the two variables. The part of the control that describes the physical processes is called the controlled system.

1.2 What is a system?

System

The controlled system has an input variable and an output variable. Its response is described in terms of dependence of the output variable on the input variable. These responses between one or several variables can normally be described using mathematical equations based on physical laws. Such physical relationships can be determined by experimentation.

Controlled systems are shown as a block with the appropriate input and output variables (see Fig. B1-1).

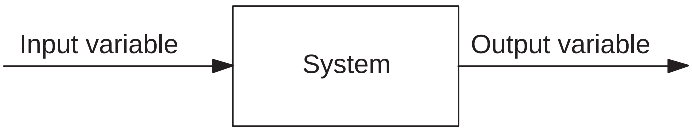


Fig. B1-1: Block diagram of a controlled system

Example

A water bath is to be maintained at a constant temperature. The water bath is heated by a helical pipe through which steam flows. The flow rate of steam can be set by means of a control valve. Here the control system consists of positioning of the control valve and the temperature of the water bath. This result in a controlled system with the input variable "temperature of water bath" and the output variable "position of control valve" (see Fig. B1-2).

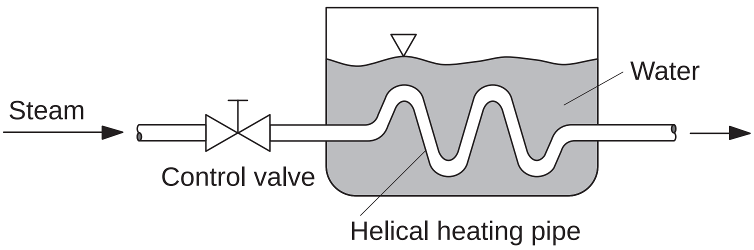


Fig. B1-2: Water bath controlled system

The following sequences take place within the controlled system:

The position of the control valve affects the flow rate of steam through the helical pipe.

- The steam flow-rate determines the amount of heat passed to the water bath.
- The temperature of the bath increases if the heat input is greater than the heat loss and drops if the heat input is less than the heat loss.
- These sequences give the relationship between the input and output variables.

Advantage of creating a system

The advantage of creating a system with input and output variables and representing the system as a block is that this representation separates the problem from the specific equipment used and allows a generic view. You will soon see that all sorts of controlled systems demonstrate the same response and can therefore be treated in the same way.

Section B 1.4 contains more information on the behaviour of controlled systems and their description.

1.3 Open-loop and closed-loop control

Having defined the term "controlled system" it only remains to give definitions of closed-loop control as contained in standards. First it is useful to fully understand the difference between open-loop control and closed-loop control.

Open-loop control

German standard DIN 19 226 defines open-loop control as a process taking place in a system where by one or more variables in the form of input variables exert influence on other variables in the form of output variables by reason of the laws which characterize the system.

The distinguishing feature of open-loop control is the open nature of its action, that is, the output variable does not have any influence on the input variable.

Example
Volumetric flow is set by adjusting a control valve. At constant applied pressure, the volumetric flow is directly influenced by the position of the control valve. This relationship between control valve setting and volumetric flow can be determined either by means of physical equation or by experiment. This results in the definition of a system consisting of the "valve" with the output variable "volumetric flow" and the input variable "control valve setting" (see Fig. B1.3).

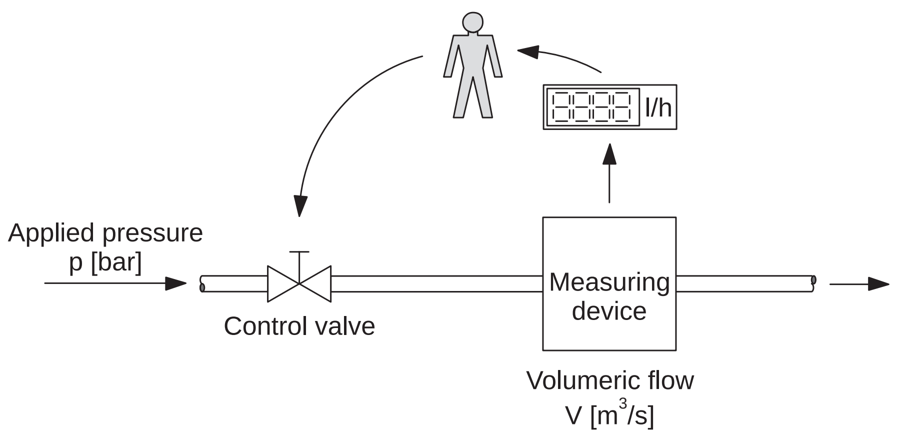


Fig B1-3: Open-loop control of volumetric flow setting

This system can be controlled by adjusting the control valve. This allows the desired volumetric flow to be set.

However, if the applied pressure fluctuates, the volumetric flow will also fluctuate. In this open system, adjustment must be made manually. If this adjustment is to take place automatically, the system must have closed-loop control.

Closed-loop control

DIN 19 226 defines closed-loop control as a process where the controlled variable is continuously monitored and compared with the reference variable. Depending on the result of this comparison, the input variable for the system is influenced to adjust the output variable to the desired value despite any disturbing influences. This feedback results in a closed-loop action.

This theoretical definition can be clarified using the example of volumetric flow control.

Deviation

Example
The volumetric flow (the output variable) is to be maintained at the predetermined value of the reference variable. First a measurement is made and this measurement is converted into an electrical signal. This signal is passed to the controller and compared with the desired value. Comparison takes place by subtracting the measured value from the desired value. The result is the deviation.

Manipulating element

In order to automatically control the control valve with the aid of the deviation, an electrical actuating motor or proportional solenoid is required. This allows adjustment of the controlled variable. This part is called the manipulating element (see Fig. B1-4).

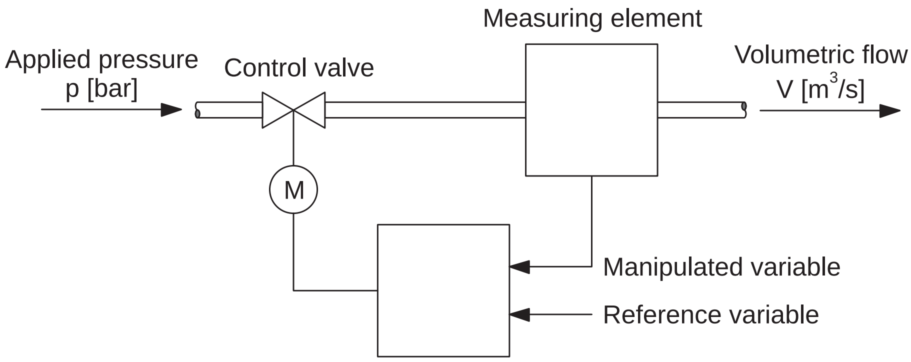


Fig. B1-4: Closed-loop control of volumetric flow

The controller now passes a signal to the manipulating element dependent on the deviation. If there is a large negative deviation, that is the measured value of the volumetric flow is greater than the desired value (reference variable) the valve is closed further. If there is a large positive deviation, that is the measured value is smaller than the desired value, the valve is opened further.

Setting of the output variable is normally not ideal:

- If the intervention is too fast and too great, influence at the input end of the system is too large. This results in great fluctuations at the output.
- If influence is slow and small, the output variable will only approximate to the desired value.

In addition, different types of systems (control system) require different control strategy. Systems that respond slowly must be adjusted carefully and with forethought. This describes some of the control engineering problems faced by the closed-loop control engineer.

Design of a closed-loop control requires the following steps:

- Determine manipulated variable (thus defining the controlled system)
- Determine the behaviour of the controlled system
- Determine control strategy for the controlled system (behaviour of the "controller" system)
- Select suitable measuring and manipulating elements.

1.4 Basic terminology

In Section B 1.3 we look at the difference between open-loop and closed-loop control using the example of volumetric flow for a control valve. In addition we look at the basic principle of closed-loop control and basic terminology. Using this example, let's take a closer look at closed-loop control terminology.

Controlled variable x

The aim of any closed-loop control is to maintain a variable at a desired value or on a desired-value curve. The variable to be controlled is known as the controlled variable x. In our example it is the volumetric flow.

Manipulated variable y

Automatic closed-loop control can only take place if the machine or system offers a possibility for influencing the controlled variable. The variable which can be changed to influence the controlled variable is called the manipulated variable y. In our example of volumetric flow, the manipulated variable is the drive current for the positioning solenoid.

Disturbance variable z

Disturbances occur in any controlled system. Indeed, disturbances are often the reason why a closed-loop control is required. In our example, the applied pressure changes the volumetric flow and thus requires a change in the control valve setting. Such influences are called disturbance variables z.

The controlled system is the part of a controlled machine or plant in which the controlled variable is to be maintained at the value of the reference variable. The controlled system can be represented as a system with the controlled variable as the output variable and the manipulated variable as the input variable. In the example of the volumetric flow control, the pipe system through which gas flows and the control valve formed the control system.

Reference variable w

The reference variable is also known as the set point. It represents the desired value of the controlled variable. The reference variable can be constant or may vary with time. The instantaneous real value of the controlled variable is called the actual value w.

Deviation x_d

The result of a comparison of reference variable and controlled variable is the deviation x_d:

$$x_d = w - x$$

Control response

Control response indicates how the controlled system reacts to changes to the input variable. Determination of the control response is one of the aims of closed-loop control technology.

Controller

The controller has the task of holding the controlled variable as near as possible to the reference variable. The controller constantly compares the value of the controlled variable with the value of the reference variable. From this comparison and the control response, the controller determines and changes the value of the manipulating variable (see Fig. B1-5).

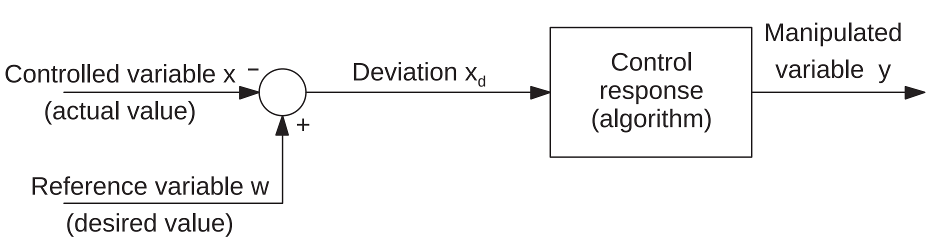


Fig. B1-5:
Functional principle of a closed-loop control

Manipulating element and servo-drive

The manipulating element adjusts the controlled variable. The manipulating element is normally actuated by a special servo drive. A servo drive is required if it is not possible for the controller to actuate the manipulating element directly. In our example of volumetric flow control, the manipulating element is the control valve.

Measuring element

In order to make the controlled variable accessible to the controller, it must be measured by a measuring element (sensor, transducer) and converted into a physical variable that can be processed by the controller is an input.

Closed loop

The closed loop contains all components necessary for automatic closed-loop control (see Fig. B1-6).

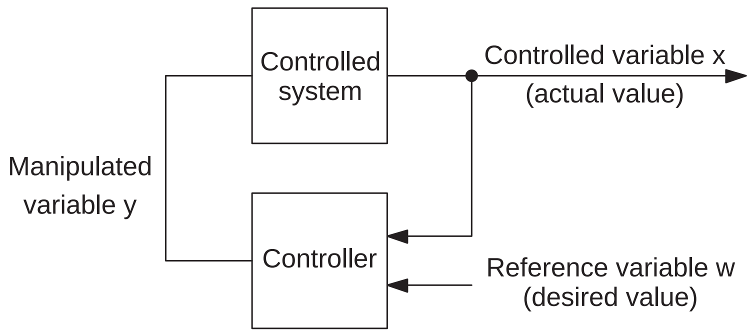


Fig. B1-6: Block diagram of a control loop

1.5 Controlled system

The controlled system is the part of a machine or plant in which the controlled variable is to be maintained at the desired value and in which manipulated variables compensate for disturbance variables. Input variables to the controlled system include not only the manipulated variable, but also disturbance variables.

Before a controller can be defined for a controlled system, the behaviour of the controlled system must be known. The control engineer is not interested in technical processes within the controlled system, but only in system behaviour.

Dynamic response of a system

The dynamic response of a system (also called time response) is an important aspect. It is the time characteristic of the output variable (controlled variable) for changes in the input variable. Particularly important is behaviour when the manipulated variable is changed.

The control engineer must understand that nearly every system has a characteristic dynamic response.

Example
In the example of the water bath in Section B1.2, a change in the steam valve setting will not immediately change the output variable temperature. Rather, the heat capacity of the entire water bath will cause the temperature to slowly "creep" to the new equilibrium (see Fig. B1-7).

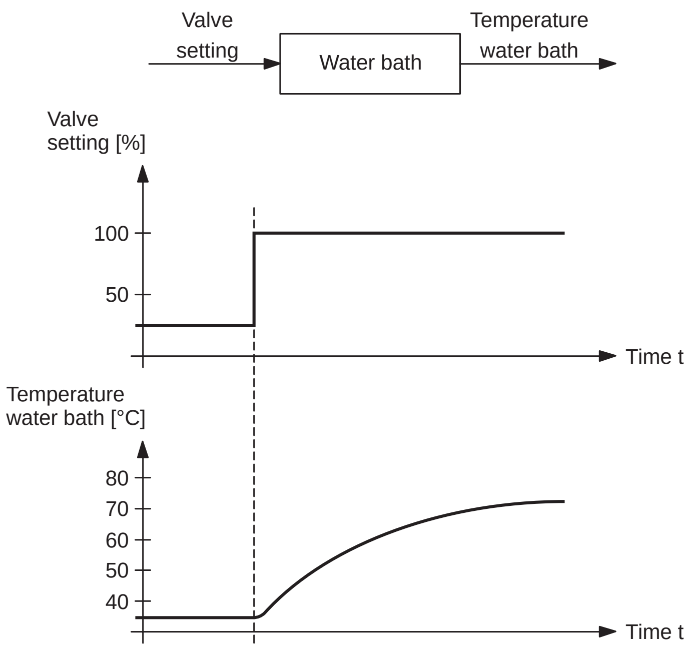


Fig. B1-7: Time response of the controlled system "water bath"

Example

In the example of a valve for volumetric flow control, the dynamic response is rapid. Here, a change in the valve setting has an immediate effect on flow rate so that the change in the volumetric flow rate output signal almost immediately follows the input signal for the change of the valve setting (see B1-8).

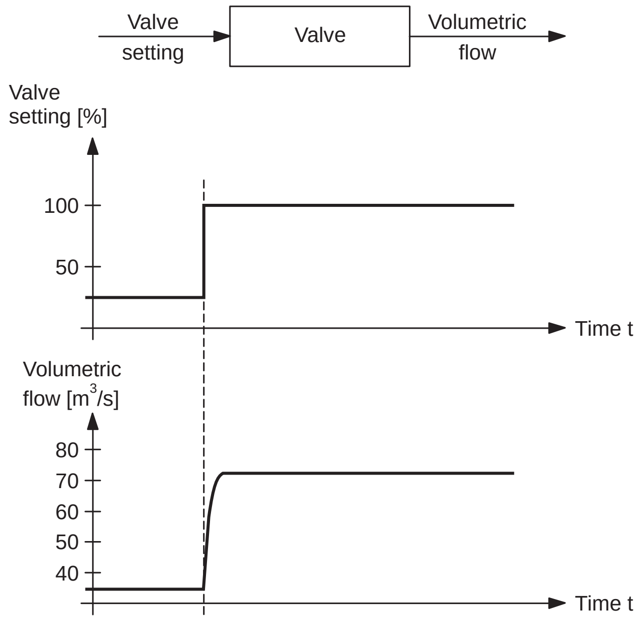


Fig. B1-8:
Time response of the controlled system "valve"

1.5.1 Description of the dynamic response of a controlled system

In the examples shown in Fig. B1-7 and Fig. B1-8, the time response was shown assuming a sudden change in input variable. This is a commonly used method of establishing the time response of system.

Step response

The response of a system to a sudden change of the input variable is called the step response. Every system can be characterized by its step response. The step response also allows a system to be described with mathematical formulas.

Dynamic response

This description of a system is also known as dynamic response. Fig. B1-9 demonstrates this. Here the manipulated variable y is suddenly increased (see left diagram). The step response of the controlled variable x is a settling process with transient overshoot.

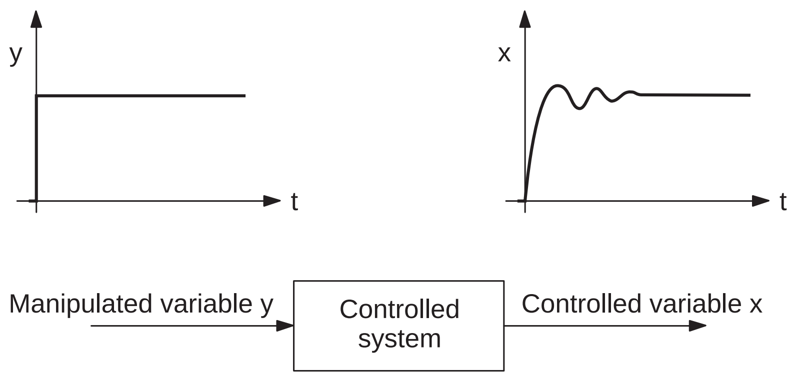


Fig. B1-9: Step response

Equilibrium

Another characteristic of a system is its behaviour in equilibrium, the static behaviour.

Static behaviour

Static behaviour of a system is reached when none of the variables change with time. Equilibrium is reached when the system has settled. This state can be maintained for an unlimited time.

The output variable is still dependent on the input variable – this dependence is shown by the characteristic of a system.

Example
The characteristic of the "valve" system from our water bath example shows the relationship between volumetric flow and valve position (see Fig. B1-10).

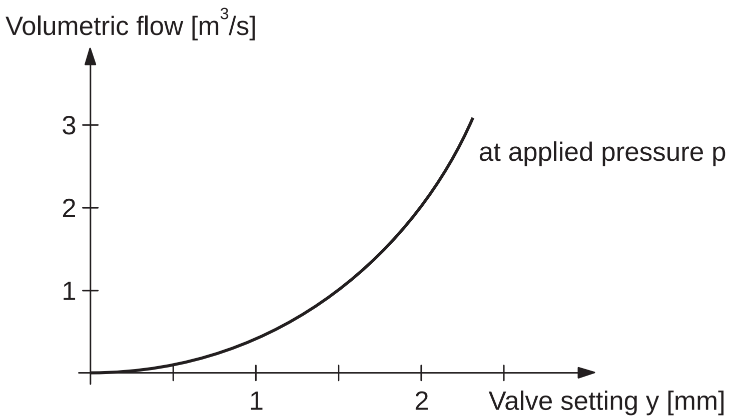


Fig. B1-10: Characteristic curve of the "valve" system

The characteristic shows whether the system is a linear or non-linear system. If the characteristic is a straight line, the system is linear. In our "valve" system, the characteristic is non-linear.

Many controlled systems that occur in practice are non-linear. However, they can often be approximated by a linear characteristic in the range in which they are operated.

1.6 Controllers

The previous section dealt with the controlled system - the part of the system which is controlled by a controller. This section looks at the controller.

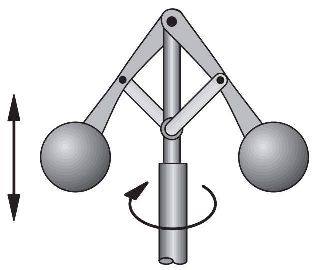
The controller is the device in a closed-loop control that compares the measured value (actual value) with the desired value, and then calculates and outputs the manipulated variable. The above section showed that controlled systems can have very different responses. There are systems which respond quickly, systems that respond very slowly and systems with storage property.

For each of these controlled systems, changes to the manipulated variable y must take place in a different way. For this reason there are various types of controller each with its own control response. The control engineer has the task of selecting the controller with the most suitable control response for the controlled system.

1.6.1 Control response

Control response is the way in which the controller derives the manipulated variable from the system deviation. There are two broad categories: continuous-action controllers and non-continuous-action controllers.

Continous-action controller

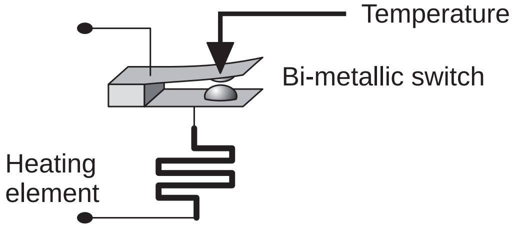


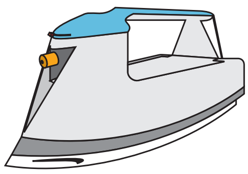
The manipulated variable of the continuous-action controller changes continuously dependent on the system deviation. Controllers of this type give the value of the system deviation as a direct actuating signal to the manipulating element. An example of this type of controller is the centrifugal governor. It changes its moment of inertia dependent on speed, and thus has a direct influence on speed.

Non-continous-action controller

The manipulated variable of a non-continuous-action controller can only be changed in set steps. The best-known non-continuous-action controller is the two-step control that can only assume the conditions "on" or "off".

An example is the thermostat of an iron. It switches the electric current for the heating element on or off depending on the temperature.





This section only deals with continuous-action controllers as these are more commonly used in automation technology. Further, the fundamentals of closed-loop control technology can be better explained using the continuous-action controller as an example.

1.6.2 Time response of a controller

Every controlled system has its own time response. This time response depends on the design of the machine or system and cannot be influenced by the control engineer. The time response of the controlled system must be established through experiment or theoretical analysis. The controller is also a system and has its own time response. This time response is specified by the control engineer in order to achieve good control performance.

The time response of a continuous-action controller is determined by three components:

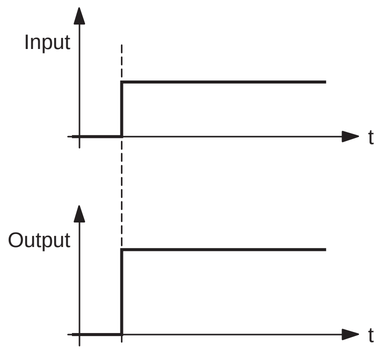
Proportional component (P component)

- Integral component (I component)
- Differential component (D component)

The above designations indicate how the manipulated variable is calculated from the system deviation.

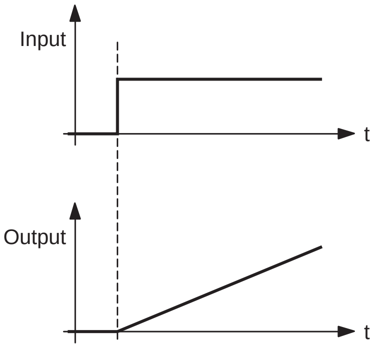
Proportional controller

In the proportional controller, the manipulated variable output is proportional to the system deviation. If the system deviation is large, the value of the manipulated variable is large. If the system deviation is small, the value of the manipulated variable is small. As the manipulated variable is proportional to the system deviation, the manipulated variable is only present if there is a system deviation.



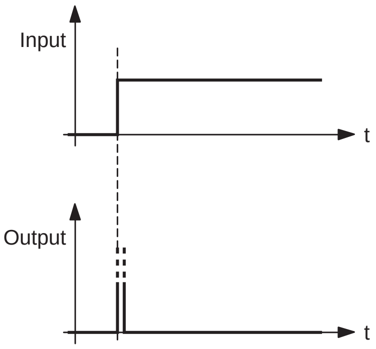
For this reason, a proportional controller alone cannot achieve a system deviation of zero. In this case no manipulated variable will be present and there would therefore be no control.

Integral-action controller



An integral-action controller adds the system deviation over time, that is it is integrated. For example, if a system deviation is constantly present, the value of the manipulated variable continues to increase as it is dependent on summation over time. However, as the value of the manipulated variable continues to increase, the system deviation decreases. This process continues until the system deviation is zero. Integral-action controllers or integral components in controllers are therefor used to avoid permanent system deviation.

Differential-action controller



The differential component evaluates the speed of change of the system deviation. This is also called differentiation of the system deviation. If the system deviation is changing fast, the manipulated variable is large. If the system deviation is small, the value of manipulated variable is small. A controller with D component alone does not make any sense, as a manipulated variable would only be present during change in the system deviation.

A controller can consist of a single component, for example a P controller or an I controller. A controller can also be a combination of several components - the most common form of continuous-action controller is the PID controller.

1.6.3 Technical details of controllers

In automation technology controllers are almost exclusively electrical or electronic. Although mechanical and pneumatic controllers are often shown as examples in text books, they are hardly ever found in modern systems.

for voltage	0 ... 10V	-10 ... +10V
for current	0 ... 20mA	4 ... 20mA

Electrical and electronic controllers work with electrical input and output signals. The transducers are sensors which convert physical variables into voltage or current. The manipulating elements and servo drives are operated by current or voltage outputs. Theoretically, there is no limit to the range of these signals. In practice, however, standard ranges have become established for controllers:

Internal processing of signals in the controller is either analog with operational amplifier circuits or digital with microprocessor systems

- In circuits with operational amplifiers, voltages and currents are processed directly in the appropriate modules.
- In digital processing, analog signals are first converted into digital signals. After calculation of the manipulated variable in the microprocessor, the digital value is converted back into an analog value.

Although theoretically these two types of processing have to be dealt with very differently, there is no difference in the practical application of classical controllers.

1.7 Mode of operation of various controller types

This section explains the control response of various controller types and the significance of parameters. As in the explanation of controlled systems, the step response is used for this description. The input variable to the controller is the system deviation – that is, the difference between the desired value and the actual value of the controlled variable.

1.7.1 The proportional controller

Proportional controller

In the case of the proportional controller, the actuation signal is proportional to the system deviation. If the system deviation is large, the value of the manipulated variable is large. If the system deviation is small, the value of the manipulated variable is small. The time response of the P controller in the ideal state is exactly the same as the input variable (see Fig. B1-11).

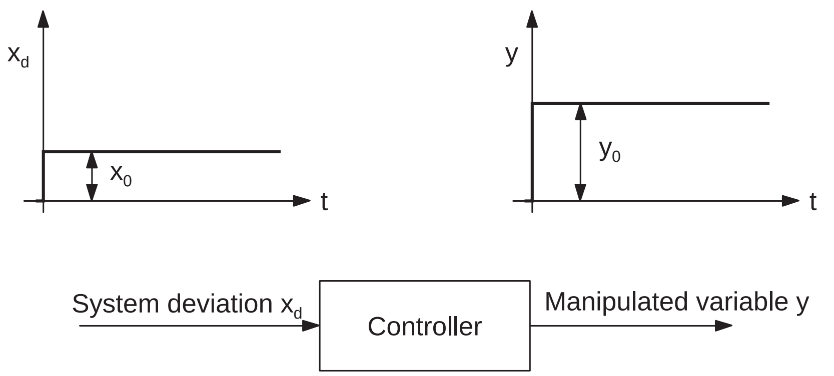


Fig. B1-11: Time response of the P controller

The relationship of the manipulated variable to the system deviation is the proportional coefficient or the proportional gain. These are designated by x_p, K_p or similar. These values can be set on a P controller. It determines how the manipulated variable is calculated from the system deviation. The proportional gain is calculated as:

$$K_p = y_0 / x_0$$

If the proportional gain is too high, the controller will undertake large changes of the manipulating element for slight deviations of the controlled variable. If the proportional gain is too small, the response of the controller will be too weak resulting in unsatisfactory control.

A step in the system deviation will also result in a step in the output variable. The size of this step is dependent on the proportional gain. In practice, controllers often have a delay time, that is a change in the manipulated variable is not undertaken until a certain time has elapsed after a change in the system deviation. On electrical controllers, this delay time can normally be set.

An important property of the P controller is that as a result of the rigid relationship between system deviation and manipulated variable, some system deviation always remains. The P controller cannot compensate this remaining system deviation.

1.7.2 The I controller

Integral-action controller

The I controller adds the system deviation over time. It integrates the system deviation. As a result, the rate of change (and not the value) of the manipulated variable is proportional to the system deviation. This is demonstrated by the step response of the I controller: if the system deviation suddenly increases, the manipulated variable increases continuously. The greater the system deviation, the steeper the increase in the manipulated variable (see Fig. B1-12).

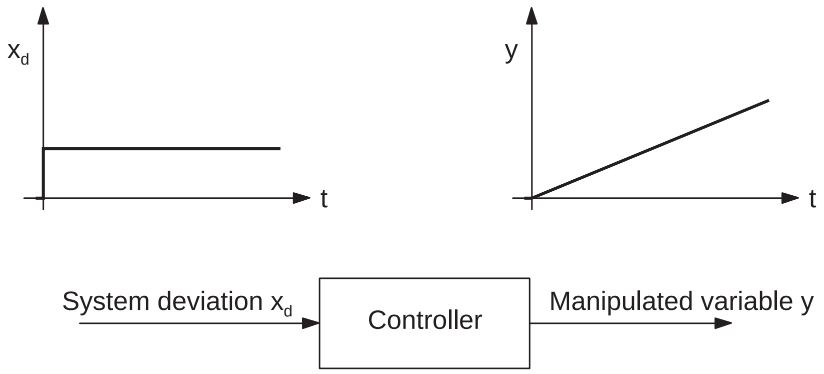


Fig. B1-12: Time response of the I controller

For this reason the I controller is not suitable for totally compensating remaining system deviation. If the system deviation is large, the manipulated variable changes quickly. As a result, the system deviation becomes smaller and the manipulated variable changes more slowly until equilibrium is reached.

Nonetheless, a pure I controller is unsuitable for most controlled systems, as it either causes oscillation of the closed loop or it responds too slowly to system deviation in systems with a long time response. In practice there are hardly any pure I controllers.

1.7.3 The PI controller

PI controller

The PI controller combines the behaviour of the I controller and P controller. This allows the advantages of both controller types to be combined: fast reaction and compensation of remaining system deviation. For this reason, the PI controller can be used for a large number of controlled systems. In addition to proportional gain, the PI controller has a further characteristic value that indicates the behaviour of the I component: the reset time (integral-action time).

Reset time

The reset time is a measure for how fast the controller resets the manipulated variable (in addition to the manipulated variable generated by the P component) to compensate for a remaining system deviation. In other words: the reset time is the period by which the PI controller is faster than the pure I controller. Behaviour is shown by the time response curve of the PI controller (see Fig. B1-13).

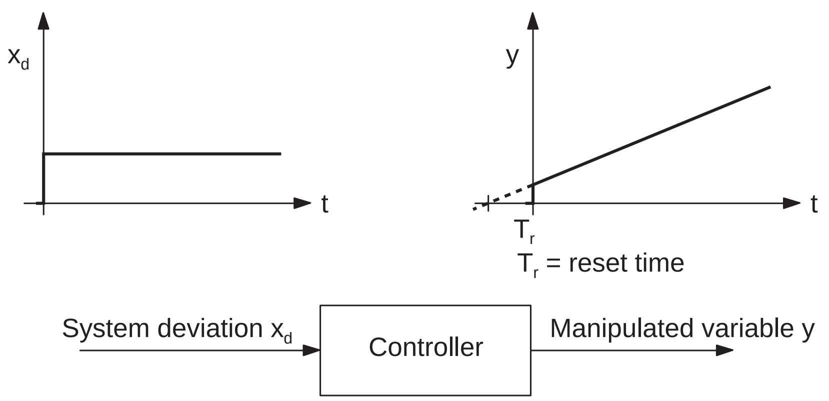


Fig. B1-13: Time response of the PI controller

The reset time is a function of proportional gain K_p as the rate of change of the manipulated variable is faster for a greater gain. In the case of a long reset time, the effect of the integral component is small as the summation of the system deviation is slow. The effect of the integral component is large if the reset time is short.

The effectiveness of the PI controller increases with increase in gain K_p and increase in the I-component (i.e., decrease in reset time). However, if these two values are too extreme, the controller's intervention is too coarse and the entire control loop starts to oscillate. Response is then not stable. The point at which the oscillation begins is different for every controlled system and must be determined during commissioning.

1.7.4 The PD controller

PD controller

The PD controller consists of a combination of proportional action and differential action. The differential action describes the rate of change of the system deviation.

The greater this rate of change – that is the size of the system deviation over a certain period – the greater the differential component. In addition to the control response of the pure P controller, large system deviations are met with very short but large responses. This is expressed by the derivative-action time (rate time).

Derivative-action time

The derivative-action time T_d is a measure for how much faster a PD controller compensates a change in the controlled variable than a pure P controller. A jump in the manipulated variable compensates a large part of the system deviation before a pure P controller would have reached this value. The P component therefore appears to respond earlier by a period equal to the rate time (see Fig. B1-14).

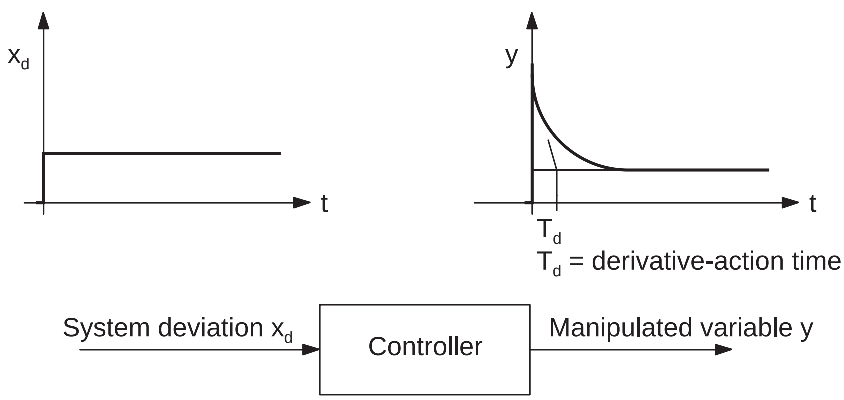


Fig. B1-14: Time response of the PD controller

Two disadvantages result in the PD controller seldom being used. Firstly, it cannot completely compensate remaining system deviations. Secondly, a slightly excessive D component leads quickly to instability of the control loop. The controlled system then tends to oscillate.

1.7.5 PID controller

PID controller

In addition to the properties of the PI controller, the PID controller is complemented by the D component. This takes the rate of change of the system deviation into account.

If the system deviation is large, the D component ensures a momentary extremely high change in the manipulated variable. While the influence of the D component falls of immediately, the influence of the I component increases slowly. If the change in system deviation is slight, the behaviour of the D component is negligible (see Section B1.6.2).

This behaviour has the advantage of faster response and quicker compensation of system deviation in the event of changes or disturbance variables. The disadvantage is that the control loop is much more prone to oscillation and that setting is therefore more difficult.

Fig. B1-15 shows the time response of a PID controller.

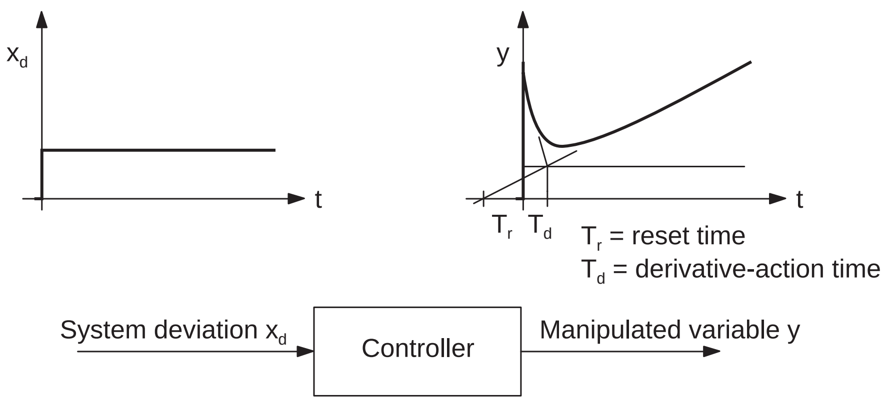


Fig. B1-15: Time response of the PID controller

Derivative-action time

As a result of the D component, this controller type is faster than a P controller or a PI controller. This manifests itself in the derivative-action time T_d. The derivative-action time is the period by which a PID controller is faster than the PI controller.

1.8 Summary

Here is a summary of the most important points to be taken into account when solving control problems.

1. Assignment of controlled variables
Which machine or plant variable is the controlled variable, reference variable, manipulated variable etc. Where and how do disturbance variables occur? The selection of sensors and actuators is based on these factors.

2. Division of the control problem into systems
Where is the controlled variable measured? Where can the system be influenced? What is the nature of the individual systems?

3. Controlled system
Where is the controlled variable to be adjusted to the desired value? What is the time response of the controlled system (slow or fast)? The choice of controller response is based on these factors.

4. Controller
What type of control response is required? What time response must the controller have, particularly with regard to fault conditions? What values must the controller parameters have?

5. Controller type
What type of controller must be implemented? Does the time response and controlled system require a P, I, PI or PID controller?

Chapter 2

Project design of automation systems

2.1 Introduction

2.1.1 Motivation

Based on the fact that currently engineering training in the field of automation technology is principally dominated by the theory of open and closed loop control, the main purpose of this training concept is to provide would-be practical automation specialists with a sound knowledge of automation methods and project design methods for automation systems. In the sense of holistic training this means that training matters such as the selection and sizing of automation equipment, project design methods, information, electrotechnology, as well as open and closed loop theory must always be taught within a joint context, demonstrated through relevant, practical examples and consolidated by means of practical exercises (learning by doing).

With this type of vocational and further training of engineers and other specialists in mind, many years' experience has been gathered by both Festo Didactic (e. g. Modular Production System / MPS), and the Department of Automation of the Technical University of Dresden, and, as part of a joint project, used to design and develop a small-scale trial station for the automation of continuous processes as in process technology.

2.1.2 Configuring a small-scale experimental module

Adopting the idea of automating process technology operations as a starting point, the first important point is the question regarding process parameters. By evaluating the experiences gained, typical process parameters such as filling level, throughput, pressure, temperature and quality (pH value) have been incorporated into suitable modules (process technology modules) based on the well-known MPS concept.

This means that these modules represent individual process sections and are designed according to a standard structure (fig. B2-1).

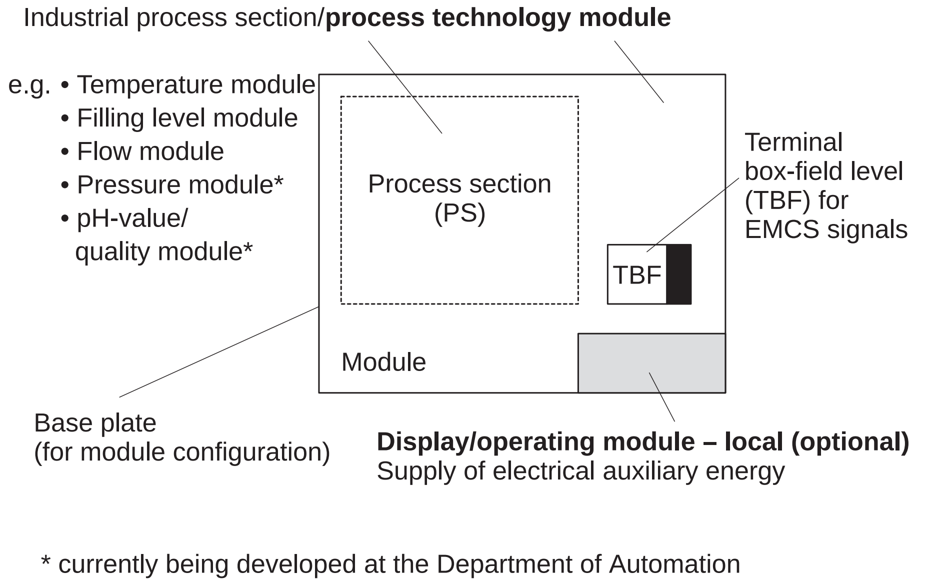


Fig. B2-1: Design of a process technology module

As such, the modules filling level, throughput, pressure, temperature and quality are available for individual use, but can also be combined or duplicated via a central EMCS (Electronic Measuring Control System) terminal and operated as a complex process technology system (fig. B2-2).

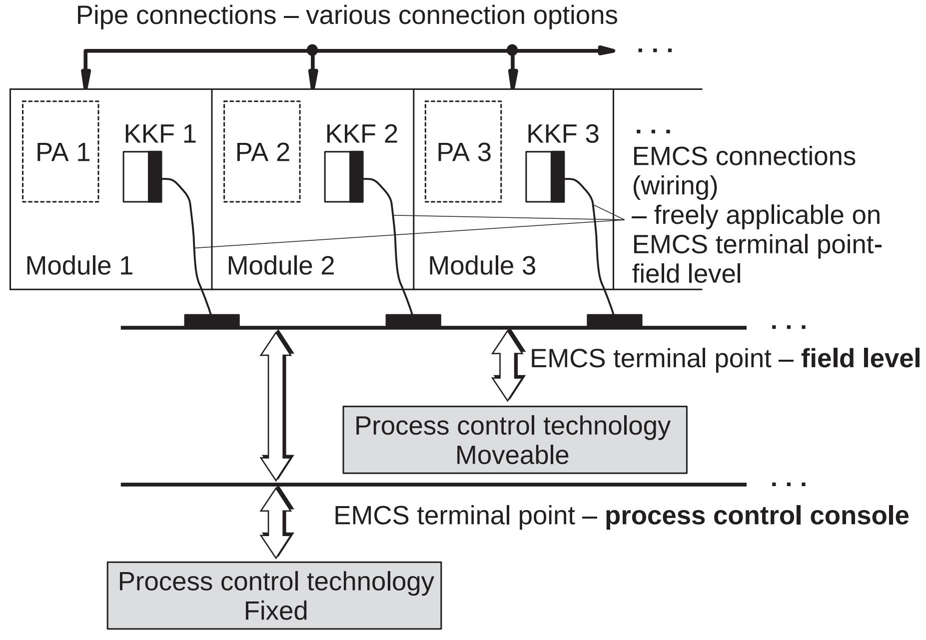


Fig. B2-2: Configuration of the process technology modules

2.1.3 Overview of project design procedure

As already mentioned, the holistic training concept requires the teaching of a sound knowledge of the different training contents typical of automation technology, plus their integration into an effective project design methodolgy. Fig. B2-3 provides an initial clarification of the extent and technical diversity of the exercises to be completed.

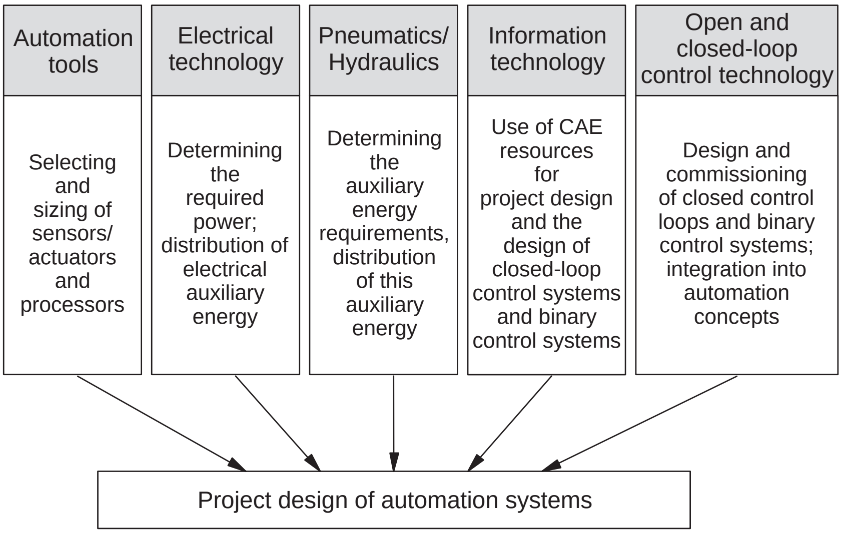


Fig. B2-3: Overview of extent and technical diversity of of the basic knowledge involved in the project design of automation systems

The broad knowledge base required for this can only be mastered and put to effective use for project design work by means of a systematic approach (project design know-how). From this viewpoint alone, the small-scale trial station represents an important auxiliary means for the tuition of the necessary training contents and for the development of the required technical and practical competence by means of systematically applying the "learning by doing" concept.

If you now set the task of working through a project design task using the example of this small-scale trial station or an industrial installation in process technology, the project design know-how forms the crucial basis for this. Fig. B2-4 therefore provides an initial introduction of the scope and sequence of the actual project design work in the form of an overview.

The starting point of every automation project are the project requirements, which are placed on the automation system. Generally, an invitation to tender is drawn up by the customer for this which, in the sense of the traditional DIN interpretation is characterised by the *specification and process flow diagram*. The contractor, as a rule the project design company, draws up a proposal (including quotation) and documents the project design work (*specification)* to be completed via a so-called *configurational draft* in the form of the *PI flow diagram* (piping and installation flow diagram).

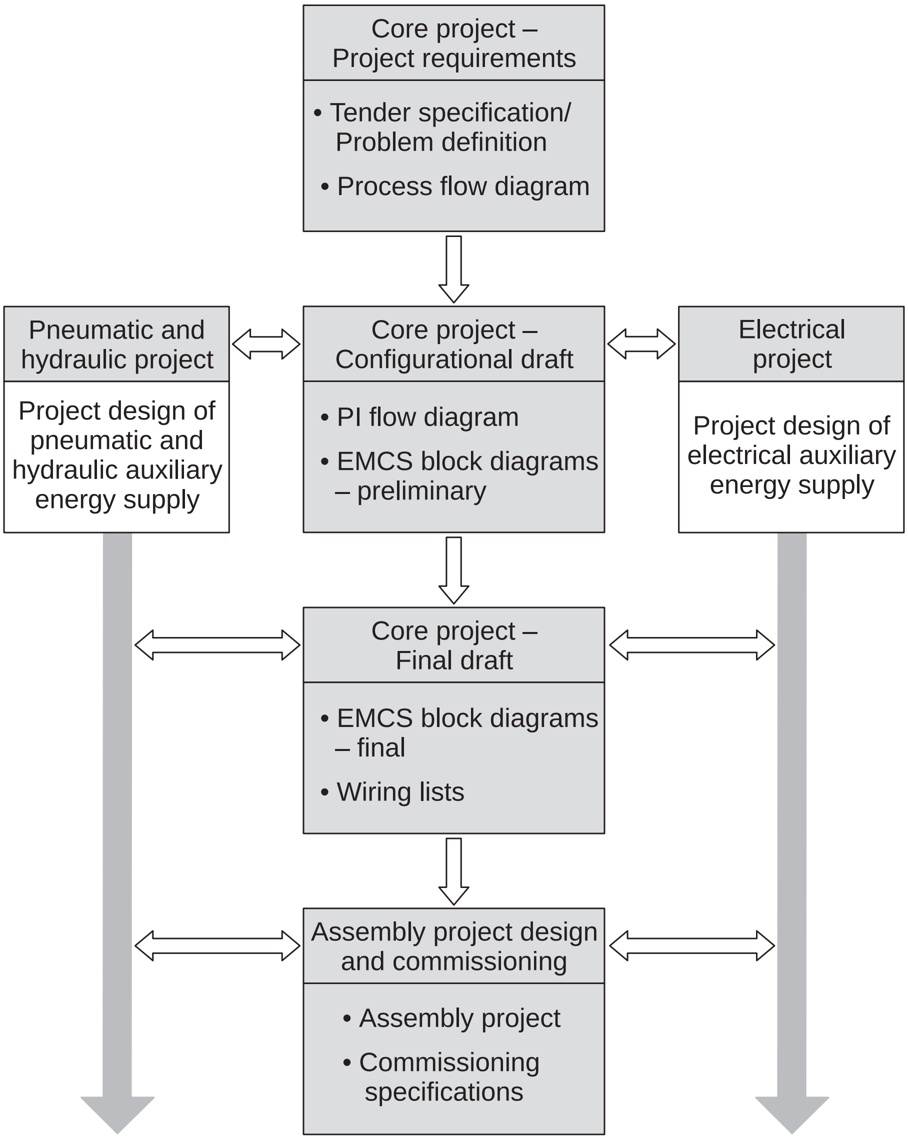


Fig. B2-4:
Sequence and content of project design work

These tasks are drawn up in the form of a complete set of project documentation by means of the *preliminary EMCS block diagrams* (electronic measuring control system block diagram) and the *final draft* (final EMCS block diagrams/wiring lists).

The subsequent *assembly project design* also forms part of the project design task and ensures the assembly of the automation system in the sense of the desired performance range. Finally, some additional tasks need to be fulfilled for the commissioning of this automation system (e.g. specifications for the controller configuration and parameterisation), which form an essential component part of this overall project.

Of parallel importance to the project design of this EMCS part, is the implementation of the electrical and the pneumatic and hydraulic project. Fig. B2-4 provides a schematic illustration of the interaction of these three project components.

The core project design now provides a methodology, which sets out the systematic preparation of this broad spectrum of tasks (the core project), and at the same time the linking up with the additional project design tasks (electrical project / pneumatic and hydraulic project).

In summary of fig. B2-4, the core project design (the core project) also encompasses the allocation of the specification, the PI flow diagram and list of EMCS points, the EMCS preliminary block diagrams with the so-called fittings lists and allocation lists, including wiring lists. Moreover, the components System Assembly and Commissioning of the automation system are identified.

To begin with, the core project design is discussed in detail in order to provide a better understanding.

2.2 Core project design – Basic methodology for the project design of automation systems

2.2.1 Comments regarding project configuration

In practice, process technology, as on the small-scale experimental modules, an automation system, apart from the field instrumentation (sensors/actuators), is dominated by process control and instrumentation technology. These tools for automation are fitted into a basic structure of the automation system, which is universally accepted as a means of reference. This basic configuration comprises the typical components *process control console, switchroom* and *fieldlevel* (fig. B2-5) and clearly sets out the use of the tools for automation, which are important as far as project design is concerned.

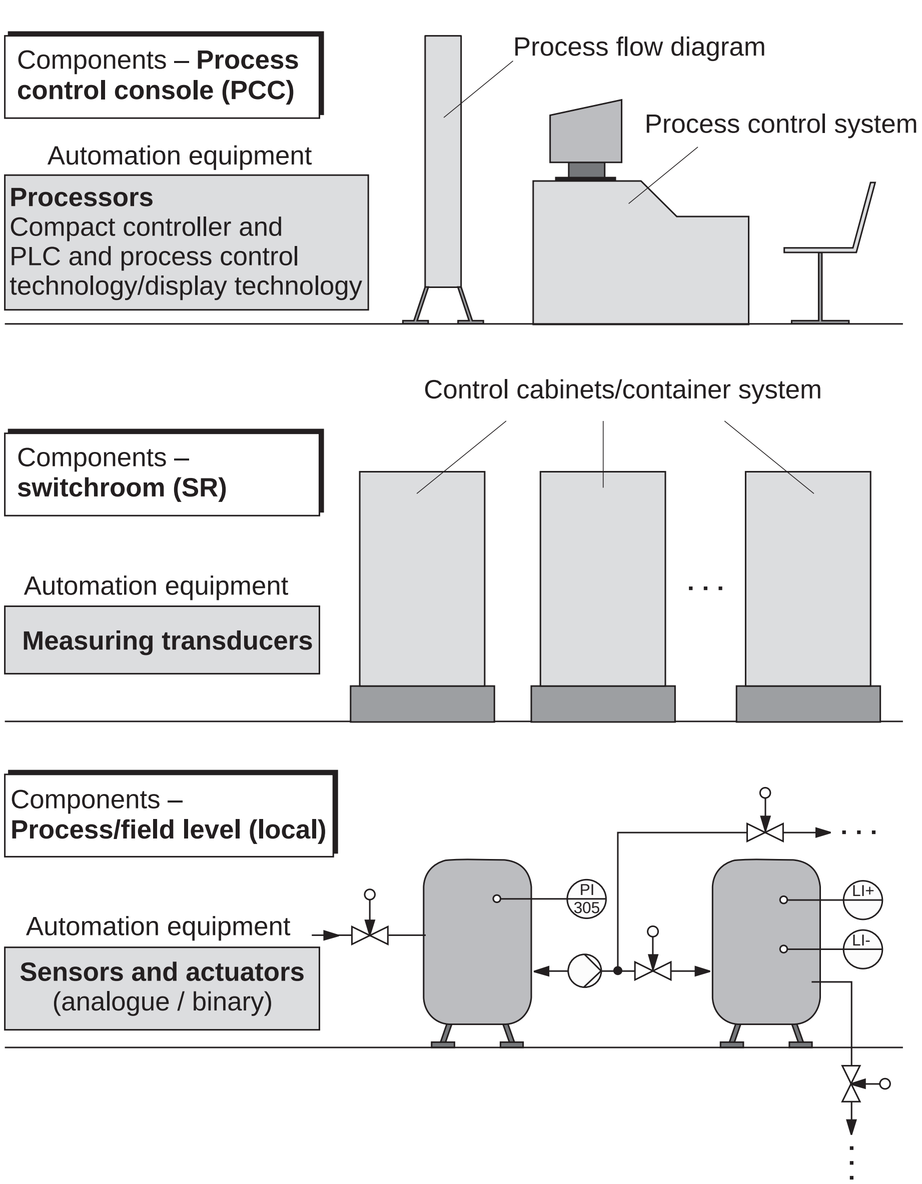


Fig. B2-5:
Basic structure of an automation system

According to this, it is possible to proceed on the assumption of the following allocation:

- Process control console ⇒ Processor technology / PLC technology
- Switchroom ⇒ Measuring transducer technology
- Process / Field level ⇒ Sensors / Actuators and measuring transducer technology

By recollecting the basic configuration of the single-loop control loop and the binary control system (fig. B2-6) in this conjunction, it is also possible allocate these in the basic configuration with the help of the automation tools used. This also works for the simple measuring chain (separate measuring point).

Finally, it is crucial to define all the *EMCS points* (electronic measuring and control points) required for the solution of an automation task.

As already established, the tender specification or customer's invitation to tender is generally available for this, on the basis of which the designer (contractor) can draw up the specification.

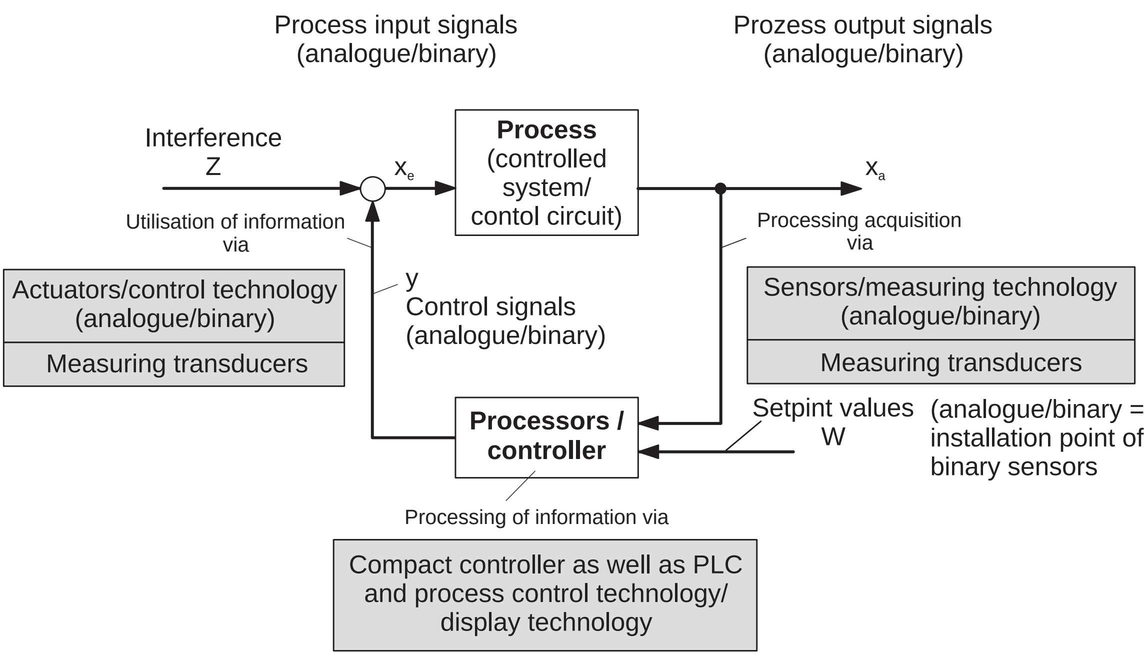


Fig. B2-6:
Automation equipment of a single-loop closed control loop and the binary control system

2.2.2 Tender specification – performance specification

VDI/VDE 3694 formally specifies that the tender specification or performance specification forms the basis of any automation project, i.e. according to VDI/VDE

- The **tenderspecification** contains the requirements from the user's viewpoint, including all parameter conditions

  "The tender specification defines,
  WHAT is to be solved and the PURPOSE of the solution ".

  (The tender specification is drawn up by the customer or commissioned by him. It acts as a basis for the invitation to bid, the quotation and/or contract basis.)

and

- the **performance specification** contains the tender specification and also details the user tasks and, enlarging on the tender specification, describes the implementation requirements, taking into consideration concrete solution approaches.

  "The performance specification defines
  HOW and WITH WHAT the requirements are to be implemented."

  (The performance specification is generally drawn up by the contractor in cooperation with the customer once the order has been placed.)

In industrial practice, reference is almost always made to the invitation to tender again, which also defines the process technology and the corresponding automation tasks, although generally not to the extent and depth required for the tender specifications as specified in VDI/VDE 3694. It is therefore essential for the contractor (project designer) to give maximum consideration to the planning and calculation of his quotation (performance specification), i.e. contents, size and costs of the automation project to be realised.

For a tried and tested practical approach, the project design engineer should therefore start with an analysis and the functional sequence of the respective process technology (evaluation of the process flow diagram, including the corresponding process description).

The **process flow diagram** for continuous processes is drawn up according to *DIN 28004* guidelines and is the diagrammatic representation of the piping and devices. An attached description and additional entries of process parameters in the process flow diagram complete the initial general documentation of the process technology and automation tasks. As such, it becomes necessary to define in detail the automation tasks (EMCS points). This is done by entering the EMCS points in the process flow diagram, i.e. the process flow diagram becomes the PI flow diagram.

The PI flow diagram is therefore the first concrete project step, which defines the number and function of the required EMCS points.

2.2.3 PI flow diagram

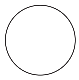
Symbols

As detailed, the necessary EMCS points are entered in the process flow diagram, and the number and function of the individual EMCS points precisely defined.

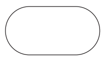
To obtain a PI flow diagram in conformance with the standard (DIN 19227/Part 1), the type, inclusion into the basic structure of the automation system and the functionality (letter code) are to be defined in accordance with steps 1 to 3:

Step 1 – Type of EMCS point

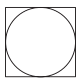
- Depending on the functional scope of the EMCS point (designation scope of letter code) the following symbols are used

Round 

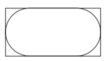
and

Oblong 

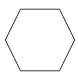
- if a process control system is used

Square with inscribed circle 

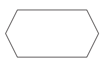
and

Rectangle with inscribed oblong 

- or if a programmable logic controller is used (PLC technology)

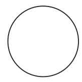
Hexagon 

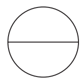
and

extended hexagon 

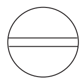
Step 2 – Integration of EMCS point into the basic structure of the automation system

- If we go back to the basic structure of the automation system introduced in section 2.2.1, the EMCS point initially determined according to type is to be further modified into

  EMCS point -"local / local"
  (in the process / at field level
  / of the installation),
  

  EMCS point process control console
  

  and

  EMCS point local control console.
  

- The project designer also defines what the EMCS point will be or which components of the basic structure of the automation system it will cover.

Step 3 – Functional content of EMCS point

- The functional content of the respective EMCS point is uniquely defined by the letter code; the letter code selected for each EMCS point specifies whether it is to be entered in the process flow diagram as a separate measuring point, closed control loop or binary measuring system.

Letter code of PI flow diagram

In accordance with DIN 19227 (Part 1/Sheet 6), the use of the letter code and the design of the PI flow diagram (interpretation of the EMCS point) are explained with the help of the introductory example (fig. B2-7).

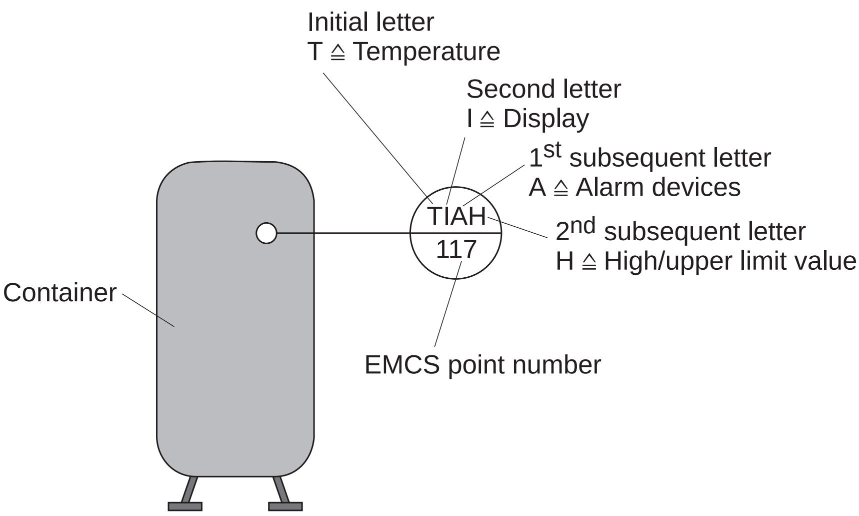


Fig. B2-7: Introductory example demonstrating the letter code in the PI flow diagram (using the example of a temperature measuring point)

Generally, letters are to be used in the following order:

Initial letter for typical process technology process parameters, e. g.

- T – Temperature
- P – Pressure
- F – Flow rate / throughput
- L – Filling level /height and
- Q – Quality (e. g. pH-value)

Second letters for the modification of these process parameters, e. g.

- D – Difference
- F – Relationship
- J – Measuring point sensing

Subsequent letters (1st subsequent letter/2nd subsequent letter) – for the typical functions for the automation of process technology operations, e. g.

- C – Closed loop control
- I – Display
- R – Registration
- S – Circuit, sequence control/logic control system and
- Y – Arithmetic function

The EMCS point number which is also defined in the introductory example is introduced dependent on the project and can, for instance, comprise three, four or more characters.

Selected examples

In accordance with the main process sections of process technology (see for instance small-scale trial system), a number of different examples are set out to provide a complete overview of EMCS points in the diagram.

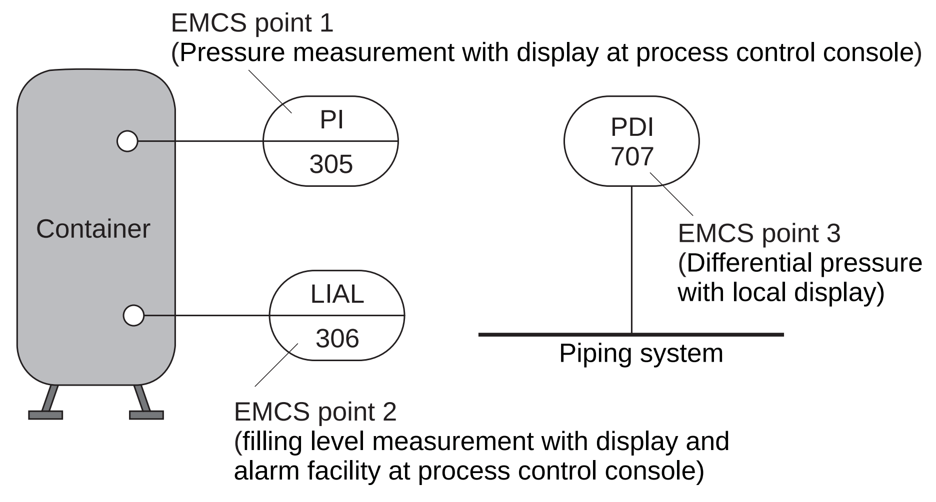


Fig. B2-8: Representation of separate measuring points (in PI flow diagram)

To begin with, the type of each of the EMCS points in the example shown in fig. B2-8 is used to demonstrate how the different measuring points on containers or the piping system are represented in a form which conforms to DIN.

Based on this form, the entering of closed control loops also becomes clear. Fig. B2-9 illustrates that, apart from the letter code for the functions of the closed control loop, this symbolic representation also defines the measuring place (the measuring signal) and the actuator with manipulation point (actuating signal).

Finally, the binary control systems also have an important part within the framework of the extent of EMCS points. Fig. B2-10 also shows an example of how the binary control system fit into the PI flow diagram. Again, the measuring place (measuring signal) and actuator with manipulation point (control signal) have been entered for the EMCS points.

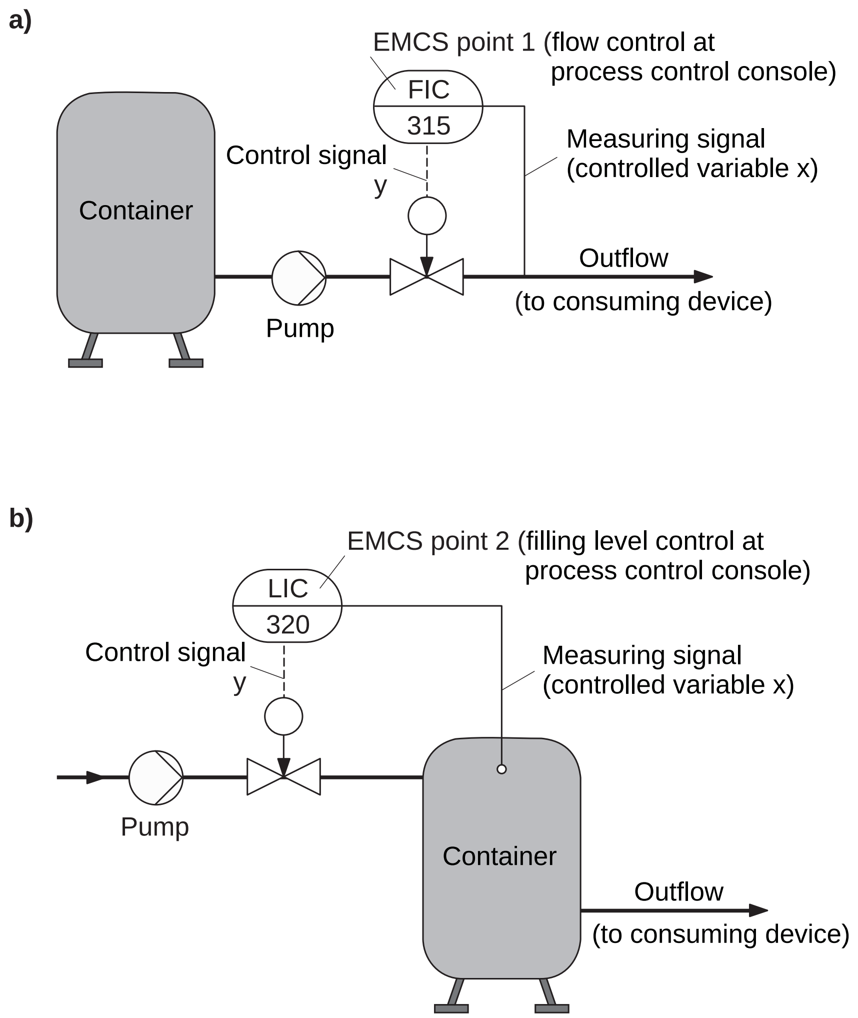


Fig. B2-9: Representation of closed control loops (in PI flow diagram)

Notes regarding the planning of the actuating method

Further to the examples demonstrated in B2-9 and B2-10, some additional information is required regarding the use of symbols for the actuators (actuating devices), because even at the stage of drawing up the PI flow diagram, the project design engineer already needs to know, which actuating devices are to be used. A closed control loop always entails the use of an actuating device consisting of actuator and regulating valve/proportional valve, and for the binary control system an actuator with on/off valve (binary valve). This valve specification does not make the PI flow diagram explicitly clear, but merely enables the placing of the valve type used by looking at the letter code of the EMCS point.

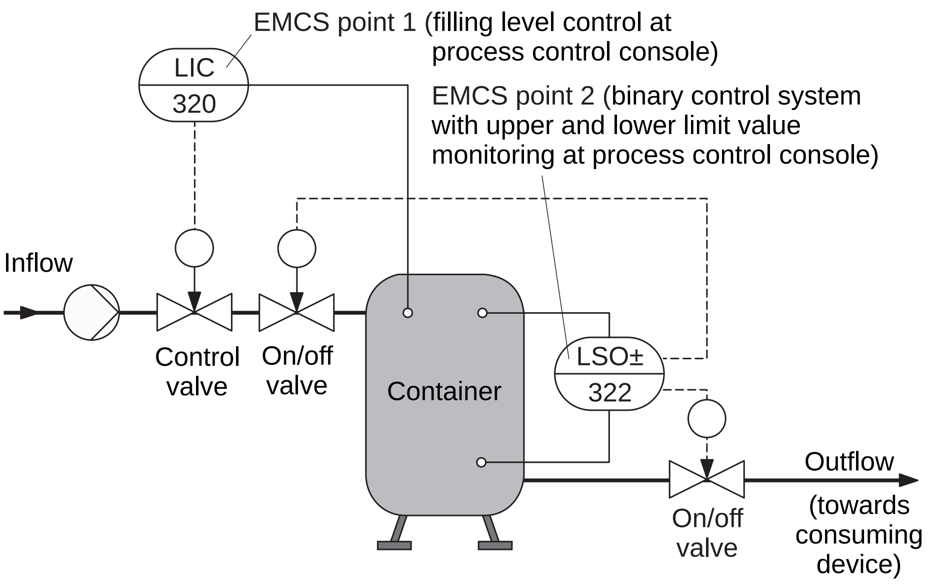


Fig. B2-10: Representation of binary control systems (in PI flow diagram)

In contrast with this, the actuator is already easy to classify from the PI flow diagram. Hence, actuators (actuating devices) using pneumatic auxiliary energy are often used which, apart from the advantages of– high correcting speed/ruggedness – assume the preferred state "on" or "off" in the event of failure of the air supply, depending on the constructional arrangement of the spring (see fig. B2-11). The majority of electrical actuators, for instance, do not have this characteristic and remain in the position assumed at the time of failure of the electrical auxiliary energy.

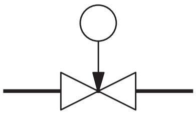
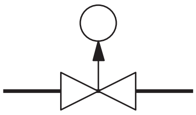
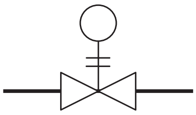
Symbol	Meaning in PI flow diagram
	Final control element/actuator with valve (control or on/off valve) – closing in the event of auxiliary energy failure
	Final control element/actuator with valve (control or on/off valve) – opening in the event of auxiliary energy failure
	Final control element/actuator with control valve – steady-state in the event of auxiliary energy failure

Fig. B2-11:
Method of operation of servo controlled equipment (in PI flow diagram)

The practical implementation of the PI flow diagram

The PI flow diagram therefore forms the definitive basis for further realisation of the automation system project with regard to technical engineering. This requires a corresponding project classification, e. g. for the selection of sensors, actuators and processors. Within this context, the selection of sensors and actuators is also designated in the form of *field instrumentation* and the additionally required second task of configuration in the form of – *selection of the process control technology* –. This enables the task to be subdivided and very often translated into practical team work. This means that, one section of the team prepares the field level instrumentation, and the other section the selection and commissioning of the process control system.

To provide a better understanding, the small-scale trial system is used as an example to introduce the official PI flow diagram in accordance with DIN, followed by the PI flow diagram variant favoured by the Department of Automation. The latter is also within the framework of DIN 19227, but specifies the allocated sensors as additional EMCS point for each closed loop control and binary control system. This creates a central interface, the *EMCS points terminal*, which provides the field signals for the connection of the process control technology (figs. B2-12 and B2-13).

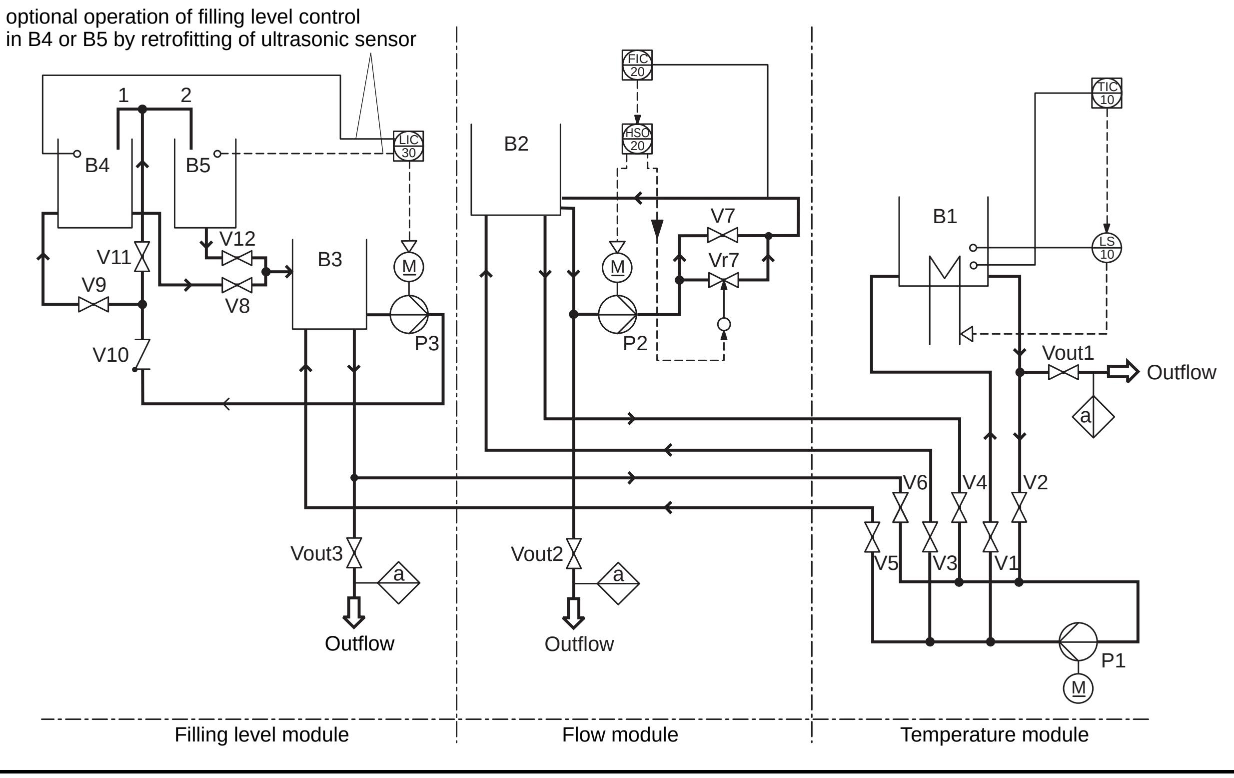


Fig. B2-12:
PI flow diagram conforming to DIN

2.2.4 EMCS block diagrams

Introductory comments

Within the framework of the core project design, the PI flow diagrams are followed by the so-called EMCS block diagrams. In the sense of a level-graded project specification, a *preliminary EMCS block diagram* and a *final EMCS diagram* are prepared for each EMCS point, whereby the preliminary EMCS block diagram defines the connection of the automation equipment involved in the configuration of an EMCS point and the final EMCS block diagram documents the detailed wiring based on this.

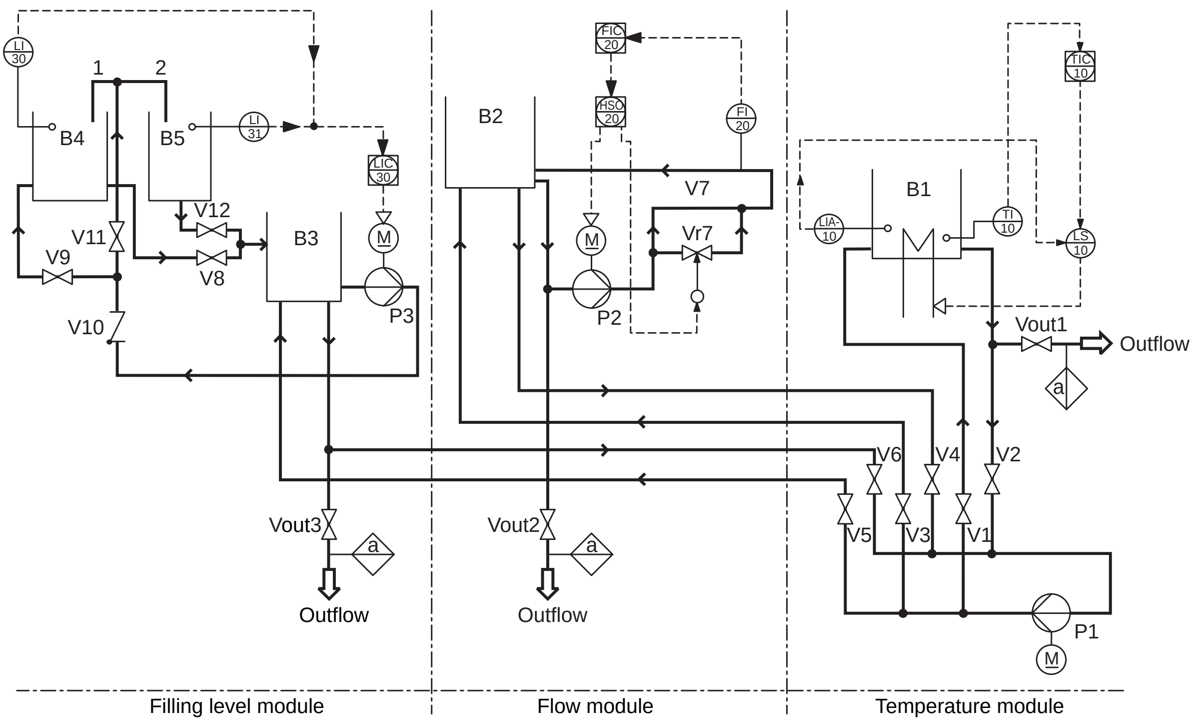


Fig. B2-13:
PI flow diagram – modified

Again, suitable symbols are used when drawing up these EMCS block diagrams to indicate how the so-called standardised signals are used to connect the automation devices deployed.

To provide a better understanding, this standardised signal concept is therefore described in greater detail first.

Concept of standardised signals

Working on the premises of the basic structure of the automation system specified in fig. B2-5 and taking into consideration the individual automation devices allocated, the question of simple and clear interconnectability of these different types of automation equipment is of some importance, particularly when considering the wide range of products on offer from the various automation equipment manufacturers. The introduction of the so-called *standardised signals* solves this problem.

Today, these standardised signals are used worldwide by manufacturers of automation equipment

for electrical auxiliary energy

- 4...20 mA (preferably)
- 0...20 mA
- 0...5 mA
- 0...10 V
- -10 V...+10 V

for pneumatic auxiliary energy

- 20 kPa...100 kPa or
- 0.2 bar ...1 bar

Fig. B2-14 demonstrates this way of thinking and as such expands on the contents of fig. B2-5.

This standard conforming representation of the integration of standardised signals into the structure of the automation system is used as a basis for the creation of the following project documentation.

At the same time, it can be seen that advanced automation tools are generally moving towards the use of standardised signals, i.e. sensors immediately provide standardised signals or the actuators are directly pressurised (e. g. pneumatic actuating devices) by means of standardised signals. As such, the integration of the standardised signals shown in fig. B2-14 is modified so that, as shown in fig. B2-15, a direct connection is realised between process and process control system (elimination of measuring transducer and signal converter). The switchroom is therefore only used to provide the electrical auxiliary energy (power supply) and for the so-called routing of field signals. This routing of field signals takes place in such a way that their distribution to the basic units of the process control system used offers the best possible process reliability (redundancy thanks to favourable distribution of monitoring signals).

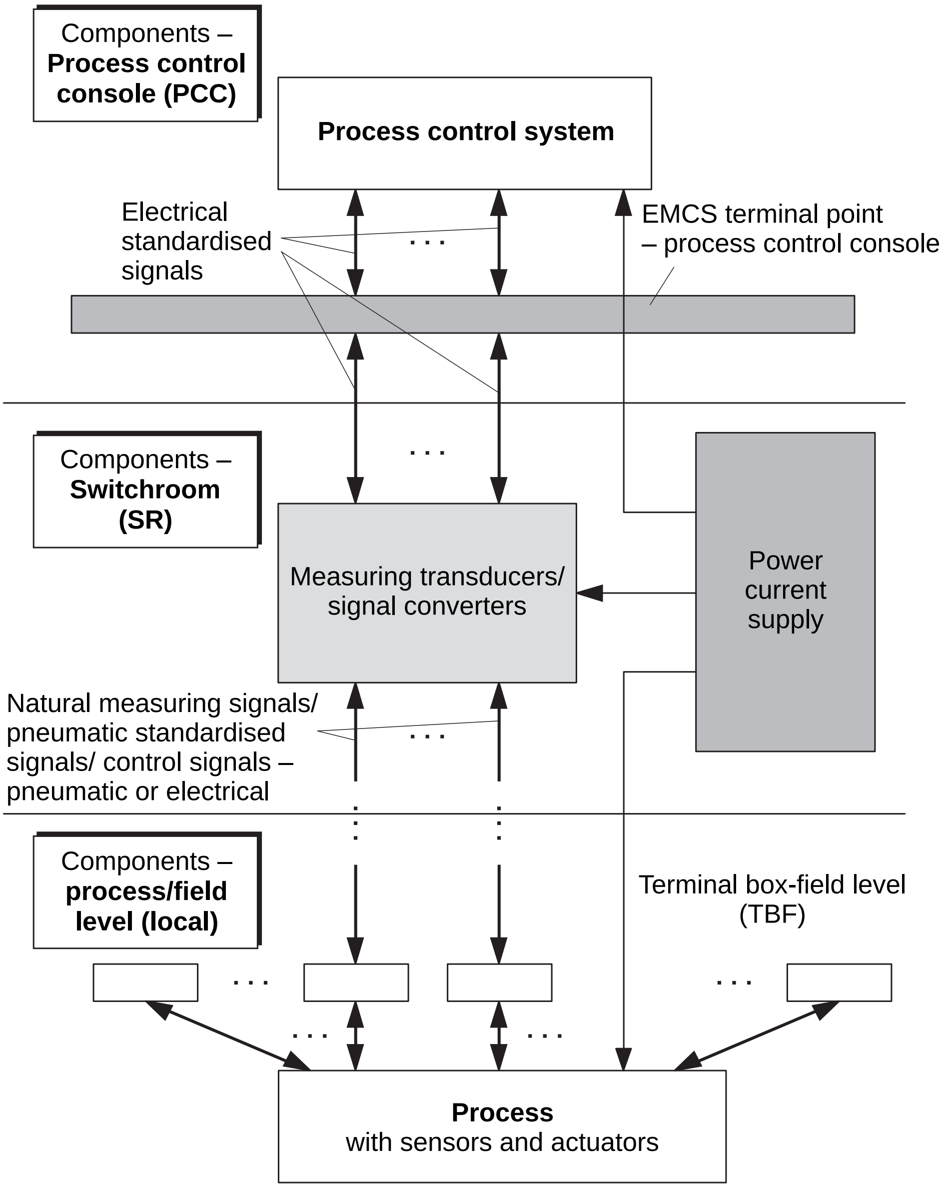


*Fig. B2-14:
Introduction of standardised signals into automation system structure*

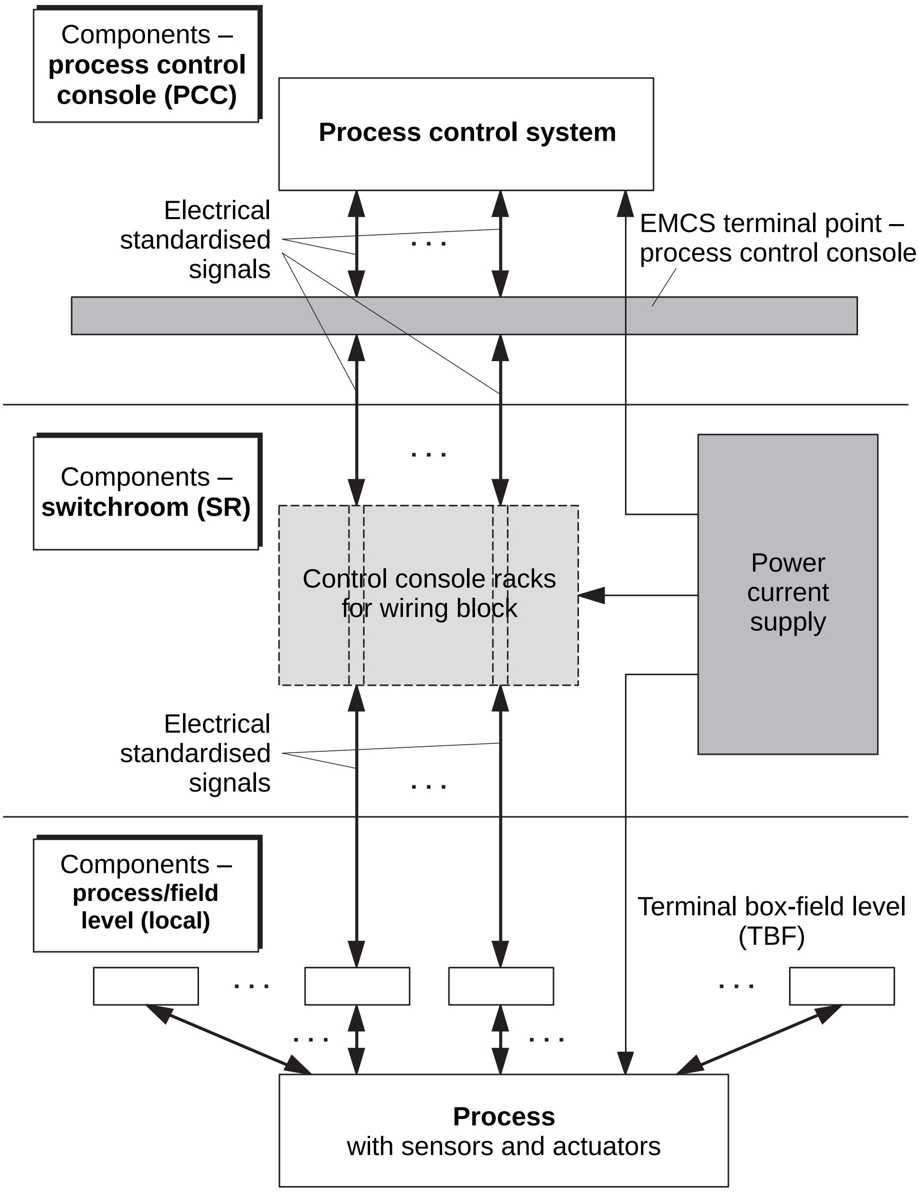


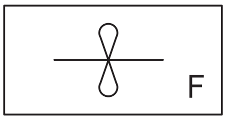
Fig. B2-15: Modified linking of standardised signal path in the automation system structure

As already mentioned, appropriate symbols are used for the creation of preliminary and final EMCS block diagrams (DIN 19227/Part 2), whereby the automation equipment actually used in the configuration of an EMCS point are defined. If we refer to the sample structure indicated in fig. B2-16, this begins with a practical method of approach with the symbols for field instrumentation, and then deals with the processors or other components (e. g. displays).

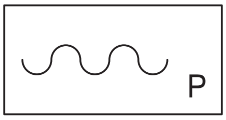
In conformance with DIN 19227/Part 2, the term 'detector' is now also given for sensors (measuring technology) and the following symbols are recommended:

Basic symbol for sensor/detector
(general representation)

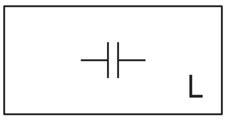
(Examples used – Sensors)



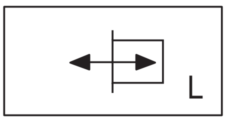
Turbine flow sensor for flow rate
(Turbine flow meter)



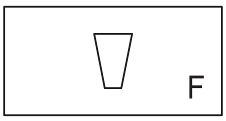
Diaphragm sensor for pressure
(pressure sensor)



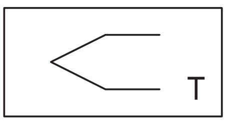
Capacitive sensor for filling level
(Filling level sensor –capacitive)



Ultrasonic sensor for filling level
(Ultrasonic sensor)

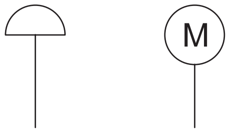


Float for flow sensing



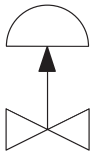
Thermo element
(for temperature measurement)

The following symbols are to be used for the actuators deployed at field level (process):

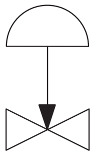


Basic symbol for diaphragm servo-drive and motor drive

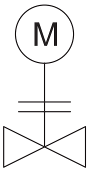
(Examples used – Actuators)



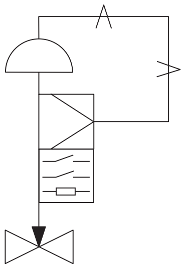
Servo-drive/Valve actuator (pneumatic) with regulating valve (opens in the event of auxiliary energy failure)



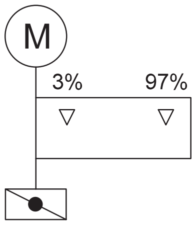
Servo-drive/valve actuator (pneumatic) with regulating valve (closes in the event of auxiliary energy failure)



Servo-drive/valve actuator (electrical) with regulating valve (maintains position in the event of auxiliary energy failure /steady-state)

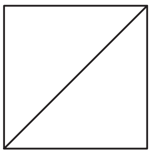


Servo-drive/valve actuator (pneumatic)
with attached position controller,
analogue and binary actuator acknowledgement
and with regulating valve



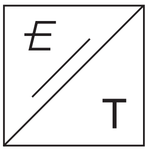
Flap actuator with limit signal generators at 3 % and 97 % of travel

DIN 19227 also provides a series of symbols for the measuring transducers / signal converters (adapters / safeguarding of standardised signal concept) installed in the switchroom.

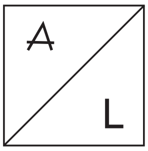


Basic symbol for measuring transducer

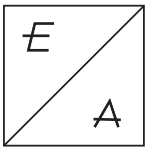
(Examples used – Measuring transducers)



Measuring transducer for temperature with electrical standardised signal output and electrical isolation

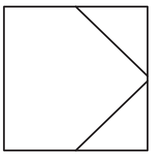


Measuring transducer for level
with pneumatic standardised signal output



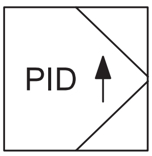
Converter for electrical standardised signal
into pneumatic standardised signal

Finally, appropriate symbols also need to be used for the automation equipment of the process control console (process control system / compact controller / display).

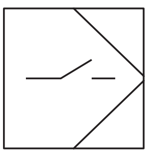


Basic symbol for closed-loop controller

(Examples used – Controllers)

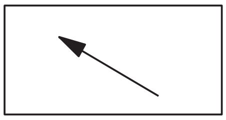


PID-controller with rising output signal
during rising input signal



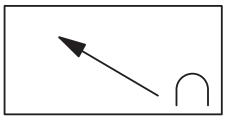
Two-point controller with switching output

Additional symbols are used as a result of the displays (outputs), which are also located in the process control console.

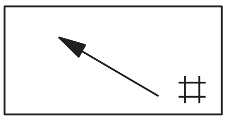


Basic symbol for display

(Examples used – Display/ outputs)

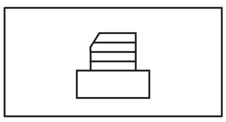


Display – analogue



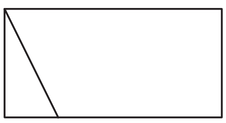
Display – digital

Limit signal generator / Limit monitor
for lower and upper limit value



Printer

The following symbols are used to represent the binary control systems, which are also required to automate process technology operations.



Basic symbol – binary control system

This set of symbols covers all the important automation equipment to be recorded in the EMCS block diagrams.

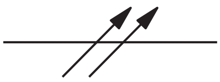
Finally, appropriate symbols also have to be used for the connection of of this automation equipment to identify the corresponding transmission lines in accordance with DIN 19227/ DIN 19227/Part 2.

(Examples used – Transmission lines)

Standardised signal line, electrical

Standardised signal line, pneumatic

Coaxial line (e. g. for use of bus systems)

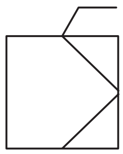


Fibre-optic cable

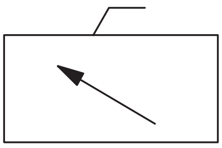
One concluding consideration of significance for the immediate preparation of these EMCS block diagrams, arises from the question concerning the type of hardware used for automation equipment.

The following should be noted in this context:

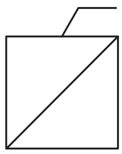
- The proposed symbols for sensors and actuators are to be used independently of the basic hardware used (e. g. size, constructional design, etc.).
- The symbols you are now familiar with are modified as follows for the equally essential processor and display technology, as well as the measuring transducers and binary control system, which can also be realised, e.g. in a process control system, by means of software functions:



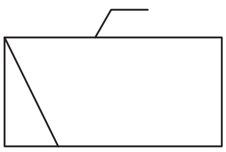
Controller realised as software function



Display realised as software function



Measuring transducer/adapter realised as software function



Binary control system realised as software function

As already indicated, the preliminary EMCS block diagram connects the automation equipment required for the configuration of EMCS points.

The small-scale installation is used as an example to set out the preliminary EMCS block diagram for the filling level closed control loop (fig. B2-16).

To this end, the following have been configured, based on the structure of an automation system: Sensors and actuators at the field level; measuring transducers in the switchroom, plus for instance also a compact controller (PLC technology), and the operating and monitoring computer in the process control console.

In parallel with the preliminary EMCS block diagram, the so-called *Equipment_list* (Table 1) is prepared.

EMCS point	Displ.	Device	Loca-tion	Range	Auxiliary energy	No. *
LIC30	1	Analogue ultrasonic sensor	Field level	0 to 20 mA	24 V DC	1
LIC30	1	Drive of centrifugal pump with pump	Field level	0 to 24 V DC		4
LIC30	1	Electr. measuring transducer (thyristor controller)	Field level	IN: 0 to 10, 24 V DC OUT: 0 to 10 V DC	24 V DC	3
LIC30	1	Digital controller/ compact controller	SR	IN: 0 to 20 mA OUT: 0 to 10 V DC	230 V AC	2
LIC30	1	Electr. measuring transducer	SR	IN: 0 to 20 mA		5
LIC30	1	Master computer (PC)	PLW		230 V AC	6

*Table 1:
Equipment list for
filling level
closed control loop (LIC 30)*

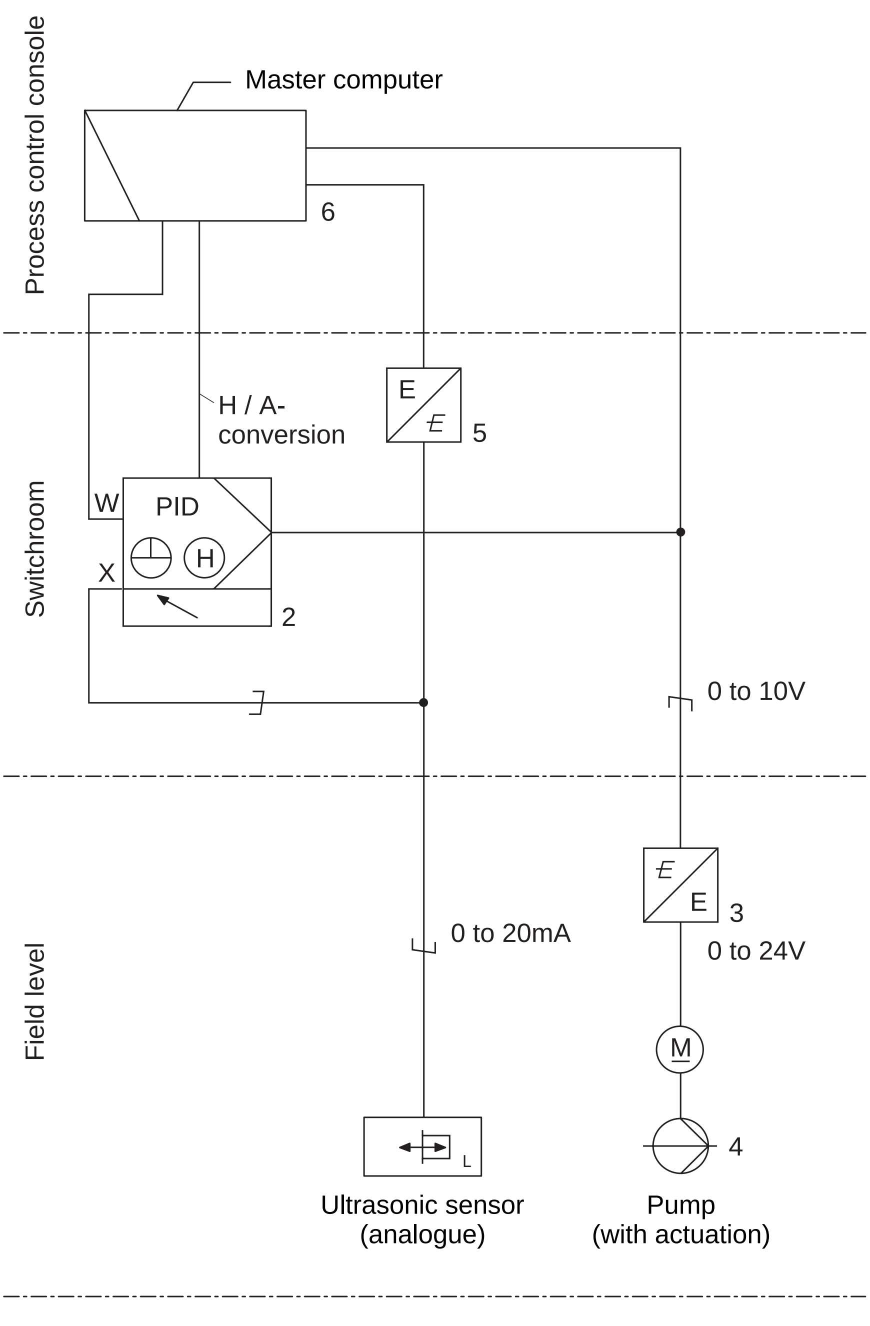


Fig. B2-16: Preliminary EMCS block diagram – filling level closed control loop

This list is drawn up for each EMCS point and in that order contains the automation equipment for sensor, actuator, transducer and processor technologies with precise designation so that, apart from the purpose of documentation, it also contains the necessary ordering information.

In addition, the so-called *allocation lists are also prepared on the basis of the preliminary EMCS block diagrams.*

The allocation lists are geared to the container systems used in the automation system and as such provide the assembly specification for the attachment of the automation equipment deployed (fig. B2-17). In this context it should be noted that the container systems used are subdivided into assembly levels and these again into assembly positions.

The allocation list is therefore a clearly arranged document used directly for the assembly of the automation equipment.

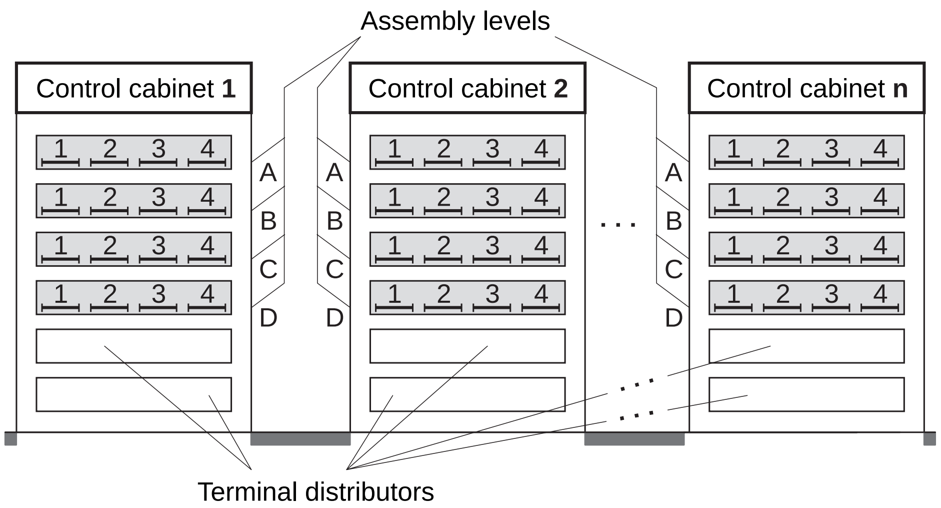


Fig. B2-17: Allocation list – basic configuration

Final EMCS block diagram

Based on the preliminary EMCS block diagram, the final EMCS block diagram documents the detailed wiring of the automation equipment and thus represents the basis for the creation of the wiring documentation. To provide a better understanding, reference is again made to the structure of an automation system defined in fig. B2-5, which now poses the task of interconnecting the components process control console, switchroom and field by means of wiring.

The basis of this wiring are the respective wiring harnesses and the corresponding terminal distributors. Fig. B2-18 illustrates the structure of the *wiring paths and the assembly points of these terminal distributors* defined in the container units of process control console, switchroom and as such in the terminal boxes at field level. This illustrates that the terminal distributors are the major support points for the wiring paths, since they accommodate the incoming cables and route them via corresponding wiring blocks to the assembly levels of the control cabinets or other container units.

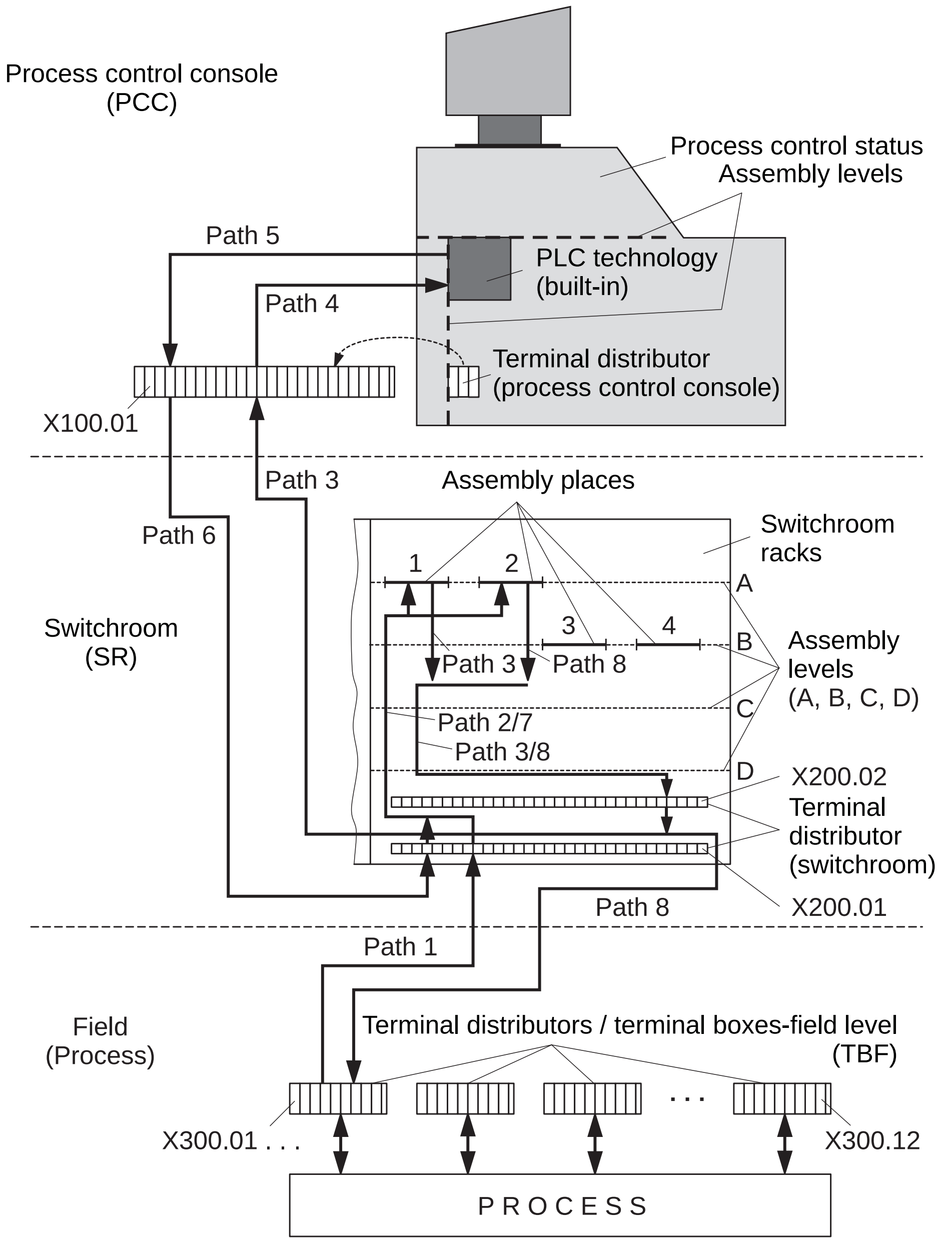


Fig. B2-18:
Structure of wiring path

Fig. B2-19 provides an initial introduction to the principle designation of a terminal distributor.

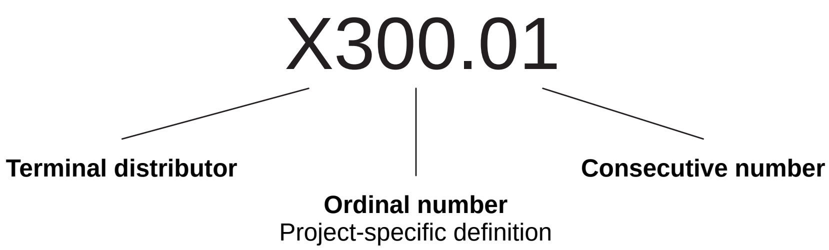


Fig. B2-19: Basic designation of a terminal distributor

It should be noted generally that the terminal distributor designation always starts with the letter X, and completed by an ordinal number and a consecutive number. Here, the hardware design of the terminal distributors is also of interest.

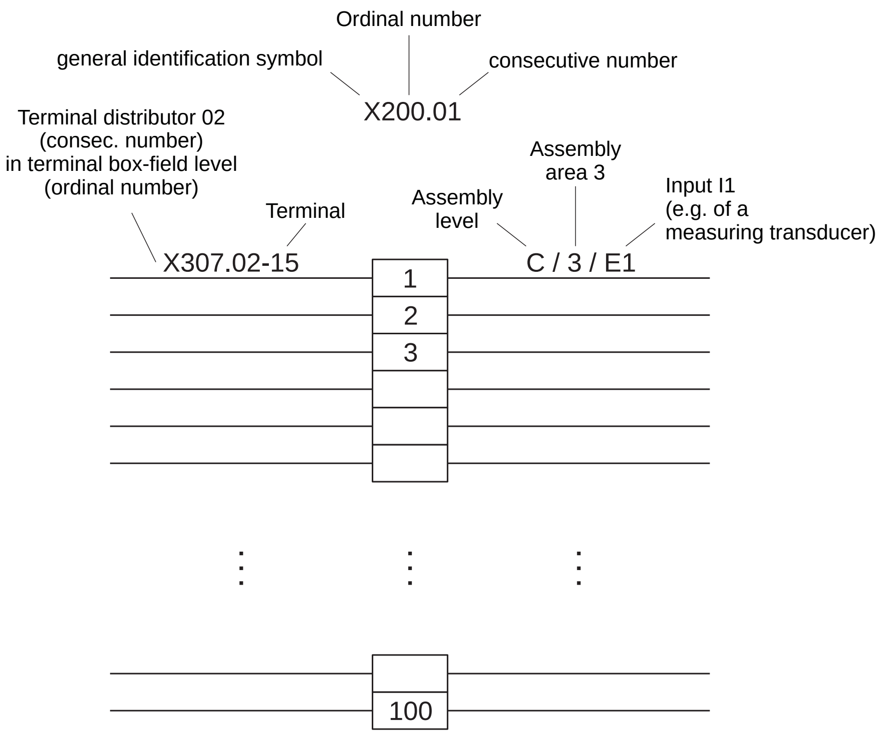


Fig. B2-20: Design of a terminal distributor

Fig. B2-20 provides a closer introduction of this design. In the sense of a general evaluation, it is always important to ask where a line (cable) is coming from (from which terminal distributor) and where it is to lead to (to which terminal distributor / assembly area).

For instance, if you consider a designation proposal (nomenclature) in this context, the following allocation is also feasible taking into account fig. B2-16:

- Terminal distributor – field level / Terminal boxes-field level
  X300.01; X300.02...X 300.nn
- Terminal distributors – switchroom
  X200.01...X200.nn
- Terminal 196 process control console
  X100.01...X100.nn

In addition, the main wiring paths are also clearly defined in fig. B2-18, and can be used as a general orientation for any automation system. On the assumption that the respective sensors and actuators are connected to the terminal boxes at field level, the following wiring paths can be defined in sequence:

Path 1

- From terminal box-field level to terminal distributor-switchroom
- e. g.: X300.01 ⇒ X200.01

Path 2

- From terminal strip-switchroom to assembly area switchroom racks
- e. g.: X200.01 ⇒ Level A/Area 1

Path 3

- From assembly area switchroom racks via terminal distributor switchroom to terminal distributor process control console
- e. g.: Level A/Area 1 ⇒ X200.02 ⇒ X100.01

Path 4

- From terminal distributor-process control console to PLC
- e. g.: X100.01 ⇒ P-I/O card of PLC (DE 1)

Path 5

- From PLC to terminal distributor-process control console
- e. g.: P-I/O card of PLC (DA 11) ⇒ X100.01

Path 6

- Terminal distributor-process control console to terminal distributor-switchroom e. g.: X100.01 ⇒ X200.01

Path 7

- Terminal distributor-switchroom to assembly area-switchroom racks
- e. g.: X200.01 ⇒ Level A/Area 2

Path 8

- Assembly area-switchroom racks via terminal distributor switchroom to terminal box field level
- e. g.: Level A/Area 2 ⇒ X200.02 ⇒ X300.01

The wiring lists are then set out in accordance with these wiring paths and, as such, the connections documented in the final EMCS block diagram of the automation equipment involved in the configuration of the EMCS points, are put into an easily manageable form for the process control engineer.

Fig. B2-21 also uses the example of the filling level control (LIC30 small-scale experimental modules) to introduce the final EMCS block diagram and to give a partial representation of a wiring list (table 2). The wiring list is partially represented in table 2, and set out in accordance with the configuration already described in section B.3.3.

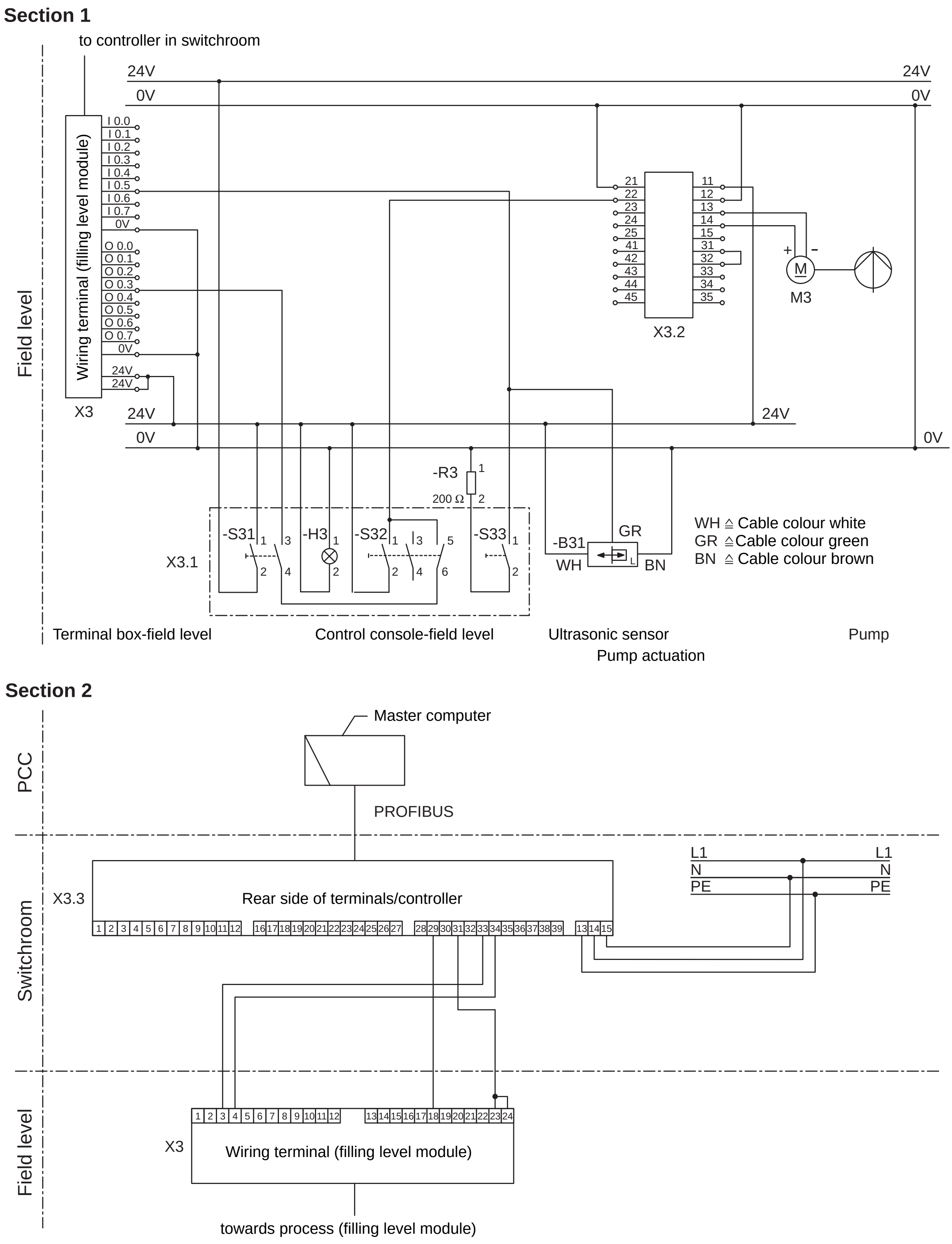


Fig. B2-21:
Final EMCS block diagram – Filling level closed control loop (LIC 30) (Part 1 and 2)

Table 2:
Wiring list (excerpt A) using the example of the filling level closed control loop (LIC30/Part 2)

Terminal strip X3.3				
from		**X3.3**	**to**	
Location/ Terminal strip	Terminal number		Terminal strip	Terminal number
Field level/X3	3	33	Profibus cable to master computer	
Field level/X3	4	34		
Field level/X3	18	29		
		13	Protective earth PE	

2.2.5 Notes regarding project design of auxiliary energy

Introductory comments

As already shown in figure B2-6, the project design work also includes the appropriate project documentation for the provision of the electrical, pneumatic and hydraulic auxiliary energy, apart from the core project. Due to the technical specifics and considerable amount of work involved, the electrical project accounts for the greater part except for the core project. The principal outlines of the electrical project design are therefore introduced in shortened form.

Determining the required electrical power (connected load)

The first point to be established is what electrical connected load is to be made available for the operation of the automation system. This is assessed on the basis of the preliminary EMCS block diagram and the automation equipment set out in the equipment list and the required electrical voltages (e. g. 230 V AC, 24 V DC) and capacities established. All EMCS points are subject to these analyses and the entire electrical power required determined by way of coordinating these.

Regarding the connection/combination of electrical project and core project

The EMCS block diagram based on the preliminary EMCS block diagram also defines the detailed cabling for the required voltage supplies. This highlights the relevance of the question for an interface for the respective reduction of the required voltages. Fig. B2-22 illustrates a structure, which provides a solution to this problem.

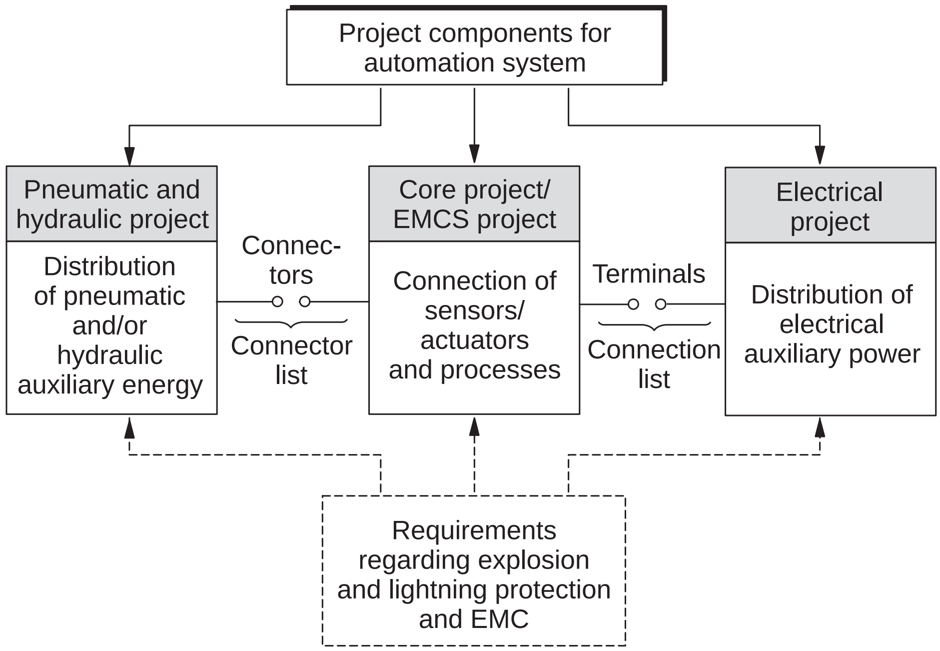


Fig. B2-22: Combination of core project with electrical and pneumatic project

This means that the selection of a voltage-proof terminal distributor provides a means of connecting the voltages resulting from the electrical project established on the input side and conducting these to the EMCS points on the output side of the terminal distributor. This allocation (block diagram) is uniquely documented in the so-called connection list. As fig. B2-22 also shows, this principle is also used to realise the supply of pneumatic and hydraulic auxiliary energy (connection list). Moreover, reference is also made to the additional problems to be solved of EMC and lightning and explosion protection.

Distribution of auxiliary electrical power

Based on the established connected load, a favourable structure is to be developed for the distribution of this electrical power. In accordance with the PI flow diagram familiar from the core project design, a general structure is also required for the distribution of the electrical auxiliary power with regard to the electrical project. Fig. B2-23 shows a generally applicable and typical structure for this. When the electrical project is further configured, this needs to be expanded by a second version comprising documentation of basic wiring and switching devices.

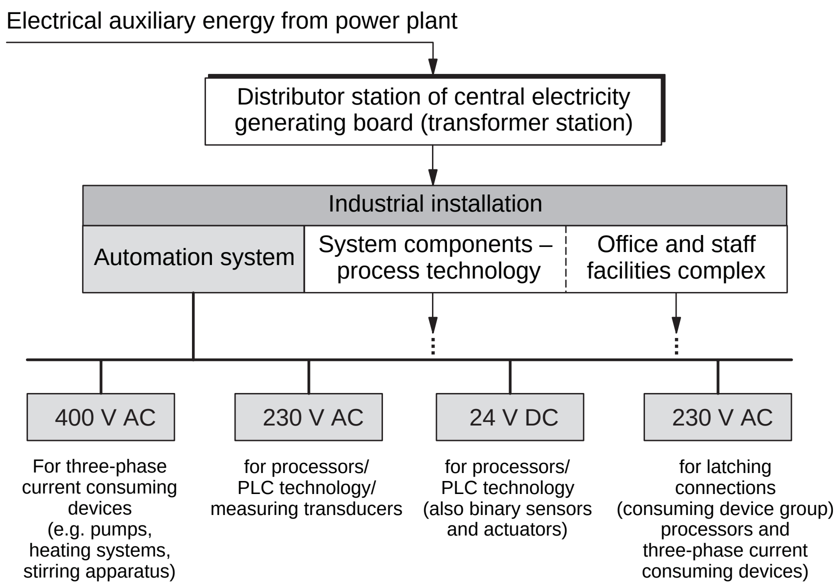


Fig. B2-23: Basic structure for distribution of electrical auxiliary energy

Breakdown of general structure

Depending on the extent of the electrical project, this general overview is followed by a further breakdown into one or several levels, by developing the so-called circuit diagrams, which are also based on the EMCS block diagrams realised during the core project design. These circuit diagrams define the detailed distribution (wiring) of the electrical auxiliary power.

The example of a typical component is used – connection of the auxiliary electrical power – to define the circuit diagram (fig. B2-24) for the latching connection of processors and three-phase current consuming devices. This circuit diagram illustrates for instance that the processors and current consuming devices must always be connected separately or that for reasons of safety, two contactors (C1/C2; C3/C4) must always be released when these are switched off or in the case of an emergency-stop.

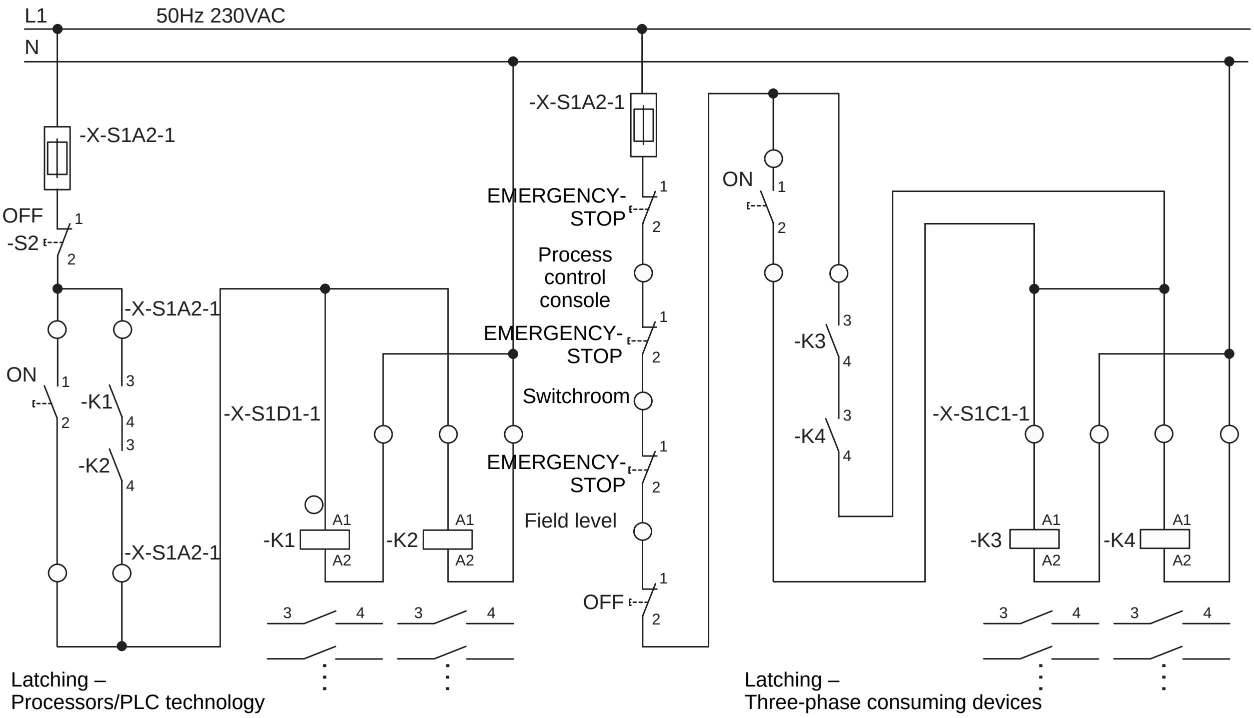


Fig. B2-24:
Circuit diagrams for electrical auxiliary energy (self-latching) for processors/PLC technology and three-phase consuming devices

Brief evaluation and comments

Understandably, the above information merely provides an idea of the extent and technical contents of electrical project design.

In the sense of a holistic preparation of the project of an automation system, it is essential to remember that, apart from the core project design, the electrical project design is the fundamental basis.

This fact should be taken into account with regard to the time schedule and cost plan to ensure the success of the project design work.

2.2.6 Notes regarding assembly project design

Apart from the core and electrical project design, the assembly project design represents the most important aspect for the realisation of an automation system. It takes into account all the construction and assembly technological aspects. Based on the design of the process technology system, including any associated building components, the assembly project design deals with problems such as

- configuration of the cable run guides (for EMCS and electrotechnology),
- determining of material requirements for cable runs (number of cable run components, supports, brackets, etc.),
- determining of cable lengths and types of cable,
- design and construction of cable harnesses,
- spatial planning of the required container units and auxiliary units (e. g. compressor room, emergency power source)

etc.

These services must also be implemented with the greatest of care, since they are crucial in determining the cost efficiency and schedule effectiveness of the practical realisation (assembly) of an automation system.

2.3 Closed control loop synthesis

2.3.1 Introductory comments

Another important task of project design work is undoubtedly the configuration and commissioning of the designed closed control loop and the binary control system. On the basis of the automation of process technology, the most important task in this respect is the commissioning of the closed control loop. The following therefore explains the main aspects involved in the solution of this problem.

2.3.2 Process analysis / Model configuration

To be able to solve an automation task (configuration and commissioning of closed control loops), it is essential to have the most comprehensive information possible with regard to the static and dynamic characteristics of the control system (processes) to be automated. The attainable quality of the solution is largely dependent on the qualitative and quantitative knowledge available concerning the technical process to be automated, in order to be able to define in detail appropriate algorithms for its control and the required hardware and software tools for its realisation.

The analysis of the behaviour and the characteristics of technical systems (controlled systems) is known as process analysis or model configuration; the result of which is known as a process model or, in short, model. Models of this type not only assist in the design of automation systems, but also are of fundamental importance for other areas of technology, natural sciences, economics, etc.

Behavioural models

In the area of technology, so-called behavioural models play a major part and are intended to reflect accordingly the system behaviour with regard to cause, effect and correlation. Behavioural models are mainly used to predict events. They are used with the intention of being able to determine future system behaviour with sufficient accuracy, i.e. to determine the reactions of the system to causes (input signals), which are not yet of importance at the model configuration point.

A "good" model reflects the behaviour of the original concept as adequately as possible with the use of simple means. It should merely reflect the behaviour of the original, which is of relevance to the solution of a particular task. Being a substitute of the original, the objective of the model must be in agreement with the functional behaviour of its original. The performance (quality) of models must therefore be sufficiently tested with regard to application prior to its practical utilisation, e.g. for the design of automation systems.

Since system behaviour is largely dependent on the signals acting upon the system (correcting and disturbance variables), a process model generally consists of a system model and a signal model. To design a controlling device, you need to know whether a system is operated primarily by means of step-type, periodic or accidental signals. A signal analysis therefore generally also forms part of the process analysis; in some cases, the signal analysis is the sole aim of the process analysis.

Models are therefore used in the design of open and closed control systems for the

- selection and definition of appropriate measured variables and correcting variables
- detection and evaluation of interference signals
- description of static and dynamic behaviour of controlled systems
- detection of functional links between process variables
- simulative calculation of design variants
- selection of control algorithms and dimensioning of the characteristic values of the controlling device.

Model configuration strategies

The model can be configured along theoretical and/or experimental lines (fig. B2-25).

In the case of theoretical model configuration, the physical/chemical processes occurring in an actual technical system are analysed and mathematically formulated with the help of the familiar laws of mechanics, thermodynamics, etc.

With experimental model configuration, the input and output signals of the actual technical systems are measured and evaluated, whereby artificially modulated or naturally occurring input signals such as step-change signals may be used. To a certain degree, the objects to be modelled are therefore analysed externally.

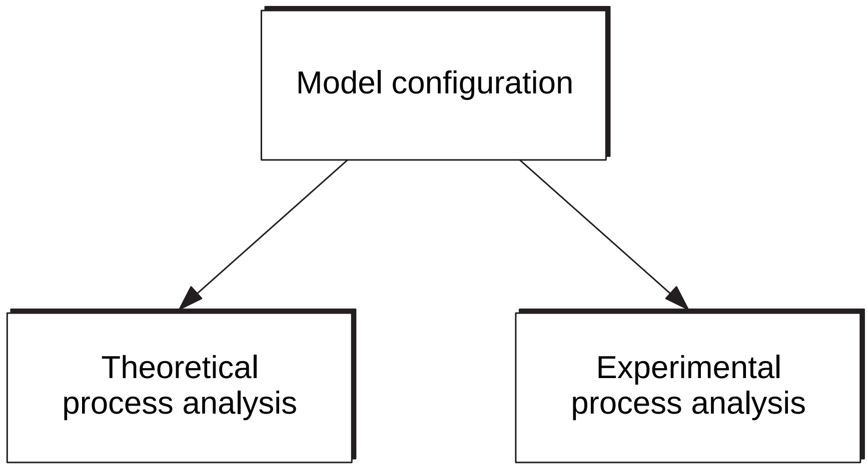


Fig. B2-25: Fundamentals of model configuration

At this point, it should be emphasised that a model obtained along this experimental line seldom permits any information about the actual physical/chemical processes in the process. The model merely describes the interaction between input and output variables and is therefore also known as an I/O model. It is therefore quite common for the two methods of model configuration to be combined by determining the model configuration by means of theoretical system analysis and the model parameters (characteristic system values) by means of experimenting .

Model configuration

In automation technology, calculation models (behaviour models in the narrower sense) are primarily used, which quantitatively describe the main relationships between process variables, e. g. in the form of mathematical correlations, characteristic functions, performance data, etc.

Fig. B2-26 illustrates the basic structure of this form of model.

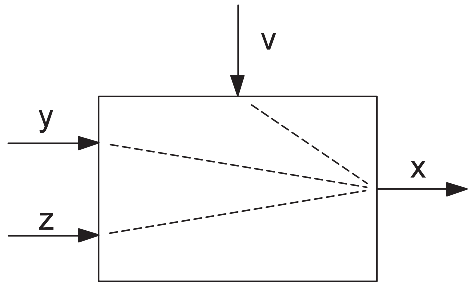


Fig. B2-26: Basic structure of calculation models, y – correcting variable, z – main disturbance variable, v – negligible disturbance variable, x – output variable

This provides an initial illustration of the line of action of the process signals, without the sometimes complicated "process content". Moreover, it is assumed that all process variables (e. g. flow rate, temperature, filling level, etc.) are dependent merely on time, but not on location (such as in the case of process technology systems of significant physical dimensions) .

In accordance with fig. B2-26, the calculation models now have to quantitatively represent the dependence of the output variable *x* on the input variable *y, z* and possibly also *v*, whereby a differentiation should be made here between static and dynamic models.

The relationship between the input and the output variables of a technical system in its steady-state condition is known as the static behaviour. A simple example of this is shown in fig. B2-27, in the form of a so-called correcting characteristic of a controlled system, i.e. the relationship between, for example, the valve position *y* as a process input variable and the temperature *x* as a process output variable with the main interference *z* (e. g. pressure) as a performance data parameter.

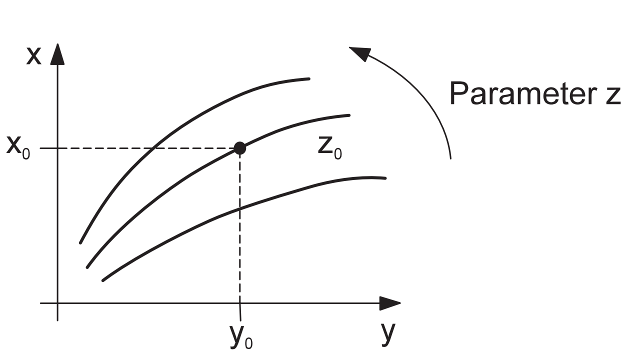


Fig. B2-27:
Control characteristic curve in the form of steady-state model

The index zero designates the working point values (process signal values during nominal operation).

However, input and output signals change from time to time during the operation of technical equipment, due to starting and shut down procedures and varying, unforeseeable disturbances. This is why it is often essential for the process model to include the description of the relationship between these time-related signal changes, which is also known as dynamic behaviour. Dynamic models in the form of linear models are often adequate, even for example for the important task of process stabilisation with the help of a closed control loop. This is possible in cases where the process signals operate sufficiently closely to the working point during the execution of technical processes, so that the process behaviour does not perceptibly change even during transitional phases. In the case of practical operation of automation equipment, it then becomes necessary to consider the limits of the linear operating range. If these are exceeded, then the results achievable in the course of the system design using the linear models are put into question.

Model configuration through experimental process analysis

The following describes the procedure of experimental model configuration in greater detail. The main feature of this is that, with the help of suitable experimental technology, the analyses are carried out immediately on the technical system and the data obtained can be converted into a process model graded according to different levels (starting with the simple manual analysis method through to computer assisted data evaluation) (fig. B2-28).

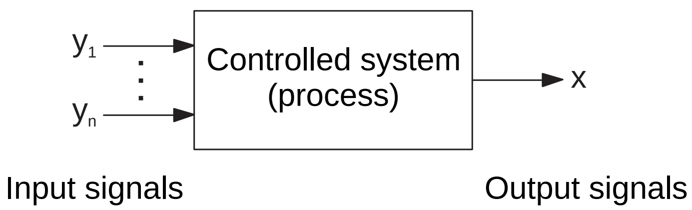


Fig. B2-28: Basic structure for experimental process analysis

The main points and problems of an experimental process analysis consists of

- the formulation of requirements demanded of the model (application aim, accuracy, validity range)
- the preparation and implementation of the experiments
- the selection of suitable methods for the analysis of the process data recorded and
- error estimation and model verification.

As part or the preliminary stage of the experiment, the following should be considered

- the auxiliary hardware and software devices
- the model structure (e. g. in the form of qualitative information regarding the process behaviour)
- the main process influencing variables, in particular also the disturbance variables
- the required measuring times.

The hardware and metrology preparations include

- the assembly of suitable control, measuring and recording techniques, unless already available on the process and
- the verification of the experimental techniques/technology under operating conditions.

As part of the experiments, it is often necessary to carry out preliminary experiments in order to establish modulation ranges, adequate signal-to-disturbance ratio and main influencing variables. With the main experiments it is important to ensure that sufficient data material is registered to determine the working point values (initial values at start of measurement). Useful signals at the system output must have sufficient noise ratio; in the case of experiments with step-type input signals, they should therefore be modified by approximately 10 % of their correcting range (caution: observe linearity range!).

Fig. B2-29 shows an example of the undisturbed (theoretical), i.e. faulty (determined during practical operation) step response x(t) of a technical system. A simple quantitative measure of the signal/disturbance ratio is the amplitude ratio $S = \frac{A_S}{A_N}$ of disturbance signal and useful signal in the steady-state condition.

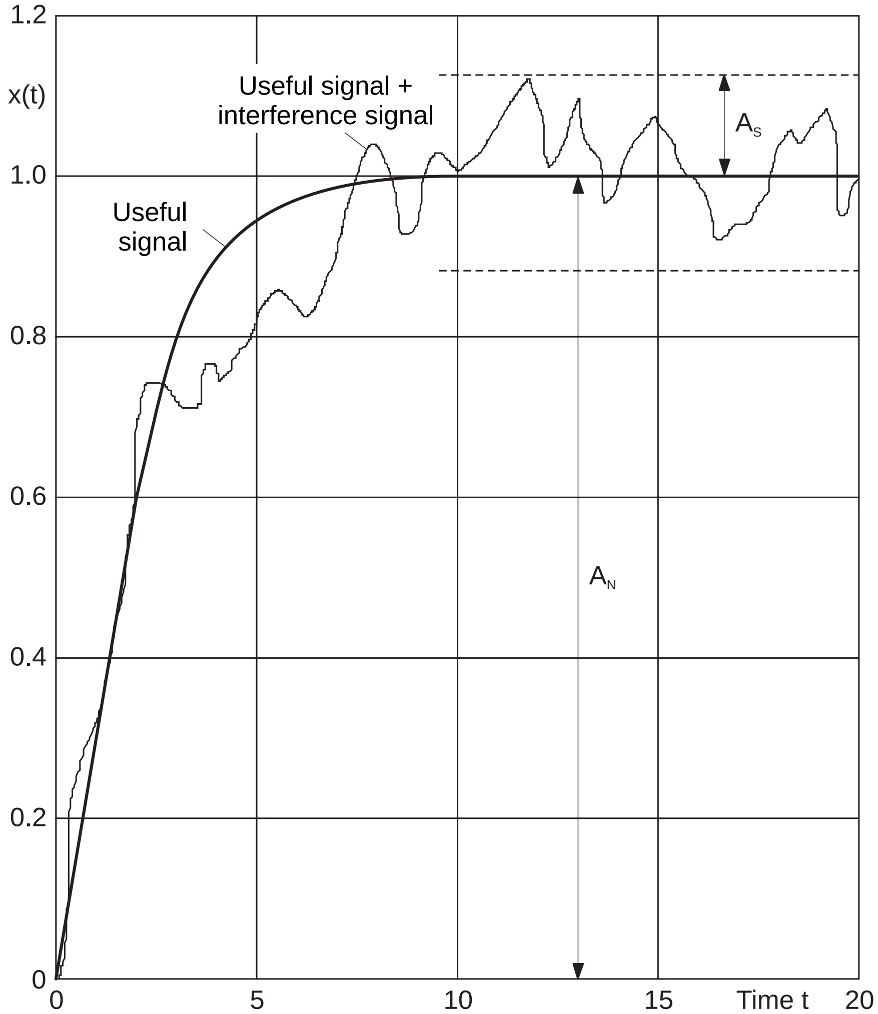


Fig. B2-29: Illustration of disturbance/useful signal ratio using the example of a faulty step response

Step responses of technical systems

When planning the experiments, two aspects are of particular importance:

- the selection of suitable test signals (system input signals) and
- the selection of the observation time, during which the signals are acquired.

The test signal must activate the system to be analysed sufficiently so that it is possible to detect the system characteristics with as large a signal-to-disturbance ratio as possible. It should also be as easy as possible to realise and detect. This is where test signals are particularly suitable which, at the start of the experiment, perform so-called step-changes, i.e. by a specific amount (zero-point stage). Examples of this are electro-mechanical or electro-thermal devices, which change their operating status during the switching on or connection of electrical voltages or outputs, or the control of material or energy flow in process technology systems via (solenoid) valves or pumps. Step-type test signals of this type are often used in practice and with success. They should therefore also be used here for the experimental process analysis.

The reaction of a system to a step-change signal is known as step-response. If this step response is related to the step-change height of the input signal (standardised representation), then this is known as the transient function of a system. This is always on the assumption that the linearity range around the operating point is not exceeded during the transition process and that the system was in the stationary state at the operating point to starting the experiment. Fig. B2-30 illustrates this process.

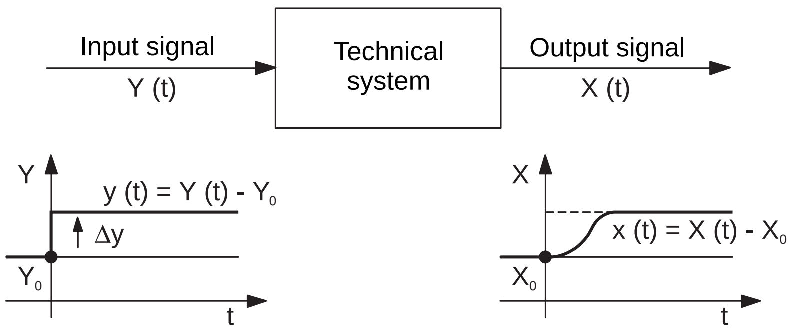


Fig. B2-30: Experimental determining of step response x(t)

X_0, Y_0 – working point values
y – step-change height of input signal y(t)
$h(t) = \frac{x(t)}{\Delta y}$ *– transient function*

At least with regard to practical matters, the step response, i.e. the transient function represents the most important form of a linear dynamic system model.

Depiction of response characteristic

The signal response characteristic of technical systems can be depicted qualitatively with the help of the transient function. Depending on the pattern of the transient function for long time periods ($t \rightarrow ...$), we differentiate between systems with P-action (P elements), I-action (I-elements) and D-action (D-elements). Following step activation, proportional elements acquire a new stationary status, differing from the operating point value; integral elements assume a constant rate of change of the system output variable for long time periods (warning: observe linearity range), and in the case of differential elements, the output variable reverts to the stationary state of the operating point value. These basic characteristics of technical systems are illustrated in fig. B2-31.

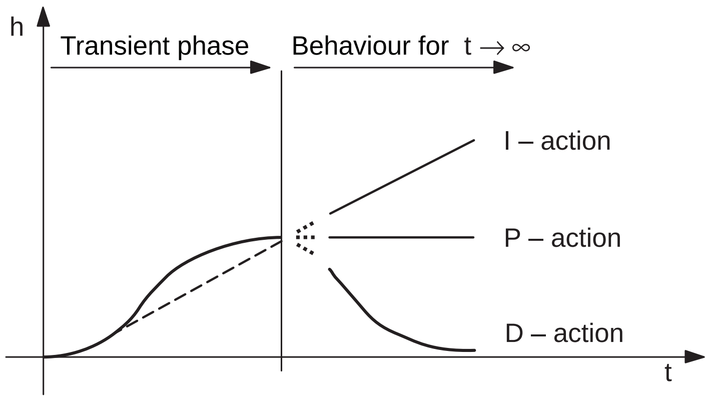


Fig. B2-31: Qualitative depiction of transient behaviour with the help of transient function

The inflectional tangent model

In numerous technical applications, particularly in the areas of process or energy technology, the system step responses occur without any oscillation ratio and only display proportional or integral action in connection with dead time. The transient function shown in fig. B2-32 in the form of a linear dynamic model is therefore often used.

The system behaviour is therefore considerably simplified, characterised by the three characteristic values: Proportional or integral coefficient, time delay and transient time.

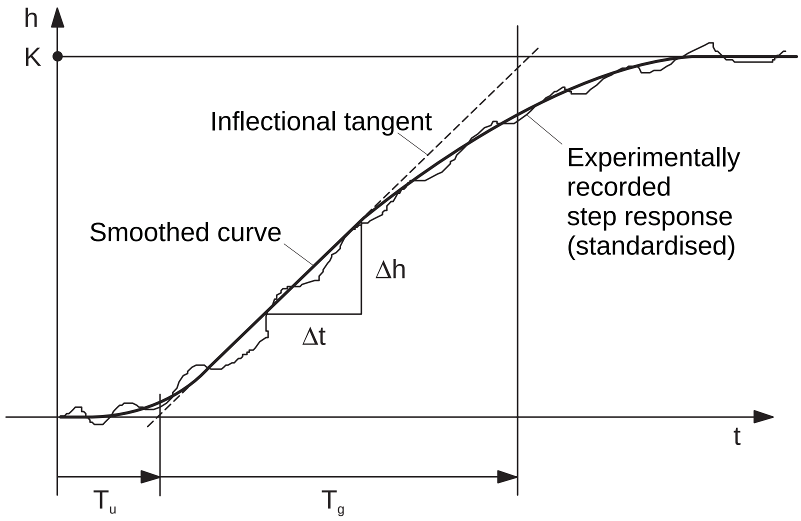


Fig. B2-32:
Frequently used transient function model (inflectional tangent model)

K – proportional coefficient
T_u – time delay
T_g – transient time
$K_{IS} = \frac{\Delta h}{\Delta t} = \frac{K}{T_g}$ *– Integral coefficient*

The inflectional tangent used to obtain the characteristic values T_u and T_g is for instance entered freehand into the experimentally determined step response. If this is subject to high-frequency interference, then a smoothing out should be carried out, if necessary by eye (or computer-assisted). In the case of low frequency interference, the process cannot be evaluated. Here, a number of repetitions of the experiment and smoothing by means of averaging can be of help.

Table 3 contains the characteristic model values of typical controlled systems.

Table 3: Model characteristic values of typical controlled systems

Variable to be controlled	Type of system	Time delay T_u	Transient time T_g
Temperature	Annealing furnace Laboratory	0.5 ... 1 min	5 ... 15 min
	Industry	1 ... 3 min	10 ... 30 min
	Distillation tower	1 ... 5 min	40 ... 60 min
	Superheater	1 ... 2 min	20 ... 100 min
	Space heating	1 ... 5 min	10 ... 60 min
Flow rate	Piping-Gas	0 ... 5 s	0.2 ... 10 s
Flow rate	Piping-Fluid	0	0

From the quotient $\frac{T_g}{T_u}$, it is incidentally already possible to estimate the degree of difficulty to be expected in the control of a system:

Table 4: Evaluation of degree of complexity of closed-loop control

Ratio $\frac{T_g}{T_u}$	Degree of complexity
> 10	Easily controllable
6	Just controllable
< 3	Controllable with difficulty

The total time constant model

Another simple basic model of proportional action controlled systems without oscillation ratio, which lends itself well for the controller design, can be determined in accordance with Strejc in the following way:

- The times | t_{20} or t_{80} are taken from the illustration of the system transient function, with which the function h(t) has achieved 20 % or 80 % of its final value,

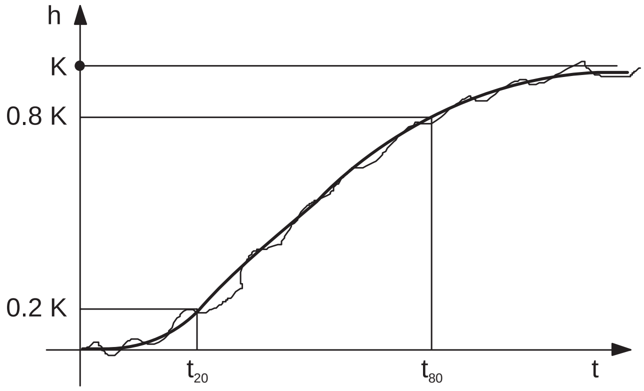


Fig. B2-33:
Controlled system transient function

- the transient behaviour of the system is then again described via three characteristic values:

K – Proportional coefficient of system

T – System time constant

T_t – System dead time.

Time constant T and dead time T_t are calculated from the time values t_{20} and t_{80} in accordance with the following formulae:

$$T = 0.721\ (t_{80} - t_{20})$$

$$T_t = 1.161\ t_{20} - 0.161\ t_{80}$$

The total of the two characteristic values T and T_t is referred to as total time constant T_Σ.

Model configuration for selected controlled systems

Flow control system

In the experimental state, the flow control system consists of a piping system, with which the water is removed from and returned to a container via a centrifugal pump (see fig. B2-34). The automation task is to regulate the flow *Q* in the piping.

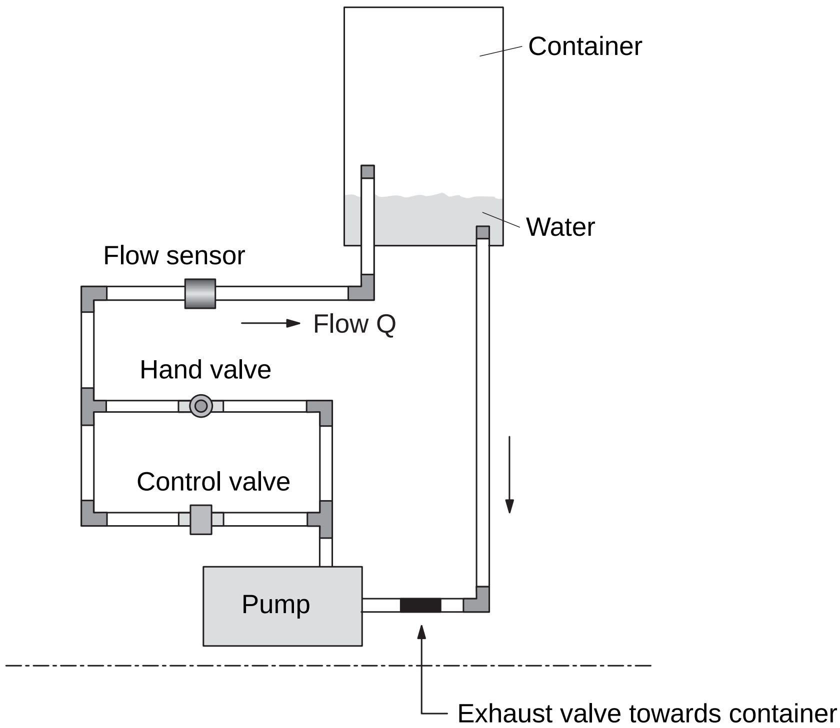


Fig. B2-34: Schematic representation of flow control system

Theoretical model configuration

Leaving apart the hardware and software details, the flow behaviour in the flow control system can be represented in a considerably simplified manner as follows (fig. B-35).

This means:

$\Delta p_0 = k_p N^2$ – Maximum delivery pressure of the centrifugal pump at speed N (for Q = 0)

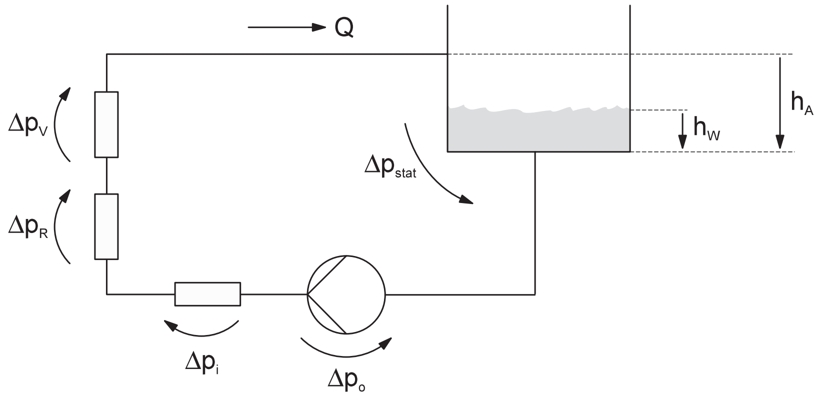


Fig. B2-35: Physical model of flow process in flow control system

$\Delta p_{Stat} = pg(h_A - h_W)$ für $h_A \forall h_W$, otherwise zero
– Differential pressure as a result of height difference

$\Delta p_i = k_i Q^2$ – Pressure drop as a result of "internal resistance" of centrifugal pump

$\Delta p_R = k_R Q^2$ – Pressure drop through the piping system

$\Delta p_V = K_S \dfrac{Q^2}{K_V^2(Y)}$ – Pressure drop through the control valve

K_V – K_V value (defined in section B2.4.2)

Y – Valve travel.

Static model of controlled system

In the stationary state (Q = *const.*), there must be a balance between the pressures, this means:

$$o = \Delta p_0 - \Delta p_{stat} - \Delta p_i - \Delta p_R - \Delta p_V$$

or

$$0 = k_p N^2 - \rho g\,(h_A - h_W) - \left\{ k_i + k_R + K_S \cdot \frac{1}{K_V^2\,(Y)} \right\} Q^2$$

If a linear characteristic flow curve is assumed with

$$K_V\,(Y) = kY$$

in the operating range (0 to 100 %) of the valve, then the following relationship is obtained from these equations assuming a constant water level h_W and constant speed N of the pump

$$Q\,(Y) = \sqrt{\frac{k_p N^2 - \rho g\,(h_A - h_w)}{k_i + k_R + K_S \dfrac{1}{k^2 Y^2}}}$$

Fig. B2-36 illustrates the qualitative pattern of this characteristic curve.

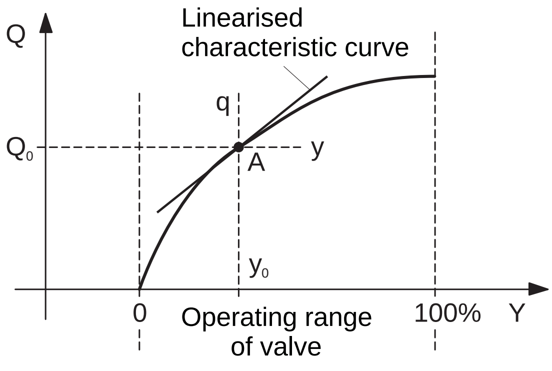


Fig. B2-36: Steady-state characteristic curve of controlled system if control valve is used to control the flow rate

In the area of the operating point A ($Q=Q_0 + q$, $Y=Y_0 + y$), the following linear correlation then applies

$$q = Ky \qquad \text{(linearised model).}$$

If the flow is regulated above the pump speed *N*, then the following linear relationship can be assumed in the operating range of the pump

$$Q(N) = k_1 + k_2N$$

between the correcting variable Pump Speed *N* and controlled variable Flow *Q* (see also fig. B2-37).

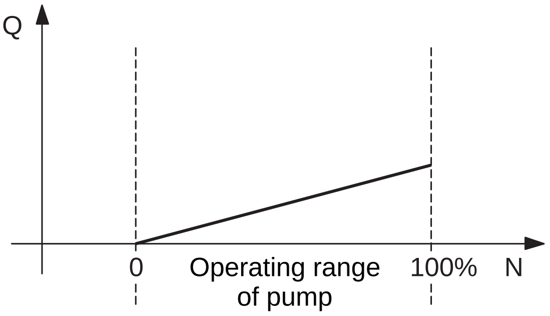


*Fig. B2-37:
Steady-state characteristic curve of controlled system if pump is used to control the flow rate*

Linear dynamic controlled system model

The flow control system for flow (input variable of valve position *y*, output variable of flow *q*) provides a good approximation of pure proportional behaviour without time delay. A change of the valve position results in a (practically) instant, proportional change in the flow. Transient phenomena caused by the acceleration of the volume of water in the piping system, can be disregarded here.

However, the time delay between the actuation of the control equipment (standard voltage signal V_e) and the valve position *y* must not be ignored. Here, proportional action with delay of the first order is to be expected. Fig. B2-38 illustrates the qualitative pattern of the step response of a transient element of this type.

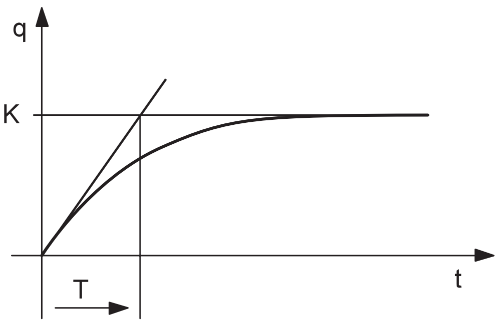


Fig. B2-38: Qualitative process of system step response

However, due to the arrangement of the piping system and the measuring technology and measured-value processing used, a (minor) system delay dead time T_t still has to be expected when the system is operated in practice, which will then have to be experimentally determined in the same way as the controlled system values *K* and *T*.

The same deliberations apply with regard to the transient phenomena relating to the use of the centrifugal pump. Here it must be assumed that the pump speed variation does not immediately affect the flow but that, due to the pump design, acceleration processes in the moving volume of water will lead to delays in the process. The same deliberations as above apply with regard to the dead time T_t.

All in all, these deliberations in the area of the operating point provide a qualitative dynamic system model (configuration model), which contains three parameters (K_S, T_t, T) still to be determined by experiment.

Filling level control system

The filling level control system in the experimental state consists of containers connected via two pipes and a pump, which are located at different height levels (see fig. B2-39). The water is conveyed from the lower to the upper container via the pump and pipe (1) and, from there, can freely flow back to the lower container again via pipe (2) by means of gravitational force. The purpose of the automation task is to regulate the water level in the upper container.

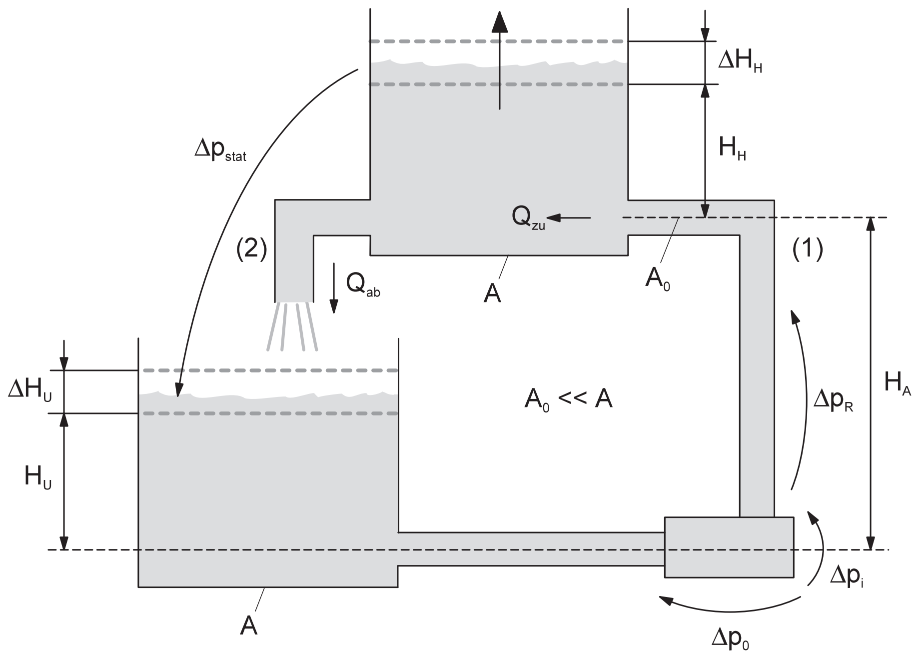


Fig. B2-39: Schematic representation of level control system

Theoretical model configuration

Model for the outflowing process from the upper container

This outflowing process can be represented in a very simplified form (see fig. B2-40).

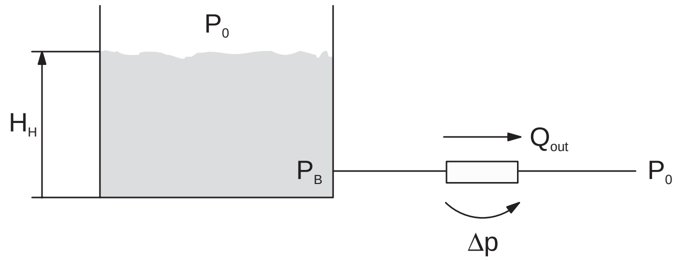


Fig. B2-40: Physical model of outflow process

The following abbreviations mean:

p_0	–	Atmospheric pressure
$p_B = p_0 + \rho g H_H$	–	Pressure at the bottom
$\Delta p = k_{R2} Q^2_{ab}$	–	Pressure drop via the pipe
Q_{ab}	–	Volumetric flow rate

and $\Delta p = p_B - p_0 = \rho g H_h$

becomes the volumetric outward flow $Q_{ab} = k\sqrt{\rho g H_H}$

Dynamic processes in piping systems, which could lead to delays of the processes, are disregarded in this instance, since the dynamic behaviour is determined mainly by the storage processes in the two containers.

Model for inflow process into the upper container

On the basis of the same deliberations as already described in detail, a balance must again exist between the partial pressures in the system, for which the following applies

$$0 = \Delta p_0 - \Delta p_{stat} - \Delta p_R - \Delta p_i$$

Using

$$\Delta p_{stat} = \rho g\,(H_A + H_H - H_U)$$

$$\Delta p_R = k_{R1} Q_{in}^2$$

$$\Delta p_i = k_i Q_{in}^2$$

results in the condition

$$0 = k_p N^2 - \rho g\,(H_A + H_H - H_U) - (k_i + k_R)\,Q_{in}^2$$

Here it should be noted that if the containers are identical in design, the total of the filling levels

$$H_W = H_U + H_H$$

remains constant.

This finally results in the correlation

$$Q_{in} = \sqrt{\frac{k_p N^2 - \rho g\,[H_A + 2H_H - H_W]}{k_i + k_R}}$$

between the pump speed N, level H_H in the upper container and inflow Q_{in} in the upper container.

The filling level H_H only changes if a difference ΔQ between inflow Q_{in} and outflow Q_{out},

$$\Delta Q = Q_{in} - Q_{out}$$

occurs.

Per time interval Δt, the volume of water V in the upper container would then change by

$$\Delta V = A \cdot \Delta H_H = \Delta Q \cdot \Delta t$$

If we use the inflow and outflow rates according to the equations quoted above are used here, this results in the following correlation in respect of the level change ΔH_H per time interval Δt

$$\frac{\Delta H_H}{\Delta t} = \frac{1}{A}\left\{\sqrt{\frac{k_p N^2 - \rho g\,(H_A - H_W + 2H_H)}{k_i + k_R}} - k\sqrt{\rho g H_H}\right\}$$

Steady-state model of the controlled system

In the stationary state *(H_H = const.)*, the inflow and outflow in the upper container must coincide,

$$Q_{in} = Q_{out}$$

and the correlation

$$\sqrt{\frac{k_p N^2 - \rho g\,(H_A - H_W + 2H_H)}{k_i + k_R}} = k\sqrt{\rho g H_H}$$

must therefore apply. If this equation is resolved with respect to the filling level H_H, this results in the following correlation for the interdependence between pump speed N and height level H_H in the stationary state

$$H_H\,(N) = \frac{k_p N^2 - \rho g\,(H_A - H_W)}{\rho g\,(2 + k^2\,[k_i + k_R]}$$

Fig. B2-41 illustrates the corresponding steady-state characteristic curve of the controlled system.

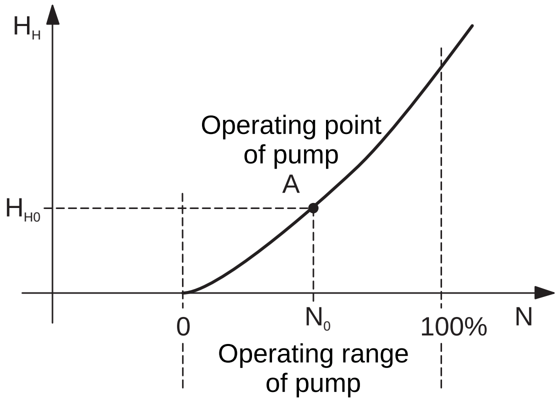


Fig. B2-41: Qualitative process of steady-state characteristic curve of controlled system

<u>Linear dynamic controlled system model</u>

The above mentioned correlation, which describes the connection between the status change ΔH_H per time interval Δt and the speed N or the height level H_H, applies in principle also to small process variable changes by their operating point values

$$H_H = H_{HO} + h_H \qquad N = N_0 + n$$

and results in the linear correlation

$$\frac{\Delta h_H}{\Delta t} = -a \cdot h_H + b\Delta n$$

with the two controlled system parameters a and b, which are system and operating point dependent.

Starting with an initial status (e. g. $h_H=0$) and specified time-related course of speed variation n (e. g. step-type change at time $t=0$), this equation can be resolved step by step and then results in the system step response shown in fig. B2-37, if a sufficiently short time interval t is used.

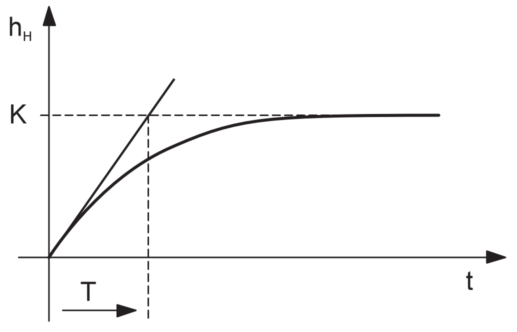


Fig. B2-42: Step response of level control system

This controlled system therefore also exhibits proportional behaviour with delay of the first order at the operating point and its characteristic values need to be experimentally determined according to the same considerations set out in the section Flow control system.

Temperature control system

The temperature control system of the small-scale experimental modules in the experimental state consists of an electrically heatable container, in which the water temperature in increased (fig. B2-43). To obtain a better distribution of temperature in the container, the water can be agitated by means of a centrifugal pump. This results in constant thorough mixing, which prevents the formation of differing heat levels.

The purpose of the automation task is to control the water temperature T (controlled variable) by means of the heat output P_{el} (correcting variable). The special characteristic of this controlled system is that the temperature is lowered solely as a result of heat dissipated to the environment. The output of this process, i. e. the heat dissipation ΔQ_{out} in the time interval Δt, is considerably less compared to the maximum heat output.

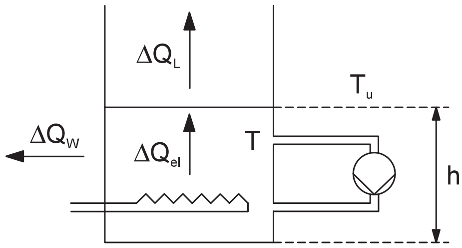


Fig. B2-43: Schematic representation of temperature control system

T	Water temperature in the container
T_u	Ambient temperature (air)
ΔQ_{el}	Quantity of heat output by heater system in Δt
ΔQ_L	Quantity of heat emitted directly to air in Δt
ΔQ_W	Quantity of heat emitted through wall in Δt
h	Filling level in container

Theoretical model configuration

The heating process in the temperature control system can be represented in a greatly simplified manner as follows (fig. B2-44).

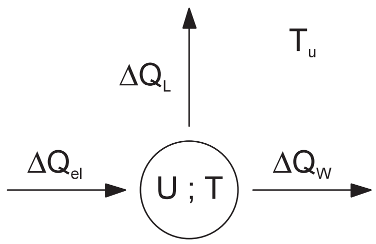


Fig. B2-44: Simplified representation of temperature control system

The following mean

$V = c \cdot m \cdot T$ – internal energy of volume of water with $m = \rho V = \rho \cdot A \cdot h$

$\Delta\, Q_{el} = P_{el} \cdot \Delta\, t$ – quantity of heat output via heating system in time interval Δt

$\Delta\, Q_L = \alpha \cdot A_L \cdot (T - T_u) \cdot \Delta\, t$ – quantity of heat (heat transmission) directly emitted to the air via the exposed water level in Δt

α – heat transmission coefficient (water – air)

$\Delta\, Q_W = k \cdot A_W \cdot (T - T_u) \cdot \Delta\, t$ – quantity of heat (heat transmission) emitted to the air via the wall in Δt

k – heat transmission coefficient (water – container wall – air)

The quantity of heat supplied and removed during time interval Δt, can be noted as follows

$$\Delta Q_{in} = P_{el} \cdot \Delta t \qquad \text{or}$$

$$\Delta Q_{out} = \Delta Q_W + \Delta Q_L$$

The temperature T only changes if a difference ΔQ occurs between the quantities of heat:

$$\Delta Q = \Delta Q_{zu} - \Delta Q_{ab}$$

This difference is the change of the internal energy of the volume of water

$$\Delta Q = \Delta U = c \cdot m \cdot \Delta T$$

Steady-state model of closed control loop

The supplied and removed quantities of heat must coincide in the stationary state (ΔQ = const., ΔT = const.),

$$\Delta Q_{in} = \Delta Q_{out}$$

and hence

$$P_{el} = \alpha \cdot A_L \cdot (T - T_u) + k \cdot A_W \cdot (T - T_u)$$

must apply. With an assumed constant ambient temperature, this equation results in the correlation

$$T(P_{el}) = \frac{P_{el}}{\alpha \cdot A_L + k \cdot A_w} + T_u$$

which indicates the dependence between heating capacity output and water temperature in the stationary state. Fig. B2-45 shows the steady-state characteristic curve of the temperature control system.

An assumed constant ambient temperature becomes less and less valid with increased heat dissipation. With increasing ambient temperature, the lost heat flow decreases, ($\Delta Q_{ab} \sim T\text{-}T_u$), whereby the water temperature becomes higher than in the ideal case.

The heating module used can be actuated intermittently, since it is either switched on at full capacity or switched off completely (two-point element). Any desired heat output can be achieved by means of periodic switching on or off of the heating module. The periodic time t_{per} is used to calculate the output from the switch-on time t_{on} and the heat output in the switched on status P_{elmax} at

$$P_{el} = P_{el\,\max} \cdot \frac{t_{on}}{t_{per}}$$

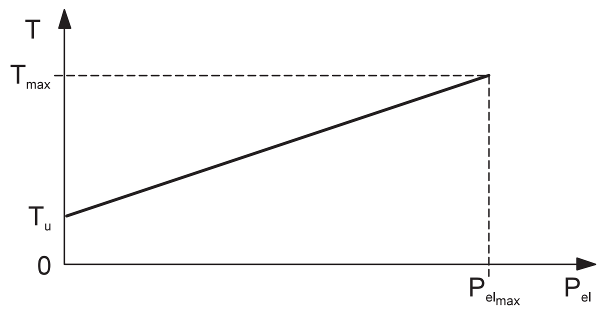


Fig. B2-45: Qualitative process of steady-state characteristic curve of temperature control system (ideal case)

The periodic time t_{per} must be sufficiently long so as not to excessively load the contactor in the control head in the heater modules as a result of frequent switching. On the other hand, the periodic time selected must be short, so that the temperature pattern remains even (fig. B2-46). This means that is must be considerably shorter than the controlled system time constant of the heating or cooling process
(e. g. t_{per} = 10 s).

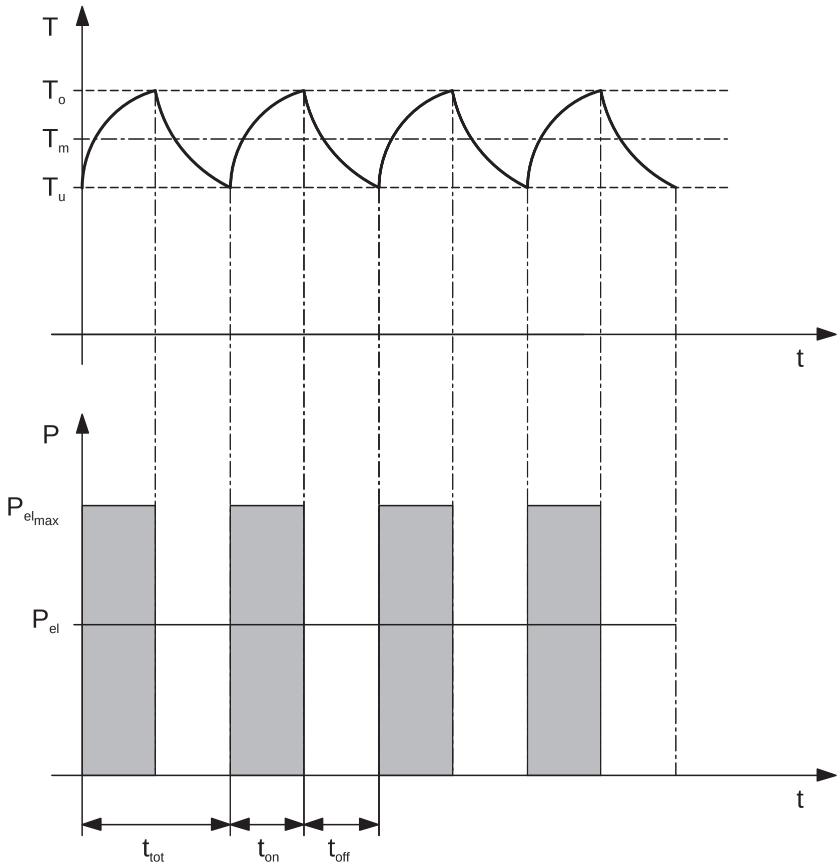


Fig. B2-46:
Temperature and performance pattern during on/off switching of heater module (two-point element)

Linear dynamic controlled system model

If we now look at the following equation again

$$\Delta Q_{in} - \Delta Q_{out} = c \cdot m \cdot \Delta T$$

and apply this for the supplied and dissipated quantity of heat, this results in the following correlation for the temperature change ΔT per time interval

$$\frac{\Delta T}{\Delta t} = \frac{1}{c \cdot m} \cdot [P_{el} - (\alpha \cdot A_L + k \cdot A_W) \cdot (T - T_u)]$$

This controlled system section represents a sufficiently small Δt selected, and is the basis of the behaviour shown in fig. B2-47a.

The temperature control system therefore has a proportional action with a delay of the first order. The change in heat output causes a gradual temperature change.

Again, it should be pointed out that the rate of change in temperature is not the same for heating and cooling. Fig. B2-47 shows the qualitative pattern of the two processes.

In addition, a considerably shorter dead time T_t occurs in the case of heating compared to the system time constant $T_{Heating}$. This is caused by the heat capacity of the heater module and the heat conduction speed in the water. This latter time constant can be lowered by moving or stirring the water. The parameters K, $T_{Heating}$ and $T_{Cooling}$ are to be determined by experiment.

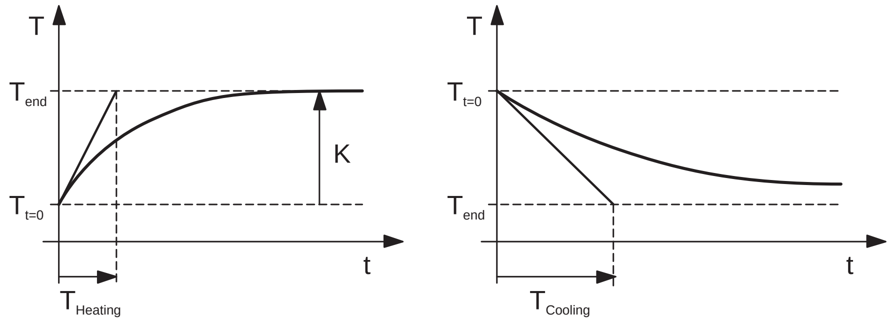


Fig. B2-47: Qualitative representation of system step response a) Heating b) Cooling

2.3.3 Controller configuration and parameterisation

Technical controllers are a component part of automation systems, whose main task is that of process stabilisation. They are used with the aim of

- bringing about and maintaining specific process states (mode of operation) automatically
- eliminating the effects of interference on the process sequence and
- preventing unwanted coupling of part processes in the technical process.

The process states addressed primarily refer to specific process parameters, such as pressure, flow, temperature, filling level and quality (pH value).

Mode of operation of closed control loop

Fig. B2-48 shows the basic structure of a closed control loop; its mode of operation can be described as follows:

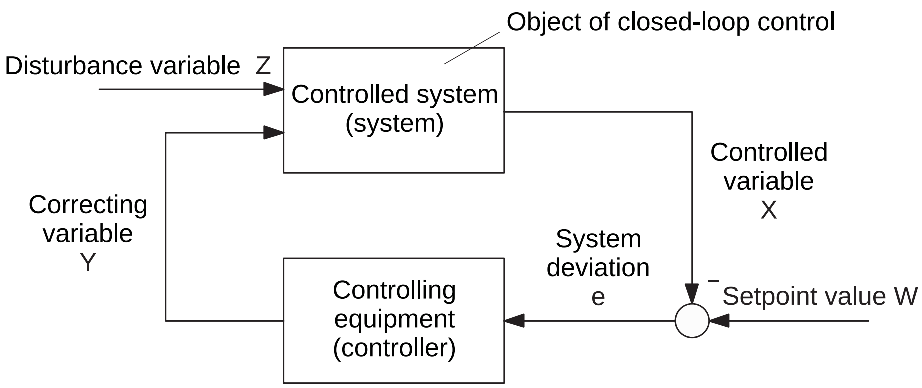


*Fig. B2-48:
Mode of operation
of closed control loop*

The required value of the controlled variable *X*, i. e. its desired characteristic as a function of time, is specified by the setpoint value *W*. This can be done manually on the control equipment of the controller or also by a controlling device, which is of higher-order to the controller. In the case of a fixed setpoint value, we talk of a fixed setpoint control, and in the case of a time varying setpoint value of a setpoint control or servo control. The controlled variable *X* is continually measured via a suitable measuring device (or at permissible time intervals) and compared with the setpoint value *W* by means of subtraction.

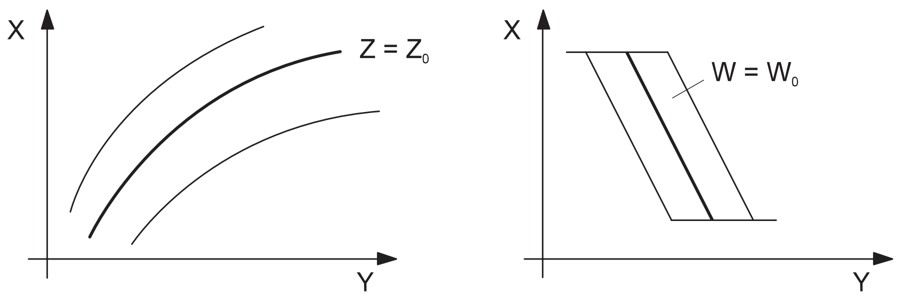
The system deviation $e = W - X$ indicates, how much and in which direction (e. g. valve to be opened or closed more) intervention in the process is necessary via the correcting variable *Y* in order to eliminate the occurring system deviation. The controlling device is used as an information processing system, which calculates the correcting variable *Y* appropriate for the control process from the existing system deviation.

Technical controlled systems are subject to a multitude of interference (load variations, changes in the quality of materials used, etc.). To simplify matters, fig. B2-48 therefore only includes one main disturbance variable *Z*. All disturbances have an effect on the controlled variable and change (e. g. in the case of a fixed setpoint control) its required operating point value $X_o = W_o$. As such, all disturbances are therefore reflected in the system deviation, and the above described control process, which is carried out continually and automatically, then ensures as complete a diminution of the system deviation as possible and thus the elimination of the effect of the disturbance on the controlled variable.

The success of a control system obviously depends critically on the time-related characteristic of the disturbance variables (and time varying setpoint values), the steady-state and dynamic behaviour of the controlled system and information processing in the controlling equipment.

Similar to the deliberations regarding the simulation of the steady and dynamic behaviour of the technical system to be controlled (in this case controlled systems), it is also essential to discuss the concepts and descriptions regarding the steady-state and dynamic behaviour of closed control loops.

The description of the steady-state closed control loop behaviour again entails the use of characteristic curves or characteristics, in this case, the steady-state models of controlled system and controller. Hence fig. B2-49a illustrates the steady-state characteristic of the controlled system and fig. B2-49b the steady-state characteristic of a proportionally acting controller. Here, Y designates the correcting variable (e. g. valve position) and X the controlled variable (e. g. temperature).



Performance characteristic of controlled system

Performance characteristics of control device

Fig. B2-49a + b

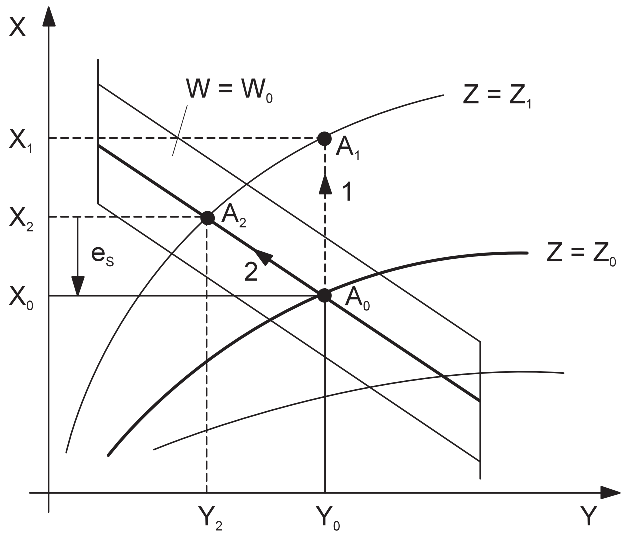
Both characteristics can be represented jointly if identical scaling is selected (Fig. B2-50).

The interface between the valid characteristics for the controlled system ($Z = Z_0$) and the controlling equipment ($W = W_0$) result in the operating point A_o and hence the operating point values Y_0 or X_0 for the actuating signal *Y* or for the controlled variable signal *X.*

If the interference then changes from $Z = Z_0$ to $Z = Z_1$, then, in the case if a fixed valve position Y_0 (to remain with the example), i.e. with a controller which is switched off or has not been started up, the operating point would drift from A_0 to A_1 and the controlled variable *X* (e. g. the temperature) would assume the value X_1 .

However, if the controller is active then, on the basis of the same considerations which apply to the interface A_0, the operating point A_2 occurs, since the now operative characteristic curves of the controlled system for $Z = Z_1$ and of the controlling device for $W = W_0$ (with unchanged setpoint value) now need to be intersected. The operating point in this case therefore drifts from A_0 to A_2. The corresponding operating point values are Y_2 and X_2. In order to prevent the unwanted increase of the controlled variable from X_0 to X_1 at least to some extent, the setpoint value is reset via the controller from Y_0 to Y_2 and the steady-state controlled variable value X_2 set.

The flatter the form of the characteristic curve of the controller in fig. B2-50, the more effective the controller probably is with regard to the steady-state behaviour of the closed control loop. In the borderline case of a horizontally running controller characteristic curve, the control objective of complete diminution of the stationary system deviation $e_s = W_0 - X_2$, could even be completely achieved. However, a horizontally running controller characteristic curve as shown in fig. B2-50 means a vertical pattern in fig. B2-49b, and as such an infinitely high proportional coefficient of the controller assumed to be of proportional action. That this optimum steady-state closed control loop behaviour can actually be realised, can only be seen by further pursuing deliberation regarding information processing in technical controllers.



1. Working point variation with fixed setpoint value Y0
2. Working point variation with active closed-loop control

Fig. B2-50: Steady-state performance characteristics of closed control loop, Interference changes from Z_0 to Z_1

Function mode of operation of technical controllers (control algorithms)

Control algorithms have proved to be a tried and tested method of calculating the correcting variable *Y* from the system deviation *e*, which relates back to the basic behaviour patterns described in the section Depiction of the response characteristic (P-, I-, D-action) of technical systems. Each action assumes its own particular role in the course of this processing of information. Fig. B2-51 shows the signal flow diagram (the graphic representation of signal processing) of the controller.

The purpose of P and D-action is to ensure an as quick as possible but smooth process of the transient phenomenon in closed control loops. The D-action does not have any effect on the stationary state of a closed control loop, since even with a steady-state deviation e_S (τμ) *0*, the output signal Y_D decays towards zero and therefore does not contribute towards the stationary value of the control signal Y. However, the effect of this action comes into force particularly quickly with variable system deviations. To some degree, the D-action therefore contributes in advance, i.e. in anticipatory manner to the control signal *Y*.

The actual action function is to keep the controller characteristic curve in fig. B2-49b vertical and thus to completely correct any permanent interference. This relates to the previously illustrated characteristic of integral-action systems to generate a constant rate of change of the system output variable after a jump activation. This is how the system output (in the case of the controller, the signal Y_I) can assume any value within its control range, even though the input signal (in this case the system deviation *e*) attains the value zero again after a transient response. An integral action system therefore has a steady-state effect in the same way as a proportionally acting system with infinitely significant proportional coefficient. Over a sufficiently long period of time, the smallest uni-dimensional input signal values lead to an output signal of some significance.

In order to be able to calculate the overall effect of the controller on the closed control loop behaviour and as such the time-related response of controlled variables *X* and Y in relation to the task, the controller actions can be introduced into the calculation of the values of setpoint specification Y. For this, every PID controllers has three freely adjustable parameters (characteristic controller values):

- the proportional coefficient K_R for the adjustment of the P-action
- the correction time T_n for the adjustment of the I-action and
- the derivative-action time T_v for the adjustment of the D-action.

Dynamic closed control loop behaviour requirements

The adjustment of the characteristic controller values K_R, T_n and T_v largely depends on

- the steady-state and dynamic behaviour of the controlled system
- the disturbances acting on the controlled system
- the demands placed on the steady-state and dynamic behaviour of the closed control loop.

The steady-state behaviour of the closed control loop (working point setting, steady-state system deviation, functions and effect of the I-action in the controller) has already been described in detail in the section Steady-state behaviour of the closed control loop.

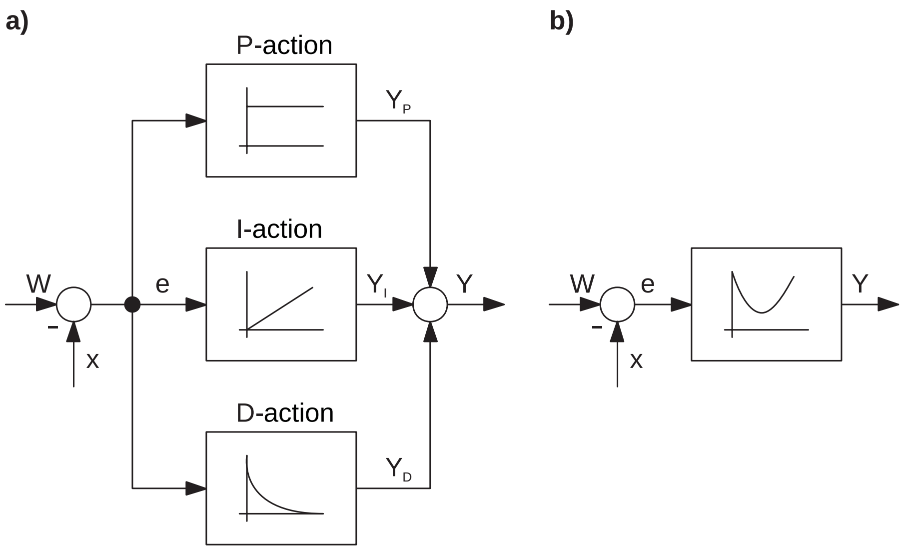


Fig. B2-51: Signal flow diagram of PID-controller

a) with individual representation of controller actions P, I and D

b) with overall representation (Addition of individual representations) of controller transient function $h_R(t)$

The same preconditions should be assumed for the discussion of the dynamic behaviour as those applied in section B.2.3.1.3 for the linear dynamic model of technical systems. Here, it is assumed that all process signals during the control processes occur in the vicinity of their working points and do not in practice deviate from the linearity range. In this way, the demands placed on the dynamic behaviour of the closed control loop, e. g. in the form of step responses can be precisely defined. However, this means that during the practical operation of the closed control loop, the boundaries of the linear working range around the working point must be observed. If these are exceeded, then the results achievable in this case with the controller settings based on the linear dynamic models are also called into question.

Fig. B2-52 illustrates a behaviour of the controlled variable *x(t)* after the sudden change of the setpoint value *w* (control step response of the closed control loop), which should be aimed for. This behaviour can be described roughly by two characteristic values:

- the overshoot time T_m and
- the standardised overshoot amplitude $\Delta h = \frac{\Delta h^*}{w}$.

The overshoot amplitude Δh usually requires a value between 0 and 20 %t. Overshoot time requirements T_m depend on the dynamic behaviour of the closed control loop and must always be viewed in conjunction with the process dead times and process constants.

If the inflectional tangent model introduced in the section *The inflectional tangent model* is used to describe the controlled system behaviour, then the overshoot time should not be less than half the total of the time delay and the transient time specified (reference value). This ensures that the control signal *y* does not assume untenably high values during the transient stage.

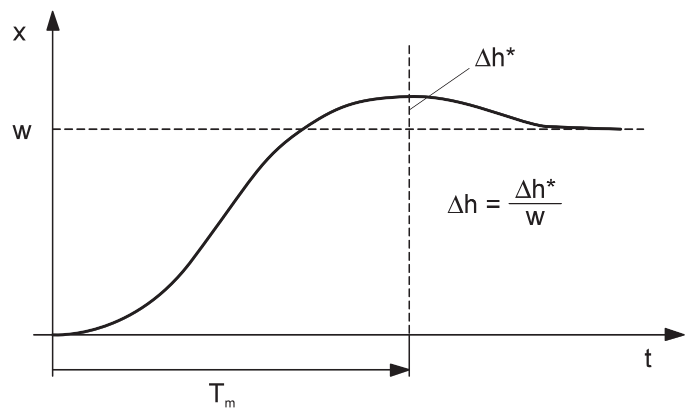


Fig. B2-52:
Favourable behaviour of control step response of a closed control loop

A similar process can be adopted with regard to a favourable course of the interference step response of the closed control loop (step-change response of the closed control loop at its input). Fig. B2-53 shows a favourable course of this process from the control technology viewpoint.

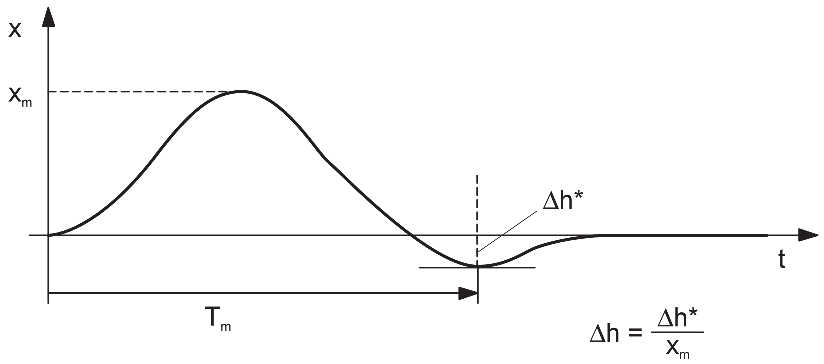


Fig. B2-53: Favourable behaviour of interference step response of a closed control loop

Here too, the process can be described roughly by means of two characteristic values (T_m and Δh^* or x_m).

Setting rules to Ziegler/Nichols

Right at the initial stage of modern control technology, J.G. Ziegler and N.B. Nichols have specified setting rules, which are still widely used today. These are intended for cases where

- no model (or inflectional tangent model) of the controlled system is available and
- the closed control loop can be operated safely along the stability limit.

These rules are as follows:

1. Set the controller as a P-controller ($T_V = 0$ $T_n = ...$).
2. The amplitude factor K_R of the controller is increased until the closed control loop is on the point of performing unattenuated oscillations (stability limit).
   This determines the critical amplitude factor K_{Rk} and the period of oscillation T_k of this sustained oscillation.
3. Based on these two parameters (K_{Rk}, T_k), the controller parameters K_R, T_n and T_V are then to be calculated as per controller type according to the following specification and set on the computer.

	K_R	T_n	T_v
P-controller	0.5 K_{Rk}	–	–
PI-controller	0.45 K_{Rk}	0.85 Tk	–
PID-controller	0.6 K_{Rk}	0.5 T_k	0.12 T_k

Table 5: Setting rules to Ziegler/Nichols

However, experience shows that these setting values only lead to workable closed control loop behaviour, if the ratio of transient time T_g to time delay T_u of the controlled system is not too great, i.e. the system in the model of the transient function shows a noticeable time delay.

Setting rules to Chien/Hrones/Reswick

If we are dealing with an inflectional tangent model of the controlled system, then the setting rules of Chien, Hrones and Reswick are to be used. The setting rules for this are shown in the following table.

Con-troller Type	Overshoot amplitude 20 % after step-change		no overshoot (0%) after step-change	
	of disturbance variable z	of setpoint value w	of disturbance variable z	of setpoint value w
P	$K_R \approx \frac{0.7}{K_S} \cdot \frac{T_g}{T_u}$	$K_R \approx \frac{0.7}{K_S} \cdot \frac{T_g}{T_u}$	$K_R \approx \frac{0.3}{K_S} \cdot \frac{T_g}{T_u}$	$K_R \approx \frac{0.3}{K_S} \cdot \frac{T_g}{T_u}$
PI	$K_R \approx \frac{0.7}{K_S} \cdot \frac{T_g}{T_u}$ $T_n \approx 2.3 \cdot T_u$	$K_R \approx \frac{0.6}{K_S} \cdot \frac{T_g}{T_u}$ $T_n \approx T_g$	$K_R \approx \frac{0.6}{K_S} \cdot \frac{T_g}{T_u}$ $T_n \approx 4 \cdot T_u$	$K_R \approx \frac{0.35}{K_S} \cdot \frac{T_g}{T_u}$ $T_n \approx 1.2 \cdot T_g$
PID	$K_R \approx \frac{1.2}{K_S} \cdot \frac{T_g}{T_u}$ $T_n \approx 2 \cdot T_u$ $T_v \approx 0.42 \cdot T_u$	$K_R \approx \frac{0.95}{K_S} \cdot \frac{T_g}{T_u}$ $T_n \approx 1.35 \cdot T_g$ $T_v \approx 0.47 \cdot T_u$	$K_R \approx \frac{0.95}{K_S} \cdot \frac{T_g}{T_u}$ $T_n \approx 2.4 \cdot T_u$ $T_v \approx 0.42 \cdot T_u$	$K_R \approx \frac{0.6}{K_S} \cdot \frac{T_g}{T_u}$ $T_n \approx T_g$ $T_v \approx 0.5 \cdot T_u$

Table 6: Setting rules to Chien/Hrones/Reswick

For I-controlled systems the expression $\frac{1}{K_{IS} \cdot T_u}$ is to be used instead of $\frac{T_g}{K_S \cdot T_u}$.

These rules can also be applied to a total time constant model, provided

$$T_u = T_t \quad \text{and} \quad T_g = T$$

are set.

2.4 Selection of automation equipment

2.4.1 Introductory comments

Now that the essential aspects of the project design work have been explained in sections 2.2 and 2.3, the following concentrates on the equally important questions in this context of the selection of automation equipment. These selections are particularly relevant for the preparation of the EMCS block diagrams and equipment lists since, apart from the functional integration of the automation equipment into these diagrams, their layout is also of importance (e.g. measuring ranges/sensors and correcting ranges/actuators).

In general, the task of the project engineer is to select the automation equipment so that it represents the optimum solution for the automation system to be constructed.

Initially, the following generally applicable requirements can be listed for this:

- **Realisability**
  The automation task is to be solved by an appropriate means of automation equipment.
- **Reliability**
  The fail-safe aspect of the automation equipment used must be adequate for the operation of hazardous processes.
- **Process condition**
  The conditions characteristic of process technology operations such as temperatures, pressures, aggressive media, explosion risks, irradiation, electro-magnetic fields etc, must be taken into consideration as a whole.
- **Customer requirements**
  Customers frequently specify from which manufacturer and with what functionality the automation equipment is to be procured.
- **Integratability**
  It should be possible to realise the expansion of an existing automation system by means of additional automation equipment with the least possible expense/trouble (e.g. without changing of existing auxiliary energy).
- **Energy consumption**
  The energy directly taken up by the automation equipment (auxiliary energy) or the energy expenditure required in the process (e.g. control valves, pump motors, etc.) is to be utilised in the most efficient way possible.
- **Cost determinants**
  The price comparison of different automation equipment for the solution of an equivalent task represents an important factor of project costing.

- **Miscellaneous**
  The aspects to be considered under this heading are, for instance, size, weight, possible installation of automation equipment, customer service, etc.

Moreover, the importance of the various evaluations of these requirements should be considered in this context whereby, for instance, the guarantee of process reliability is always of greater importance than a reduction of costs.

If we now revert back to the already mentioned small-scale experimental modules or other process technology systems, then the analysis of the PI flow diagrams and the EMCS block diagrams clearly shows that the selection of automation equipment mainly applies to actuators and sensors.

The following lists the essential fundamentals for the selection of this automation equipment, integrating it into a strategy for selection.

2.4.2 Essential fundamentals

General

Using the example of flow and filling level control you are familiar with from the small-scale experimental modules, there now follows an explanation of the essential fundamentals of the theory of flow. Both closed control loops start from the premise of one fluid flow (water throughput), whereby flow q and pressure p represent the characteristic process parameters. Here, it should be noted that in the relevant literature on pump function and pump design, the term 'output flow' is often used instead of flow rate.

The object of the exercise now is to realise a corresponding flow rate or output flow for the respective specifications.

In process technology, centrifugal pumps (also adjustable) and control valves are primarily used for this purpose.

The centrifugal pump

Fig. B2-54 initially provides a more detailed account of the design and configuration of the centrifugal pump.

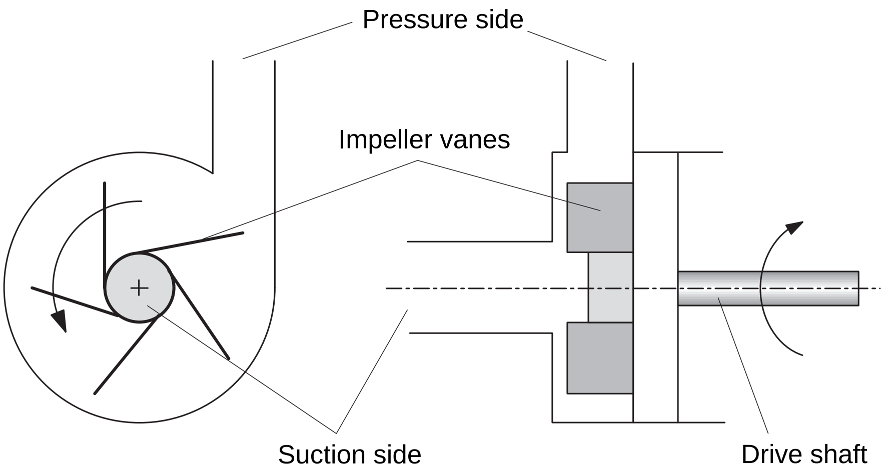


*Fig. B2-54:
Design of a centrifugal pump (front and side view)*

The most important characteristic of the centrifugal pump is the unclosed pump chamber, whereby the fluid is sucked into the pump housing, accelerated by the rotating impeller and due to the available centrifugal force forced through the outlet opening again. This creates a pressure difference between the pump inlet and outlet, whereby a vacuum is created on the pump input side as a result of the outward flow of the fluid from the impeller axis. Consequently, if for instance the pump draws in fluid from a container at a lower level, the lift is limited by the difference between the container vacuum and achievable vacuum.

If a vacuum is created on the pump input side, which is less than the so-called vapour pressure of the fluid, this results in evaporation, so that when the created gas bubbles are imploded this may lead to damage of the impeller in areas of higher pressure. **This phenomenon is known as cavitation.**

Moreover, the constructional design of a centrifugal pump means, that it cannot be closed off. With excessive reverse pressure, this leads to an opposing flow. To prevent this, a non-return valve is to be fitted in the pipe downstream of the pump, which only opens if there is a delivery pressure.

However, a centrifugal pump is also able to operate for a shorter period of time against a closed valve (shut-off valve) without overloading or damaging the drive unit. **In the case of large centrifugal pumps, it is necessary to keep the shut-off valve closed during start-up and shut-down.**

Furthermore, the centrifugal pump is characterised by the so-called *Pump characteristic curve*. This indicates the correlation between output flow and delivery pressure at a constant speed.

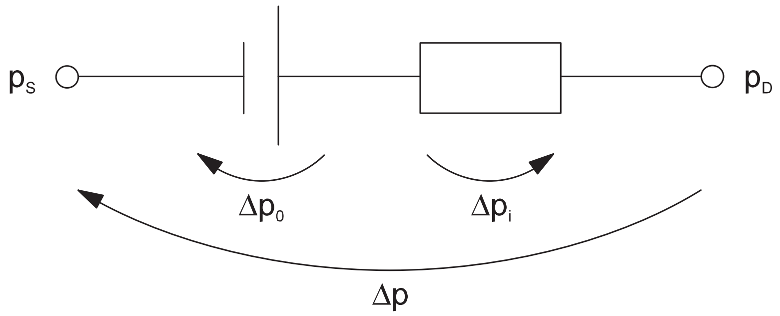
With increasing output flow, a rising pressure drop is created on the internal flow resistance of the pump – housing and guide blade –. In an ideal case, the delivery pressure of the pump will be Δp, whereby

$$\Delta p = \Delta p_0 - k_i \cdot q^2$$

applies.

Δp	–	Delivery pressure
Δp_0	–	Maximum delivery pressure (at Q=0)
k_i	–	Fluidic constant of pump
q	–	Output flow.

As an addition, fig. B2-55 illustrates the equivalent electrical circuit diagram of a centrifugal pump and should be regarded in this sense as a reference to possible similar considerations, which will however not be dealt with in this context.



p_S – Pressure on pump suction side/vacuum
p_D – Pressure on pump delivery side/excess pressure
Δp_i – Pressure drop subject to internal resistence of pump
$\Delta p = \Delta p_o - \Delta p_i$ corresponds to differential pressure between pump output and input side

Fig. B2-55:
Equivalent electrical circuit diagram of a centrifugal pump

Very often the delivery pressure Δp, the *delivery head h* in relation to a specific fluid, is often specified as a typical pump parameter as an alternative to delivery pressure, e. g. example for water (density p = 1 g/cm^3), the delivery head is calculated as

$$h = \frac{\Delta p}{\rho \cdot g}$$

This is how corresponding characteristic curves are obtained for different speeds (fig. B2-56) and the fundamentals of the *efficiency factor* of a centrifugal pump can be discussed.

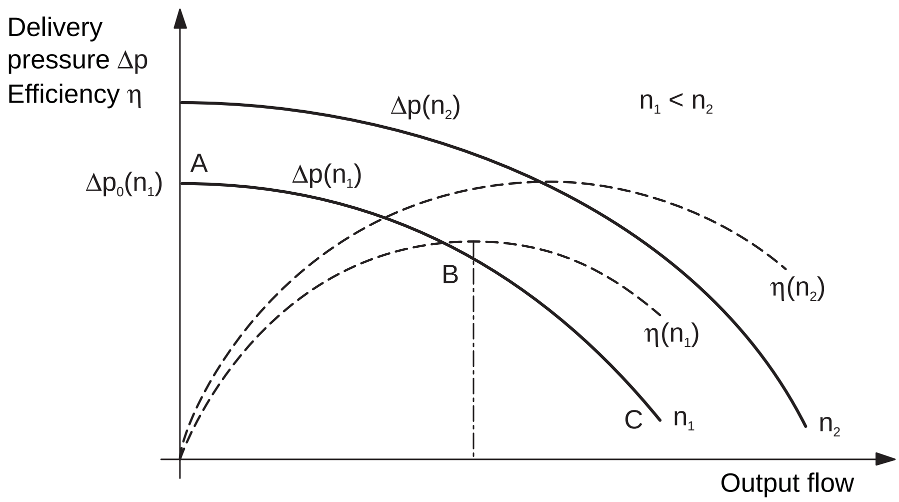


Fig. B2-56: Qualitative representation of pump and efficiency characteristic curves

With an output flow of zero (point A in fig. B2-56), i.e. the pump is operated against a closed valve or the static differential pressure in a pipeline is identical to the delivery pressure, this results in a situation where, although the pump is working, no fluid is transported. This means that efficiency is 0 and the energy consumed is converted into heat in the pump housing. However, over an extended period and with insufficient cooling, this may lead to pump damage, whereby this working point can no longer be maintained over an extended period.

Once the output flow has increased, the pump reaches its maximum efficiency (point B) at a working point.

If the output flow further increases (point C), the recorded drive capacity increases, which leads to a deterioration in efficiency in the case of a squared degressive delivery pressure. The increase in power consumption may lead to overloading of the drive motor. This is why a predetermined output flow must not be exceeded.

If you now assume the task of selecting a centrifugal pump, this process of selection can be conducted along the lines of a relatively simple procedure.

First of all, differentation must be made between two types of pump application. In the first case, the pump is used as a pressure increase facility to maintain the flow (of the output flow) in a pipe, whereby the pump operates at a constant speed. In the second case, the pump is used as a throughput regulating element, whereby its speed is used as a correcting variable.

Fig. B2-57 deals with the first case, i.e. the pump operates at a constant speed. In addition, the steady-state characteristic curve of the pump and system (system section) are entered in a diagram (fig. B2-57) and the planned working point of the pump defined at the

point of intersection of the pump characteristic curve and system curve. Furthermore, the efficiency of the pump is also used to determine the working point (the nominal ratios) (fig. B2-58).

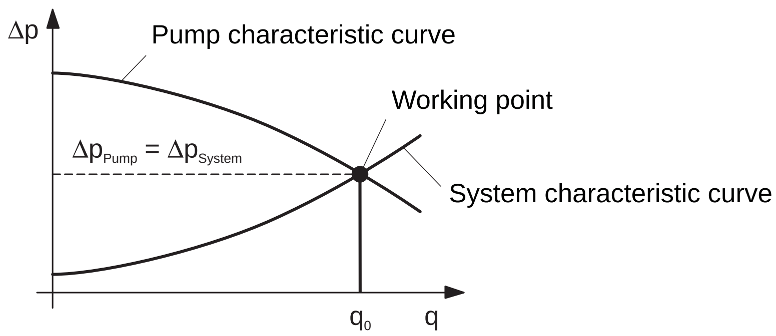


*Fig. B2-57:
Selection of a centrifugal pump with the help of the steady-state characteristic curve of system section and pump (q_0 – delivery rate within working point)*

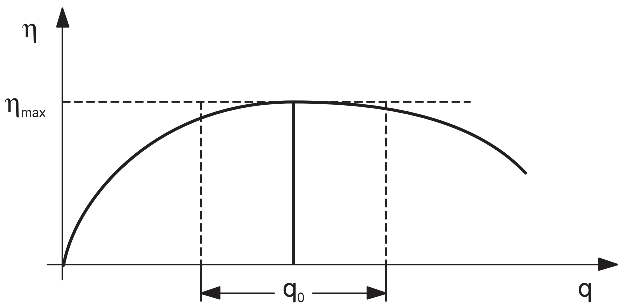


Fig. B2-58: Efficiency of centrifugal pump in relation to delivey rate (q0 – delivery rate within working point)

This means that apart from defining the working point of the centrifugal pump (output flow q_0) at the intersection of the above characteristic curves, it is also necessary to take into account the maximum efficiency as a specification for the output flow q_0. Depending on the pump selection available, it is often not possible to avoid a compromise in the sense of deviations from η_{max}.

In the case of the centrifugal pump with variable speed, the basic requirement – definition of q_{min} and q_{max} – must be met to begin with (in accordance with corresponding process technological specifications) (fig. B2-59).

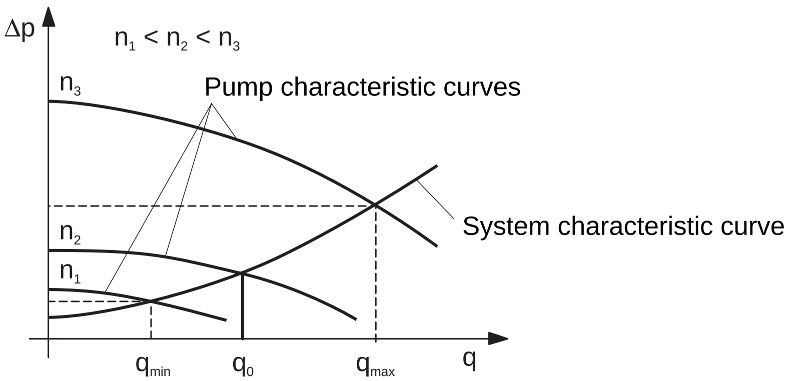


Fig. B2-59: Characteristics of a pump with variable speed range (q_0 – Delivery rate within working point)

Furthermore, the speed range /control range (speeds n_1 to n_3) of the pump to be selected are to be defined. To this end, the characteristic curves shown in fig. B2-59 illustrate, that any volumetric delivery can be achieved by varying the speeds of the centrifugal pump. As far as the optimum pump selection is concerned, one should again aim for a pump speed to be effective in the working point (output flow q_0), which also represents the best possible efficiency for the output flow q_0. The required efficiency η_{max} in this case is also available in the form of a characteristics field (fig. B2-60) whereby, as already explained, a compromise to a certain extent is unavoidable, since the intersection of the pump characteristic curve (speed at working point – e. g. n_2) and system characteristic curve do not always ensure the most optimum efficiency η_{max} (see fig. B2-60).

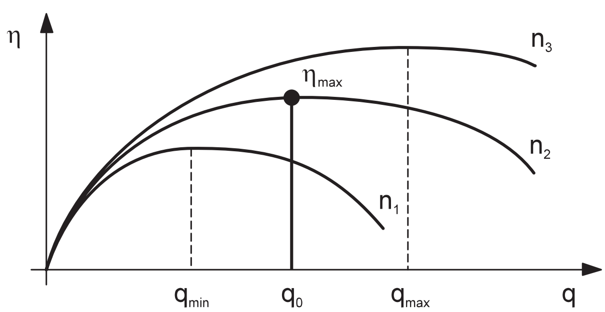


Fig. B2-60:
Efficiency characteristics of a centrifugal pump in relation to the delivery rate (q_0 – Delivery rate within working point)

Based on a summary of the above mentioned descriptions, the following schematic drawing fig. B2-61 is obtained for the pump selection.

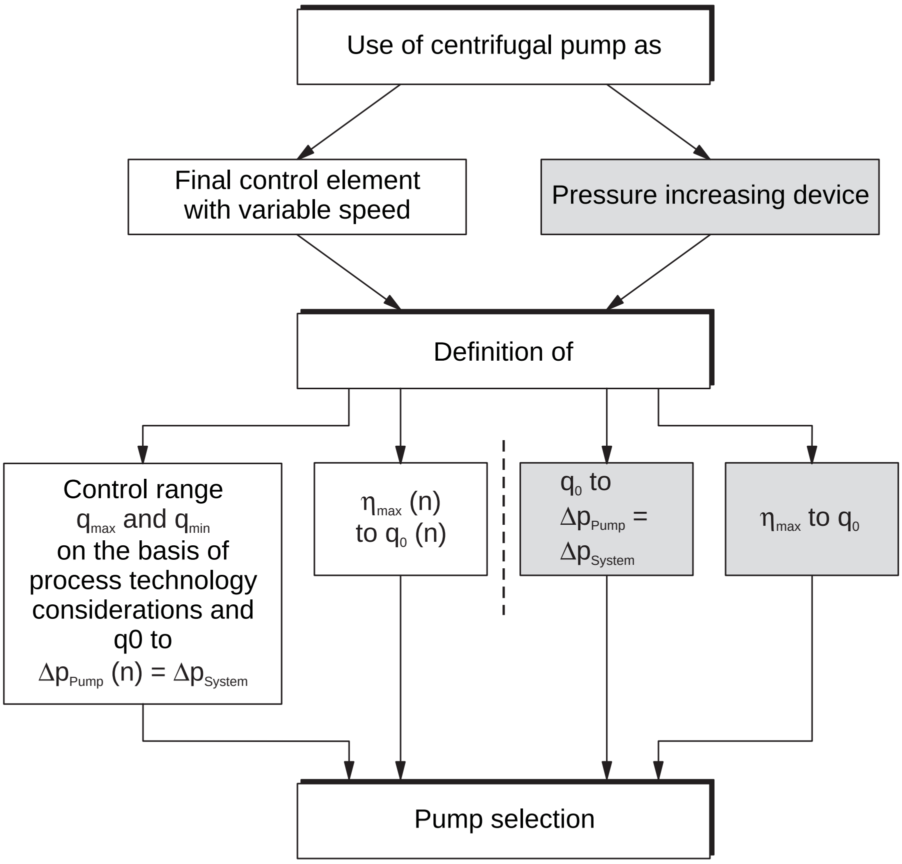


Fig. B2-61: Selection of a centrifugal pump

The final control element (regulating valve / control valve / valve actuator)

The function of a final control element in a piping system is to change the fluid throughput by means of its variable flow resistance

Fig. B2-62 provides a schematic representation of customary final control elements, of which the control valve is undoubtedly the most frequently used regulating device.

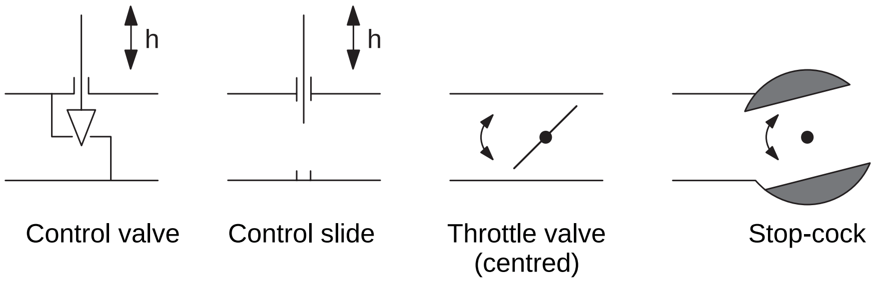


Fig. B2-62:
Final control elements in flow technology

Fig. B2-63 therefore illustrates the design of a control valve (schematic), whereby an equivalent electrical circuit diagram is also provided to facilitate any possible similar considerations (fig. B2-64).

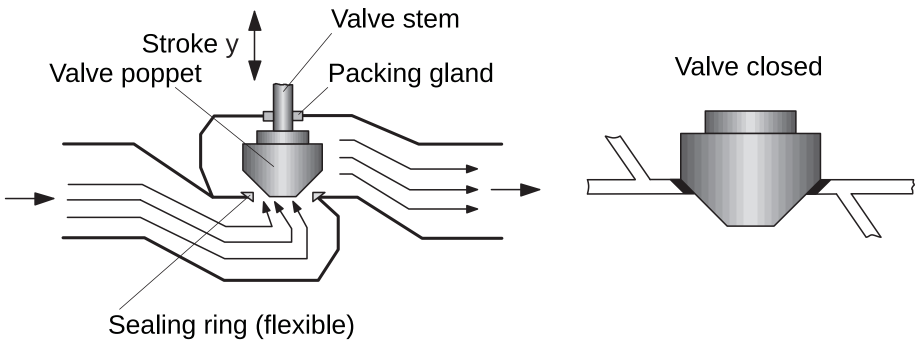


Fig. B2-63:
Design of a control valve

Faced with the task of selecting a final control element, the first step is to examine the basic behaviour of the final control element in a system section (pipe section). In this context, it should be noted that due to the flow resistance of this final control element a dynamic pressure drop occurs Δp, which quadratically depends on the flow velocity or throughput. This means that part of the overall pressure available at the start of the pipe is reduced in the final control element (loss of energy).

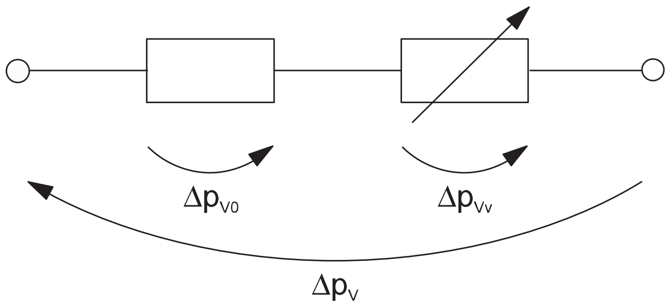


Fig. B2-64: Equivalent electrical circuit diagram of a control valve

Due to its nature, it follows that a process technological system will always be equipped with numerous control valves, in that different flow and pressure conditions will occur. It is therefore necessary to introduce the main parameters and facts in order to classify these control valves.

To be able to make a permanently (experimentally) reproducible comparison of control valves, manufacturers work on the basis of a standard state (standard flow rate) of the valve to be used and define the so-called k_v value. This means that for a pressure drop of 0.98 bar (0.98 – 10^5Pa), manufacturers specify water flow rates of ($\rho = 10^3$ kg/m^3) passing through the valve. These standard flow rates depend purely on the valve stroke y and are referred to as k_v *value*. The throughput associated with the nominal stroke of the control valve is known as k_{vs} *value*.

The dependency of the k_V values on the respective valve stroke is recorded in the so-called steady-state characteristic curve or *basic characteristic curve* of the control valve. The most typical basic forms of this basic characteristic curve can be most frequently found in

- *the linear characteristic curve* (a variation of valve stroke causes a change in linear throughput – see fig. B2-65) and
- the *equal-percentage characteristic curve* (variation of valve stroke and throughput have a non-linear correlation – see fig. B2-65).

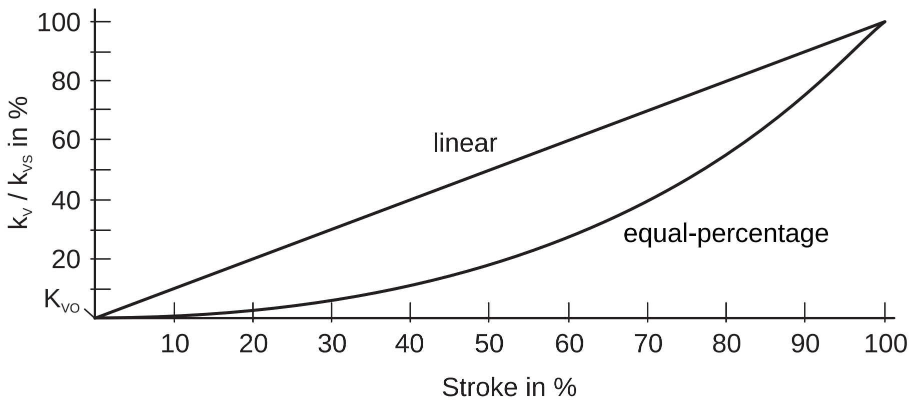


Fig. B2-65:
Basic characteristic curve of control valves

On the basis of the actual automation task (design of process technological system section) it has to be decided, which basic characteristic curve is to be used. To give a practical indication, the following procedure can be recommended:

- If the static characteristic curve is known (estimation) for the process technological section intended for the use of the valve, then the basic characteristic curve of the control valve is to be selected in such a way that, with the added superimposing of both characteristic curves (with the interaction of system section, and control valve) a as near as possible linear steady state characteristic curve (operating characteristics) is obtained for the flow behaviour.

Furthermore, it should be noted that various control valves, depending on the constructional design, do not completely seal during a zero valve stroke. The resulting residual throughput is referred as the *k_{Vo} value* of the control valve. From the point of view of cost and function, this should not necessarily be regarded as a disadvantage, since the comparatively simple On/Off valves are often used to completely close off pipes. Moreover, the control valve can be fashioned into a completely closing version by means of corresponding design changes (e. g. use of compressible seals). In this case, one also speaks of the so-called zero-point suppression. In this case, the characteristic curve greatly deviates from the actual basic characteristic curve in the case of a small stroke (fig. B2-66).

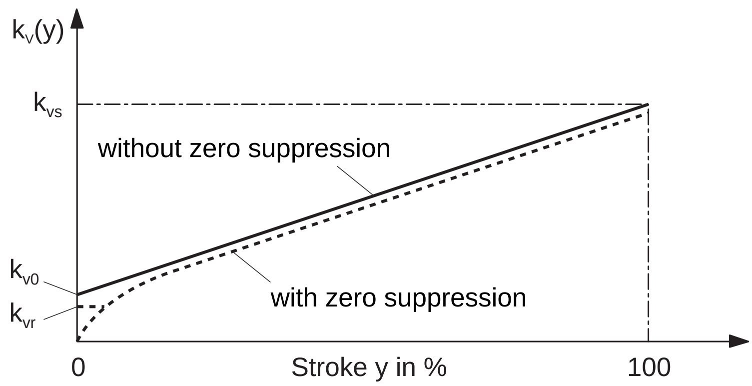


Fig. B2-66: Linear basic characteristic curves of control valves with and without zero suppression

The parameters k_{vs} and k_{vo} are used to form the so-called *theoretical control ratio k_{vs}/k_{vo}*, which is generally specified as a typical parameter by the valve manufacturer and, in practice is often also replaced by the *effective control ratio k_{vs}/k_{vr}*. This takes into account the tolerance between the targeted and the actually measured basic characteristic curve (see also fig. B2-66).

If we now turn to the impending valve selection then, according to the above information, we start with the k_v value. For a pressure drop $\Delta p \approx 1$ bar (specification resulting from practical experience) this can be determined as follows by the project engineer, taking into account the flow rate of the system section (specification resulting from practical experience:

$$K_v = 0.032 \cdot q \cdot \sqrt{\frac{\rho}{\Delta p}}$$

q – Output flow in m^3/h (flow rate)

ρ – Density of passing medium in $10^3 kg/m^3$

Δp – Pressure drop via control valve (specification 1 bar)

This means that by defining (estimating) the maximum and minimum flow rates (q_{max}/q_{min}) in the system section in question, the following characteristic values are calculated with the help of the above formula

$$k_{vs} = 0.032 \cdot q_{max} \cdot \sqrt{\frac{\rho}{\Delta p}}$$

(maximum valve stroke y/ also $K_{v\,max}$) and

$$K_{v_{min}} = 0.032 \cdot q_{min} \sqrt{\frac{\rho}{\Delta p}}$$

(minimum valve stroke y).

For practical purposes, it should be noted that, in most cases it is not possible to find a control valve with the k_{vs} value calculated from the system data. Consequently, for practical reasons, (e. g. also taking into account any other occurring changes in the system data) one should always select a control valve with a higher k_{vs} value (than that calculated), i.e. the control ratio k_{vs}/k_{vr}.

Additionally, it should be mentioned that by changing the formula to determine the k_V value, it is also possible to obtain a formula for the above mentioned operating characteristics, which is as follows:

$$q = k_V \cdot 31.62 \sqrt{\frac{\Delta p}{\rho}} = g\,(y, \Delta p)$$

However, in this case Δp represents the actual pressure drop via the control valve for the respective flow rate, which can only be recorded metrologically, but in practice is not realised in the form of a measuring point. The formula is therefore less relevant in practical terms and the satisfactory (practically linear) operating characteristic can only be achieved by means of the already mentioned superimposition of basic characteristic curve and system characteristic curve.

In conclusion, a few comments should also be added with regard to the classification /estimation of the steady-state characteristic curves of process technology system groups.

As can be seen from fig. B2-69, differentiation is made between system sections with dominant static pressure drop and dominant dynamic pressure drop. However, in fig. B2-67, it can be clearly seen that in systems with static pressure drop, this only marginally depends on the flow rate, also known as output flow q.

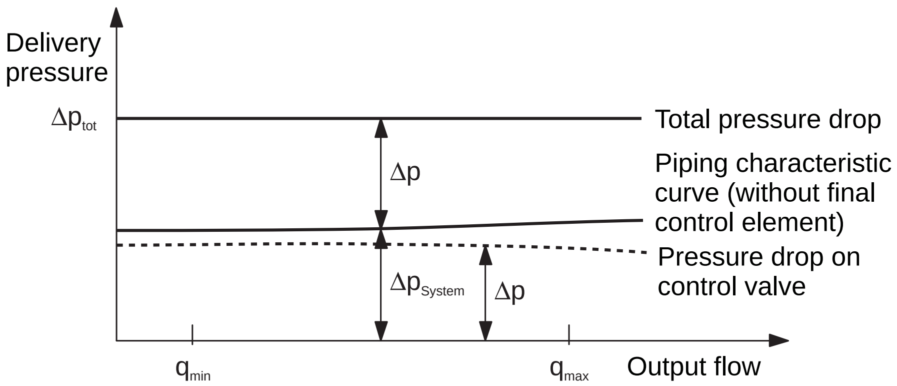


Fig. B2-67: System with steady-state pressure drop (ideal case – pump resistance neglected)

It therefore generally applies that the overall pressure drop remains constant and as such also the pressure drops via the system section and control valve.

In the case of system sections with dynamic pressure drop, the pressure changes in relation to the output flow q and via the system section itself, and via the control valve as per fig. B2-68.

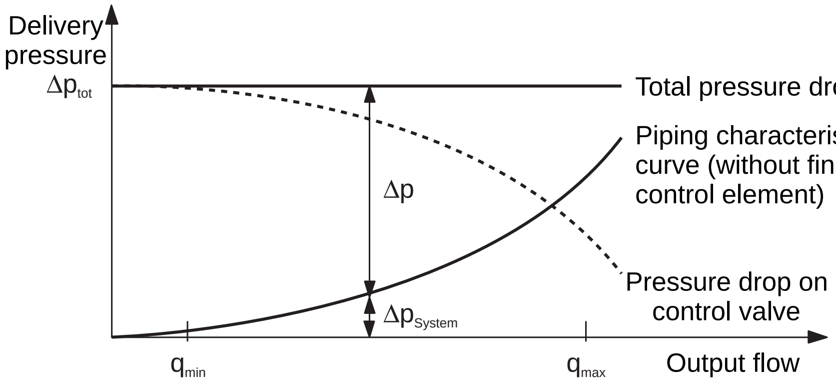


Fig. B2-68:
System section with dynamic pressure drop (ideal case – pump resistance neglected)

Fig. B2-69 represents a summary of the main considerations involved in selecting a control valve, which are documented in the form of **basic rules of procedure** via points 1 to 4.

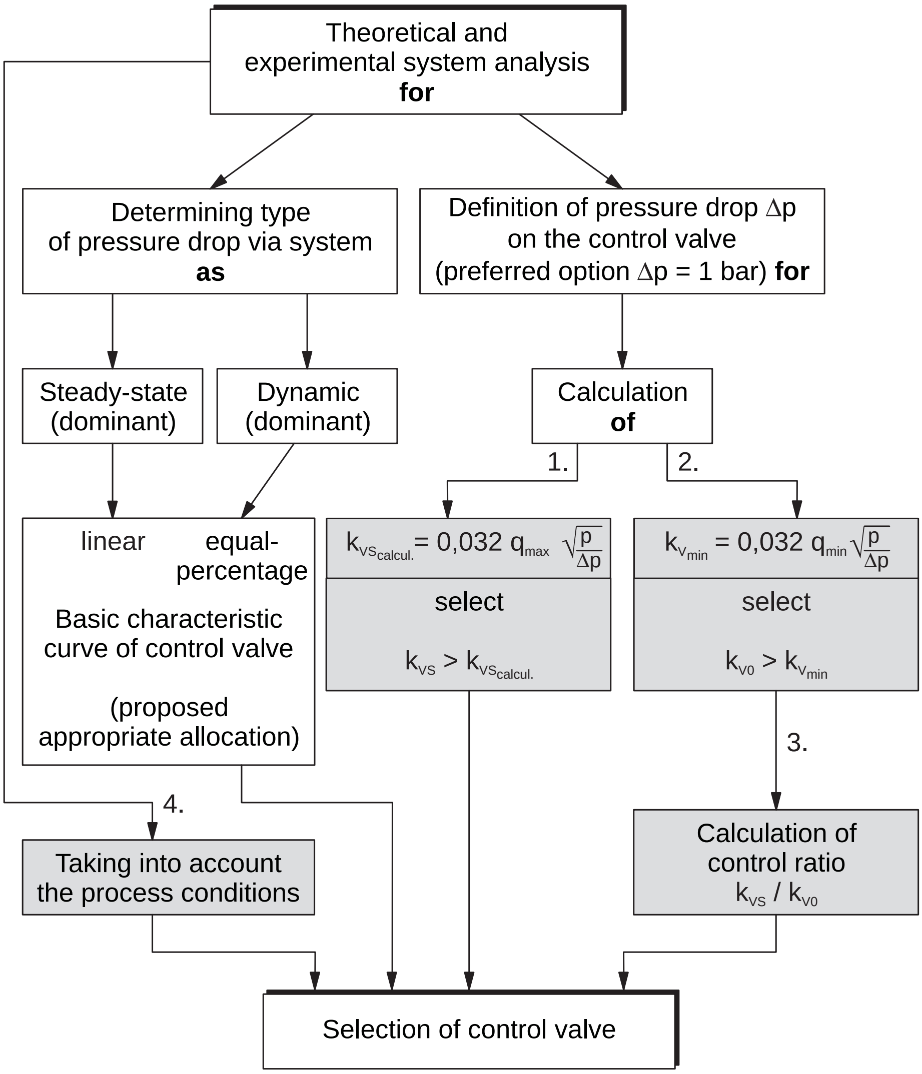


Fig. B2-69:
Selection of a control valve

Selection of sensors

As a rule, the selection of sensors within the framework of an automation project is more straightforward than the selection of actuators described in the last section.

The selection by means of evaluating the respective company literature is relatively simple for the project engineer. By using the measuring ranges associated with process technology, all that remains for him to do is to select a corresponding sensor.

Fig. B2-70 illustrates this procedure. Needless to say, the environmental operating conditions of the sensor also are to be taken into account (e. g. aggressive medium, assembly conditions, etc.).

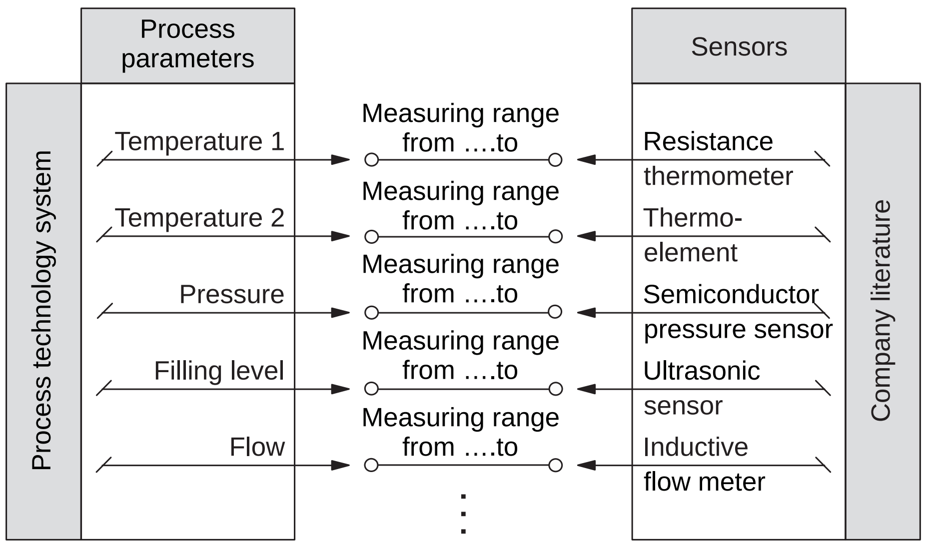


Fig. B2-70: Selection of sensors

2.5 Process protection measures

Since the previous chapters solely represented an account of the main aspects of project design work, the question of process protection has not been dealt with explicitly. It therefore has to be said that this question can be a particularly important additional factor of project design work in relation to process technology. For example, the requirements for the automation of an atomic power station will be considerably higher than those for the automation system of a brewery.

Consequently, the project design engineer must be aware of the respective essential requirements for process protection and incorporate these into the project design.

Fig. B2-71 sets out the basic aspects of process protection.

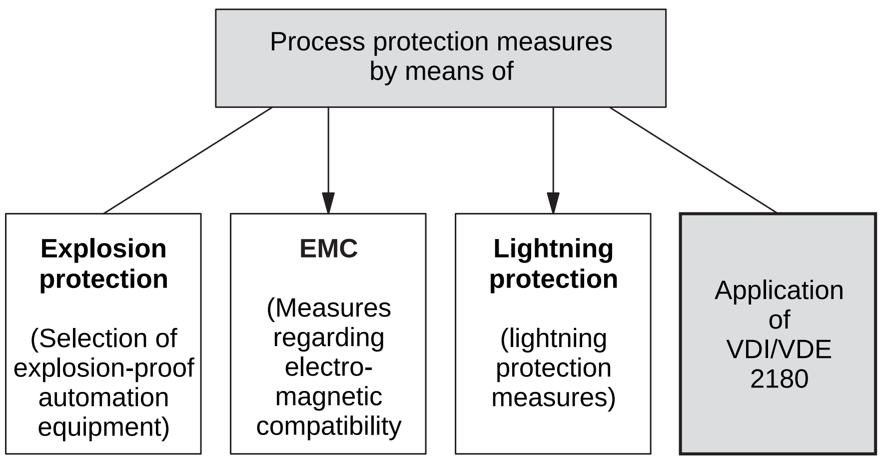


Fig. B2-70: Overview of basic aspects of process protection

According to this, the project design engineer will be confronted with problems such as explosion protection (explosion-proof design of automation equipment and systems). There is generally sufficient company documentation available for this, whereby the requirements arising from process technology can be implemented quite successfully.

The problem of EMC (electro-magnetic compatibility), which is also shown in fig. B2-71 is even more complex compared to an explosion-proof design of automation equipment. However, depending on process requirements it also needs to be taken into consideration in the design of an automation system. Here, as with no other main area dealt with in this book, the project engineer's experience is of some importance, since the appropriate know-how is at best only partially available in technical literature. It is therefore, as previously mentioned, up to the experience of individual companies to realise a well configured automation, system as far as EMC is concerned.

Similarly, the problem of lightning protection must be accorded its proper place in this context, since it also plays an important role in advanced system automation. Again, only fragmented specifications can only be found in the technical literature, including DIN documentation; hence the experience of the project design engineers is again crucial as far as this aspect of process protection is concerned.

Apart from the above mentioned topics, which doubtless require further details, there remains the important matter of VDI/VDE2180. In the author's experience, this guideline is of the greatest practical relevance and is to be incorporated unequivocally and practically in the project design.

VDI/VDE guideline 2180 is based on the following basic precept. (fig. B2-72):

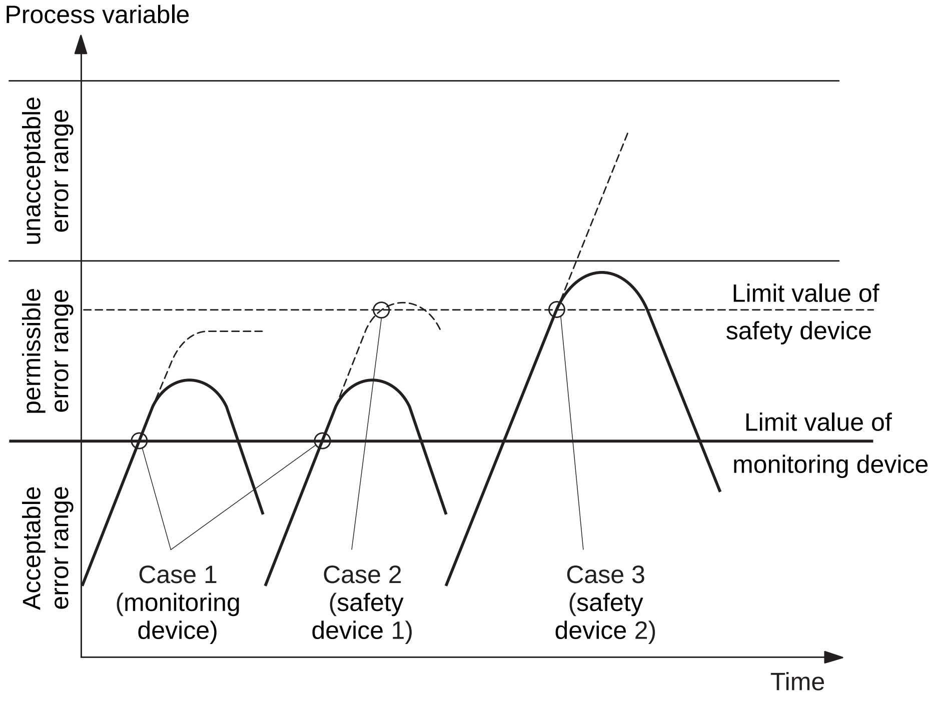


Fig. B2-72: Mode of operation of monitoring and safety equipment

- In the case of a process technological system, differentiation is made between the *so-called acceptable range*, the *permissible error range* and the *unacceptable error range*. Here, it is assumed that a process technological system in the course of normal operation (steady-state operation) moves within the so-called acceptable range, i.e. in the event of a drifting of process parameters from the working point, the system operates in the permissible error range.
  The protection of this operating regime is realised by means of the actual automation system, whereby a corresponding *monitoring device* (limit value encoded) ensures that if the acceptable range is exceeded (steady-state operating status), the system is automatically returned to the acceptable range or, if governed by the process technology, by manual intervention (case 1).

- If this monitoring device fails, then a so-called *safety device* (safety device 1) is indicated, which is also realised by means of a corresponding limit value encoder and at the very least returns the process parameters into the permissible error range (case 2).
- Irrespective of these measures described, an additional safety device (safety device 2) must be provided, which comes into effect in the event of failure of the previously described safety technology. This safety device requires a hardware basis which is completely independent of the previous automation equipment, which encompasses both sensors and actuators and also processors (case 3).

This ensures that in the event of failure of monitoring or safety equipment 1, an additional automation structure becomes effective in the process technology system, thereby preventing any drifting of the process parameters into the unacceptable error range (system damage or breakdown).

Depending on the process class, the project design engineer must therefore decide to what extent the specifications of VDI/VDE 2180 must be incorporated in the project design work.

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Project design

Chapter 3

Commissioning and maintenance

3.1 Commissioning of process and automation systems

3.1.1 Introductory comments – Commissioning strategy

To be able to solve the tasks set out in the main heading, it is first of all necessary to establish that the process technology system (the process) and the automation system should always be regarded as one entity. In this respect, the interaction between process (process technological system section) and the automation structure should always be taken into account as far as commissioning is concerned.

Fig. B3-1 therefore provides an overview of the main aspects of commissioning of process and automation systems, categorised into levels I and II. Here, it is of major importance, in which order (according to which commissioning strategy) the individual commissioning actions are carried out, thus determining the actual time period, costs arising and the success of system commissioning. A first evaluation of fig. B3-1 enables you to define the following main activities for commissioning:

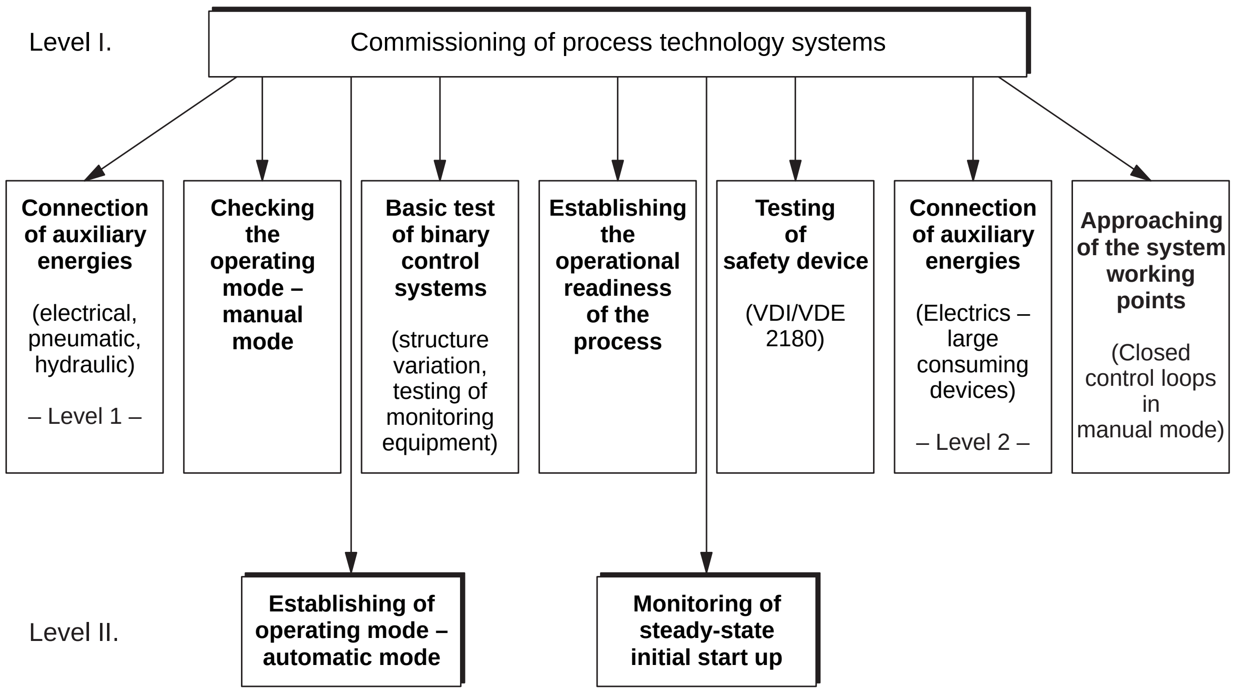

Fig. B3-1:
Main activities involved in the commissioning of technical process systems

Group 1 (step 1)

- Connection of electrical (and pneumatic) auxiliary energy for processors and other automation equipment (with the exception of large electrical consuming devices).
- Checking the operating mode – manual mode – for the existing closed control loops and binary control systems on the technical process system.
- Basic test of binary control systems, e. g. for the switching on and off of pumps, open/closed valves, etc., structure variations of the system and the testing of monitoring equipment.

Group 2 (step 2)

- Establishing the operational readiness of the process, e. g. availability of required media (basic materials) in the appropriate output containers, necessary filling of piping systems, etc., (all operating steps in manual operation).

Group 3 (step 3)

- Testing of safety devices (as specified in VDI/VDE 2180), whereby safety device 1 (sensors, actuators and processor algorithms are to be tested first, followed by safety device 2.
- Connection of electrical auxiliary energy for large consuming devices.
- Approaching of the working points of the process technological system, i.e. the closed control loops are moved into the required working points in manual mode, whereby the controller structure and the controller parameters are programmed for each closed control loop.

Level II

Group 1

- Establishing of operating mode – automatic mode – by means of a smooth transition, manual/automatic changeover (control signal-manual and control signal-automatic coincide).
- Monitoring of steady-state initial start-up and testing of control and disturbance behaviour.

3.1.2 Connection of auxiliary energies (Part 1 and Part 2)

As already discussed in section 2.2.5, the main concentration of work concerning the connection of auxiliary energies (electrics, pneumatics, hydraulics) is on the electrical auxiliary energy. This form of auxiliary energy is the dominant factor in the operation of an automation system. Because of the different groups of consuming devices (see power consumption), the sequence of connecting different voltage levels is determined and a procedure (steps 1 to 3) introduced as shown in fig. B3-2, whereby these voltages are made available:

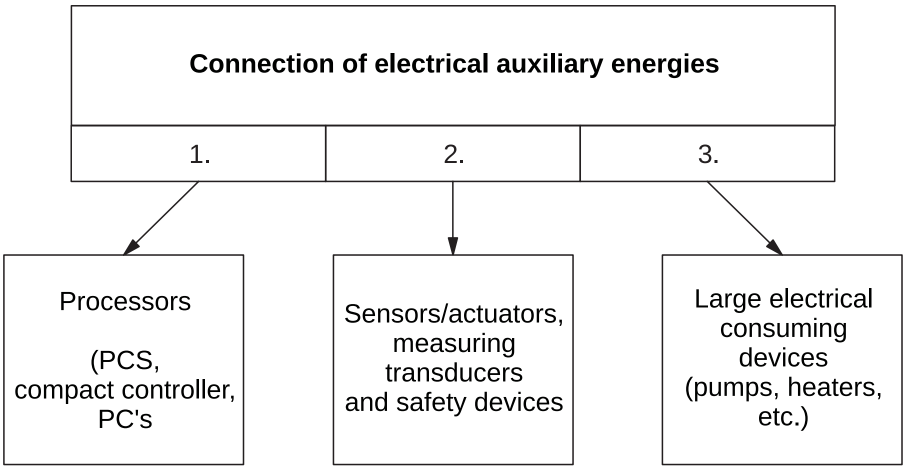

Fig. B3-2: Principal aspects regarding the connection of electrical auxiliary energy

Step 1:
Connection of electrical auxiliary energy for processors (process control system, compact controller, PLC technology and PC's)

- Typical voltage levels
  230 V AC and
  24 V DC (made available via power supply units)

Step 2:
Connection of electrical auxiliary energy for automation equipment – *standard consuming devices* (such as sensors, actuators, measuring transducers and safety devices)

- Typical voltage levels
  230 V AC (main supply)
  24 V DC (made available via power supply units)

Step 3:
Connection of electrical auxiliary energy for automation equipment – *Large consuming devices* (such as pumps and heaters)

- Typical voltage levels
  400 V AC (main supply)
  230 V AC.

Figs. B3-3 to B3-6 provide examples of this, which represent technically, a typical circuit solution in line with the connection procedure (steps 1 to 3).

Fig. B3-3 shows an example of how, by implementing steps 1 to 3, the electrical auxiliary energy for the small-scale experimental module is to be connected. This illustrates that the compact controller (processor) is the first to be supplied with auxiliary energy, followed by the sensors, actuators, small pumps and safety devices and, finally, the heater (being a large consuming) device.

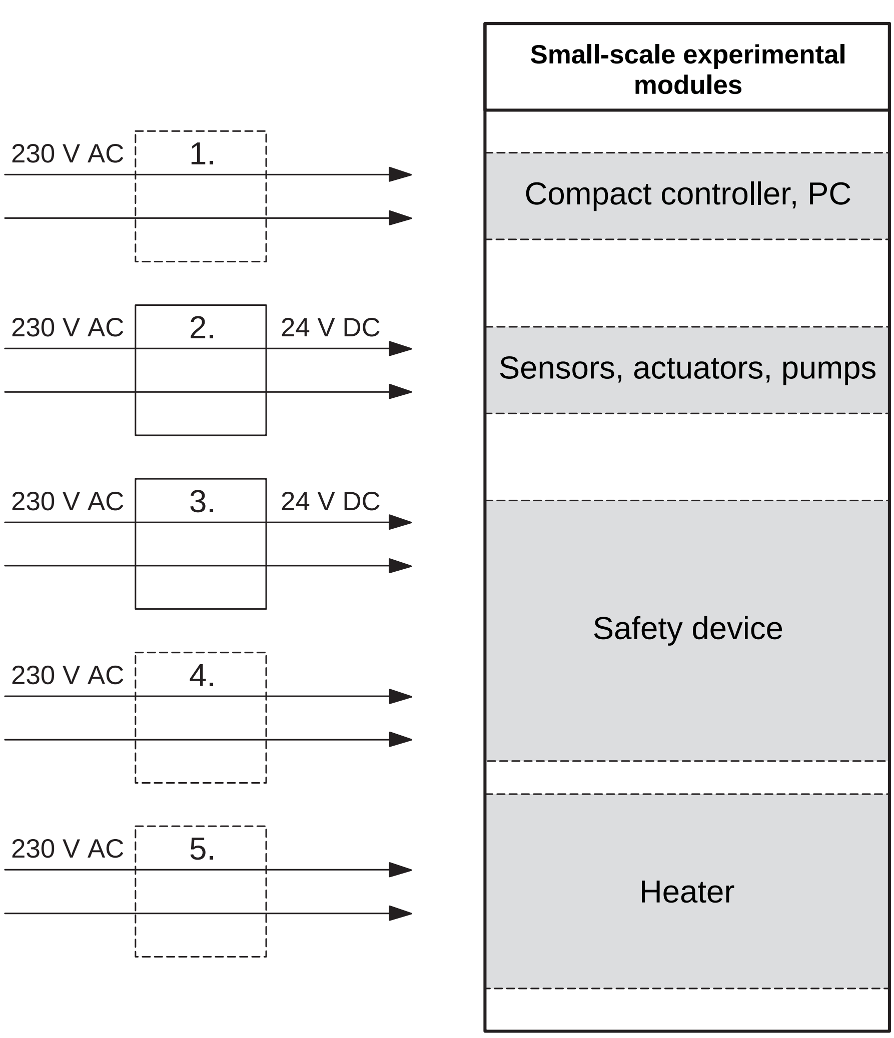

Fig. B3-3: Connection of electrical auxiliary energy using the example of a small-scale experimental module

An individual example then illustrates, which proposed circuit is more favourable for the supply of electrical auxiliary energy for the processors (fig. B3-4), whereby the safety device as well as the pneumatic auxiliary energy is supplied via the additional contacts of contactors K1 and K2. (fig. B3-6). Fig. B3-5 demonstrates an example of the connection of electrical auxiliary energy for large consuming devices, whereby the allocated pumps and heaters are supplied with the required 40 V AC via contactors K3 to K6.

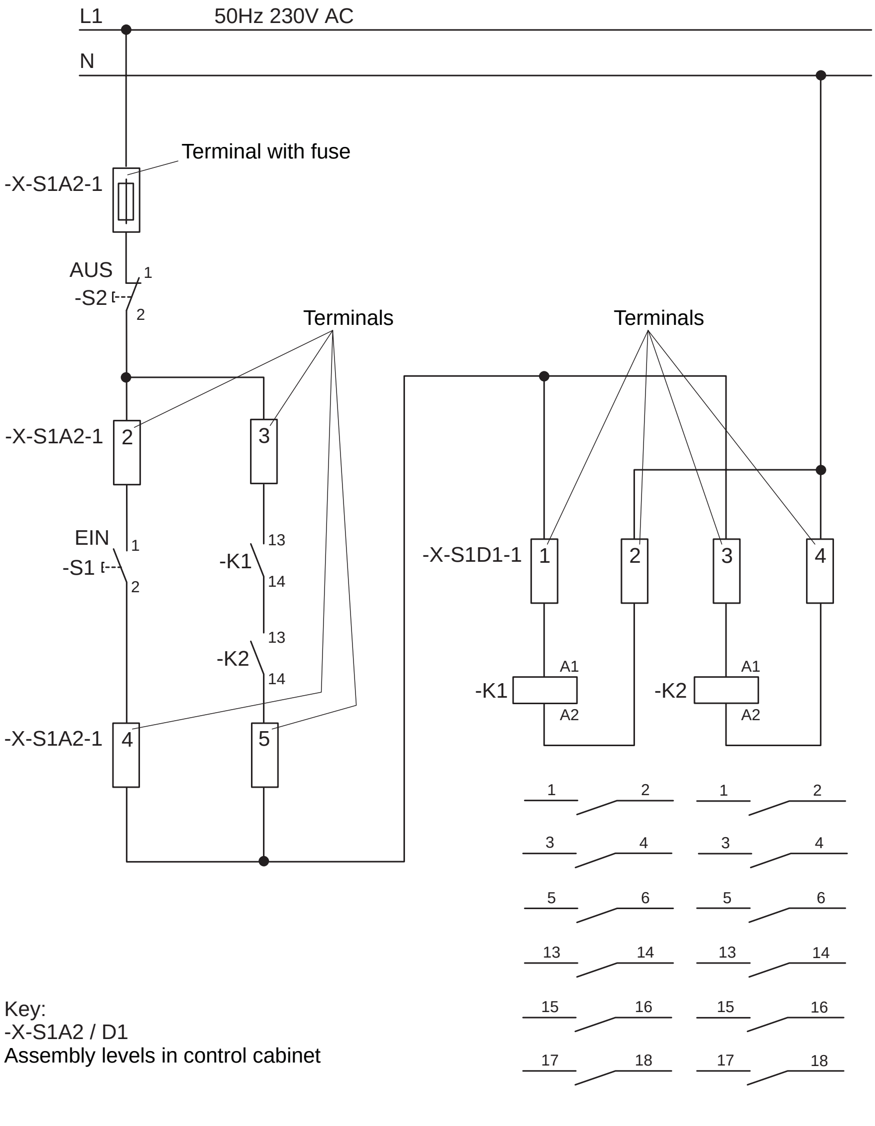

Fig. B3-4:
Connection of auxiliary energy for processors

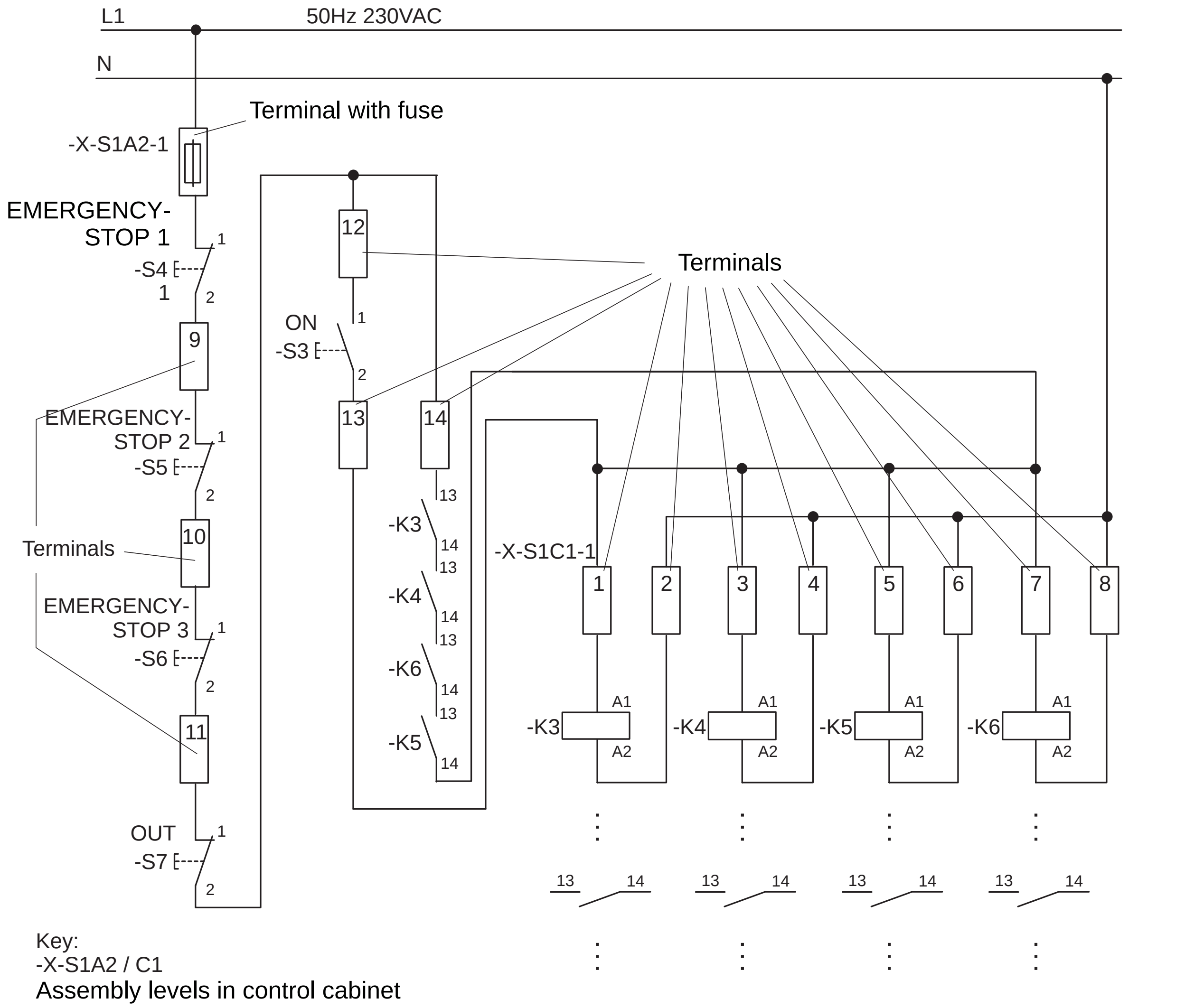

Fig. B3-5:
Connection of electrical auxiliary energy for heavy consuming devices

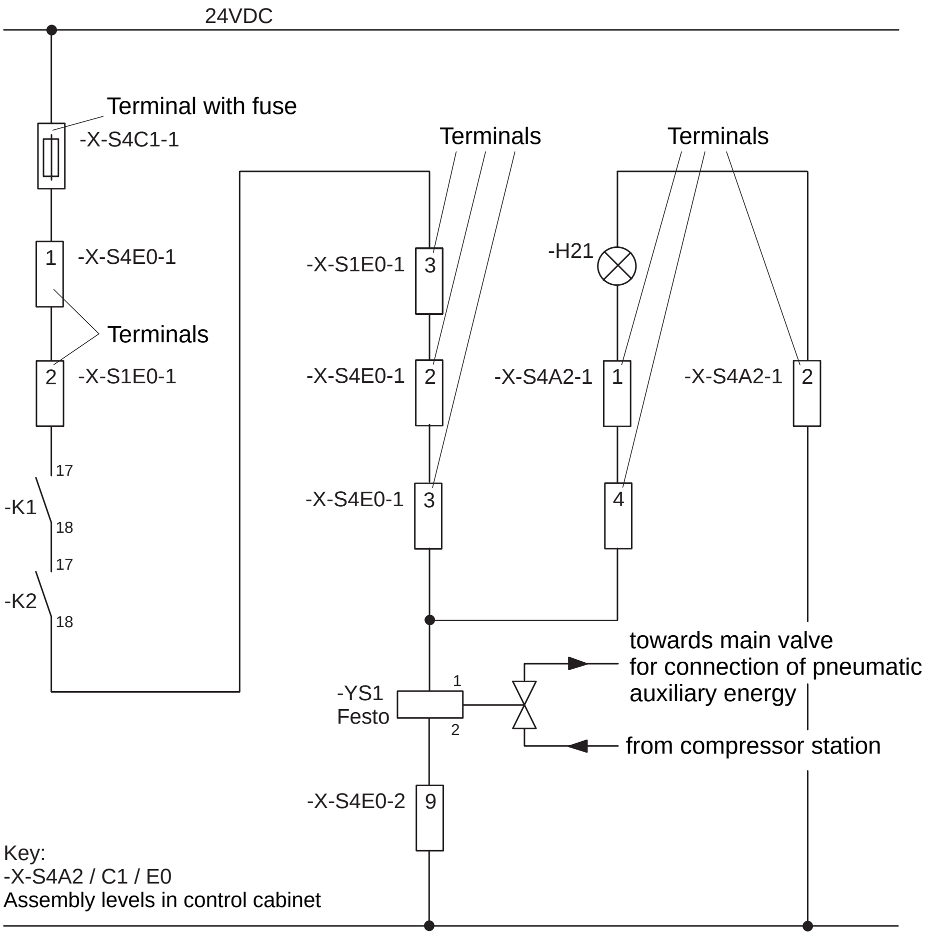

Fig. B3-6:
Connection of
pneumatic auxiliary energy

3.1.3 Testing of closed control loops, binary control systems and safety devices

Now that required auxiliary energies have been made available, the testing of the automation configuration/structure can be started. The following procedure is recommended to successfully realise this task (fig. B3-7).

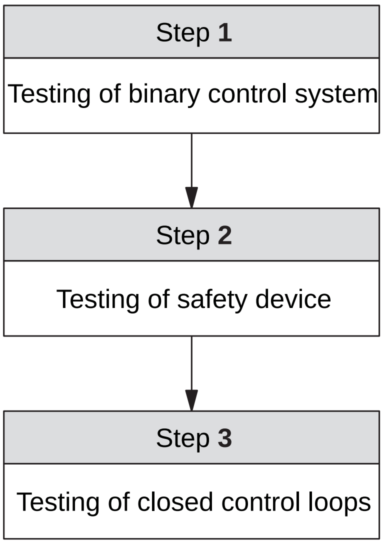

Fig. B3-7: Testing of automation configuration of a technical process system

With step 1, the binary control systems are tested as a first measure. This involves, for example, the testing of the on/off valves provided for configurational changes and their interaction with the corresponding binary controllers. In this connection, the signals resulting from the so-called final control element feedback in particular (see also section B.2.2.4) are to be evaluated visually or by means of binary monitoring (binary control systems). Similarly, the allocated binary control systems for the switching on and off of corresponding pumps and heaters are to be tested. Here again, the allocated binary control systems are to be tested via the manual control elements and corresponding feedback sensors.

Equally, the testing of safety devices also includes the monitoring of binary control systems. However, to do this, the associated sensors are to be activated by means of suitable manipulation and any actuators thus actuated evaluated in the familiar manner for correct functioning (visual and logic final control element acknowledgement).

If the binary control systems including safety devices are then fully functional, the actual commissioning of the closed control loop can be started. To do this, the closed control loops are brought into line with the respective specified working points in manual mode and then switched over to automatic mode. After a sufficiently long evaluation of the guiding and interference behaviour of the activated closed control loops, the system can be handed over to the user.

3.1.4 Establishing the standby mode of a technical process

By utilising the available auxiliary energy (electrical and pneumatic) and the operational automation configuration (binary control systems and closed control loops in manual mode), the technical process is to be put into standby mode, which guarantees the activation of the actual steady-state operation of the continual process. In particular, the following preparatory steps are to be carried out:

- Filling and venting of necessary piping sections to ensure the delivery capacity of the pumps used.
- Provision (pump supply) of a sufficient quantity of materials to the output containers.
- Configurational changes to container and piping system for the production start-up by means of actuation of selected on/off valves and corresponding hand valves.

3.2 Upkeep of technical process systems (small-scale experimental module)

Undoubtedly, the extent and cost of maintenance of modern technical process systems is to a large extent determined by the quality of the automation system (the automation project), whereby the use of modern automation equipment plays a vital role. Here, it should be acknowledged that the recognised procedure for conventional instrumentation has to be reconsidered for the maintenance and commissioning of a technical process system. In this context, the following aspects should be taken into account:

- Modern automation equipment is highly reliable, requires little or no readjustment, or can be easily adjusted via control and instrumentation systems or similar control elements, whereby any readjustments can be easily made if required.
- The universal use of process control engineering, being a typical characteristic of modern automation systems, facilitates a new and efficient approach to realising the required measures for maintenance and upkeep.
- The emerging use of fieldbus systems (bus systems in effect) similarly is to be taken into consideration and also influences the maintenance and upkeep operations.

It is therefore essential, in particular as far as advanced process technology systems is concerend, to reconfigure any previously used maintenance and upkeep strategies, whereby the tried and tested (from previous practice) should be adopted and new strategies (e.g. by evaluating the above points) should at the same time be pursued.

3.3 Fault finding and error handling – Damage prevention training

Fault finding and error handling represents an extensive area of functions in a an operational technical process. A wide variety of errors can occur, which need to be analysed and eliminated by maintenance personnel. As far as a systematic grouping of these errors is concerned, fig. B3-8 defines different categories which are discussed below.

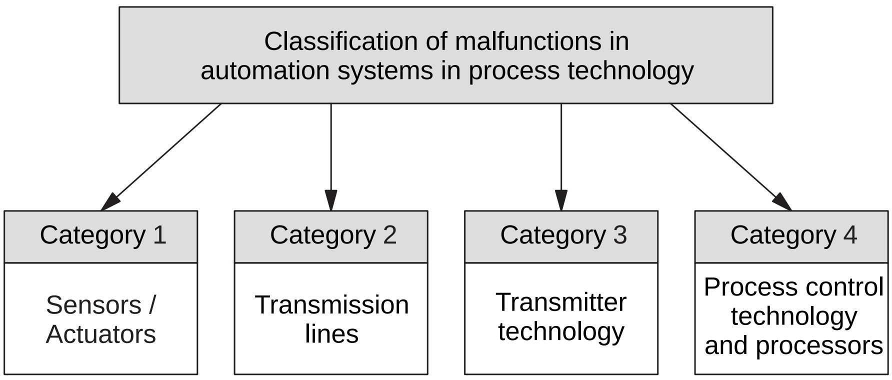

Fig. B3-8: Classification of malfunctions in automation systems

Group 1 covers the typical errors, which are caused as a result of a failure of sensors or also non-operational actuators. Here, the following advice is given for error elimination.

Category 1

Sensor faults

- Metrological checking immediately at the sensor terminals themselves or on the EMCS field terminal points.

Actuator faults

- Testing of the incoming control signal on the actuator
- Testing directly on the actuator – signal path from the positioning to the servo drive (checking of calibrating accuracy)
- Testing directly on the actuator – mobility of the valve poppet and spindle (error – e. g. as a result of jamming or rusting of valve poppet or spindle).

Category 2

Errors in transmission lines

- Transmission measurements by means of checking of terminals on the EMCS field terminal points and process control console.
- Visual checking of cable guides or cable trays (cable racks) to determine any mechanical damage.

Category 3

Errors in transmitter technology

- Checking of input/output behaviour by applying defined input signals to the input terminals of the measuring transducer.
- Checking of or repeating the calibration of the measuring transducer (checking of supply voltage).

Category 4

Errors on processors

- Checking of supply voltages
- Checking of input/output signals according to allocations resulting from algorithm processing (e. g. off-line testing of PLC or compact controller).

Apart from the above mentioned typical errors on technical process systems, which can generally always be eliminated with the help of appropriate know-how, malfunctions can also occur, which may lead to damage of entire system complexes, including personal injury or at the very least serious danger.

However, with the help of so-called damage prevention training, all system personnel are trained in how to react sensibly in the event, particularly of disaster, and to minimise any unavoidable material or personal damage. Doubtless, this damage prevention training is of particular importance in high risk installations (e. g. in atomic power stations, power stations, chemical plants, etc., but generally always needs to be adapted to the actual process technology.

A number of fundamental main points are listed below regarding the essence of damage prevention training.

- First of all, the technical process system is to be broken down into important individual sections from the point of view of process technology and system safety.
- Personnel are then to be completely familiarised with this structural breakdown (individual sections and their interaction), e.g. small-scale experimental module divided into the individual sections of filling level, flow and temperature control systems and supply module).
- On the basis of the breakdown of the system structure, a strategy is to be developed for the isolation of individual technical process system sections. To this end, manual intervention (emergency intervention) with the help of the designed automation systems should be possible which, owing to the configuration of the transmission lines (e. g. stainless steel pneumatic lines), ensures a refractability of at least 1 to 2 minutes even in an emergency.
- Personnel are to be trained in the handling of these emergency interventions.
- Furthermore, appropriate fire extinguishing and other damage controlling devices are to be incorporated in the emergency operation training.
- Finally, the most effective withdrawal of personnel from a damaged installation is to be defined and taught in the event of any damage occurring.
- Personnel must also be given training in recognising any damage which has occurred as a result of an emergency (e. g. environmental damage), plus any other systems including personnel in danger, and in informing any other parties in close proximity as appropriate (to be evacuated) or to include these in the damage control.

Chapter 4

Fault finding

4.1 What is meant by maintenance?

The term maintenance refers to all measures regarding the preservation and re-establishing of the setpoint status and the determining and evaluation of the actual state of technical resources of the system (DIN 31051).

More specifically, maintenance can be divided into three areas (see fig. B4-1):

- Service
- Inspection
- Repairs.

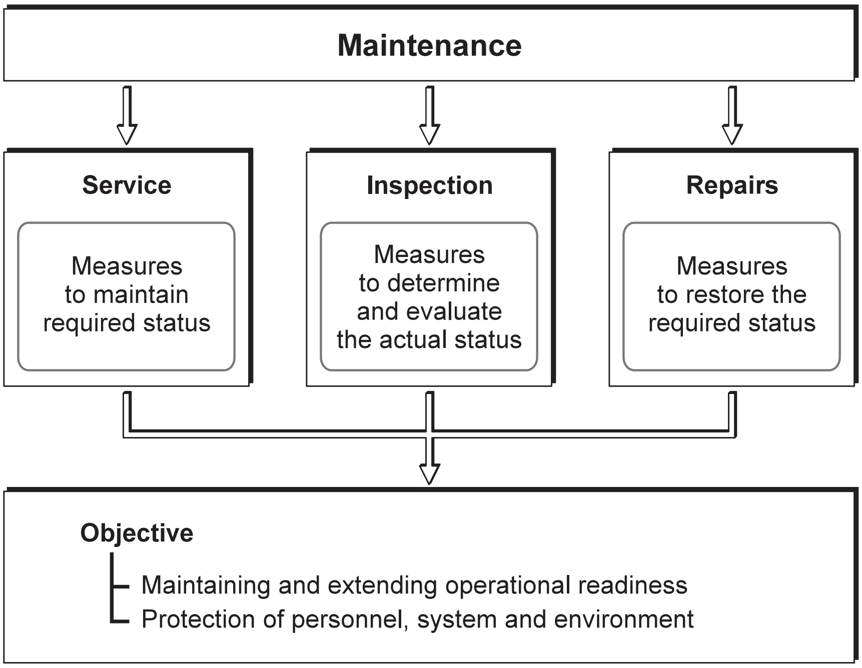

Fig. B4-1: Areas of maintenance

4.1.1 Service

The term Service refers to preventive measures to prolong operating times. Servicing of technical installations covers:

Service

- According to service schedule at defined intervals
- Preventive
- Wear-reducing measures
- Extending service life

Fig. B4-2: Service

4.1.2 Inspection

Inspection

- To detect wear at defined time intervals in accordance with inspection schedule
- To detect and evaluate visible and audible signs and extent of wear
- Measuring, experience and checking of safety elements and their required setting values – instigate required official inspection

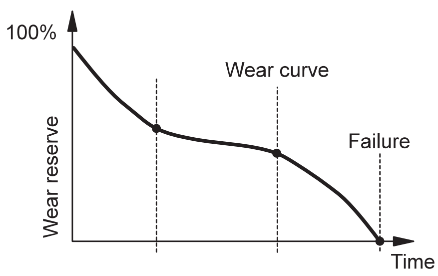

Fig. B4-3: Inspection

4.1.3 Repairs

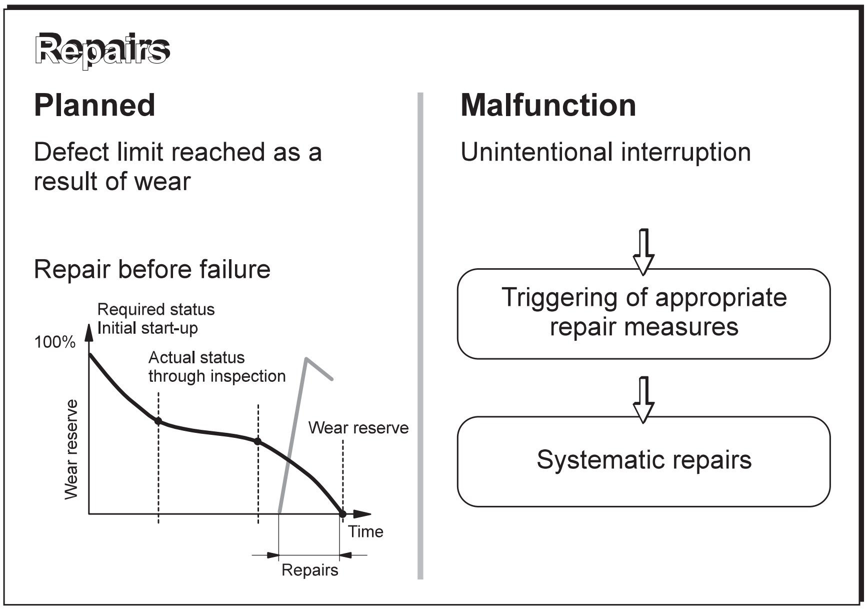

Fig. B4-4: Repairs

4.2 Systematic repairs in the event of malfunction

In the event of an inadvertent interruption, repairs are to be carried out according to the following plan.

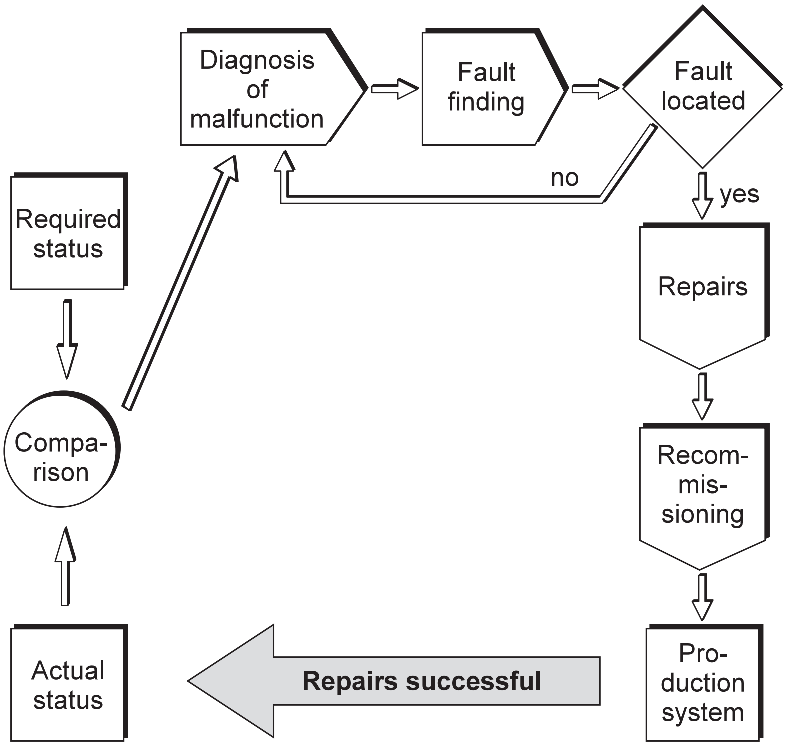

Fig. B4-5: Systematic repairs

4.2.1 Prerequisite for systematic repairs

The basic prerequisite for systematic repairs and fault finding is knowledge of the system. This means that only when you have familiarised yourself with the system and know how it is structured, will you be able to carry out systematic repairs.

Familiarisation with the system by:

- closely observing the installation.
- making available the entire system documentation.
- knowing the product and processing technology.
- exchanging information with the user, operator.

Structuring of the system into:

1. System and controller structure
- Program flow charts
- Function charts
- Description

2. Mechanical design
- Structure and support unit
- Function units
- Adjustment

3. Drive technology
- Electrical system
- Hydraulics
- Pneumatics
- Mechanical system

4. Final control element
- same as 3

5. Control system
- Electrical relay control
- Programmable logic controller

6. Signal generator
- Binary sensors
- Analogue sensors
- Digital sensors

7. Power supply
- Electrical
- Hydraulic
- Pneumatic

4.2.2 Procedure

The first thing that must be done in the event of an error signal is to establish the actual status. The following options are available for this:

- Discussing the fault with the user
  (Does the system operate incorrectly?)
- Start failure
- Stopping during process step
- Faulty process
- Incorrect working practice

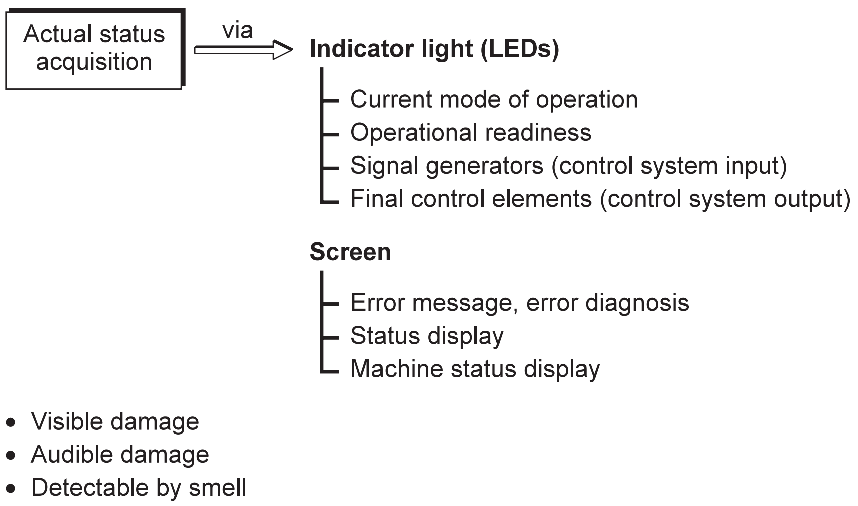

Fig. B4-6:
Acquisition of actual status

4.3 Fault finding

The actual fault finding starts once the **actual status** has been established and compared with the **required status**. This comparison frequently leads to the discovery of the error source, if the fault is

- visible (e.g. mechanical damage to a signal generator),
- audible (e.g. leakage on a valve),
- detectable by smell (e.g. cable burnt out)

If this is not the case, the fault can only be found and eliminated by means of a systematic procedure.

4.3.1 Systematic fault finding

Again, the required/actual status comparison forms the basis for systematic fault finding.

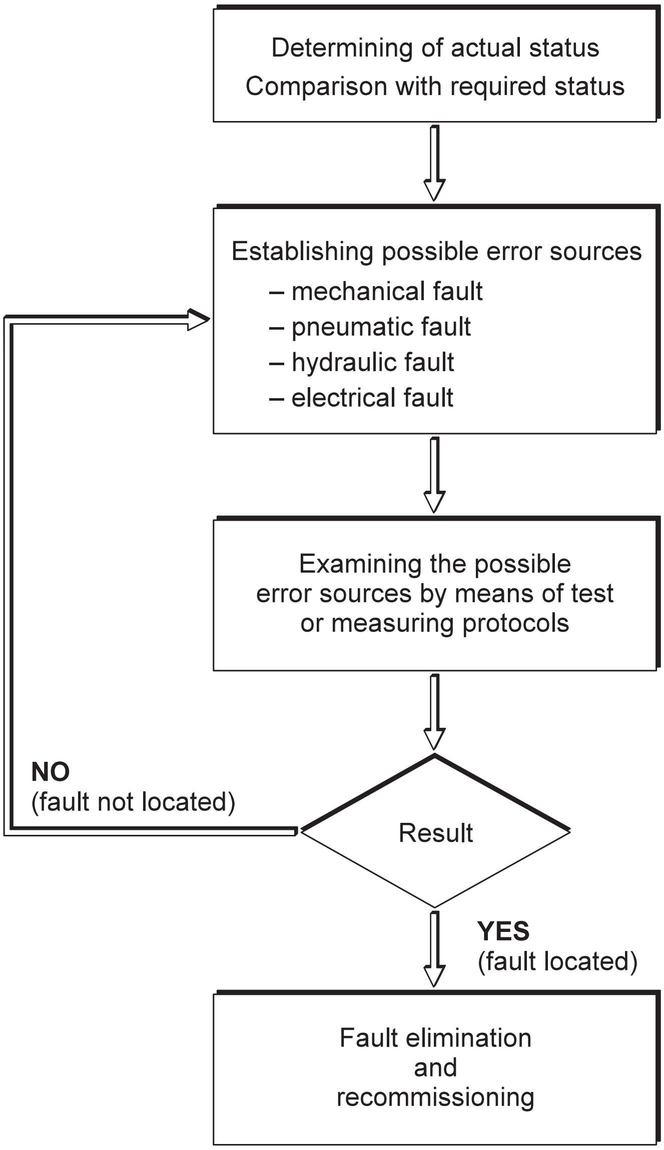

Fig. B4-7: Systematic fault finding

4.3.2 Fault documentation

Once a fault has been found, it is not sufficient just to rectify this, but at the same time the cause of the problem should be determined. A useful tool for this is a faults list, which should be kept with the installation. This list describes the malfunctions and their causes. It may take a number of different forms.

The following is an example.

Mach. No.	**Date / Time**	**Fault**	**Cause**	**Fault index**	Rectified by

This list can be useful in detecting frequently recurring faults and their causes. The **fault index** makes it easier to establish the nature of the error.

A = Incorrect working practice
(e.g. a retaining screw is not properly tightened on an assembly part)

M = Mechanical fault
(e.g. sensors are maladjusted)

E = Electrical fault
(e.g. relay is not energised or solenoid does not switch)

S = Controller error
(e.g. program or program part is not activated)

L = Leakage fault
(e.g. water escaping from threaded connection)

B = Operator error
(e.g. shut-off valve not closed)

W = Service error
(e.g. filter not cleaned)

Example

Mach. No.	**Date / Time**	**Fault**	**Cause**	**Fault index**	Rectified by
1303	04.01.95 / 11.00	Part system Filling level, Controller does not operate correctly	Filling level sensor maladjusted	M	TZI

4.3.3 Fault analysis

With the help of the faults list, it is possible to establish whether a fault or damage occurred and thus to pinpoint weak points in the system. Once these have been identified, it is advisable to introduce technical improvements. If damage has occurred, the following procedure should be adopted.

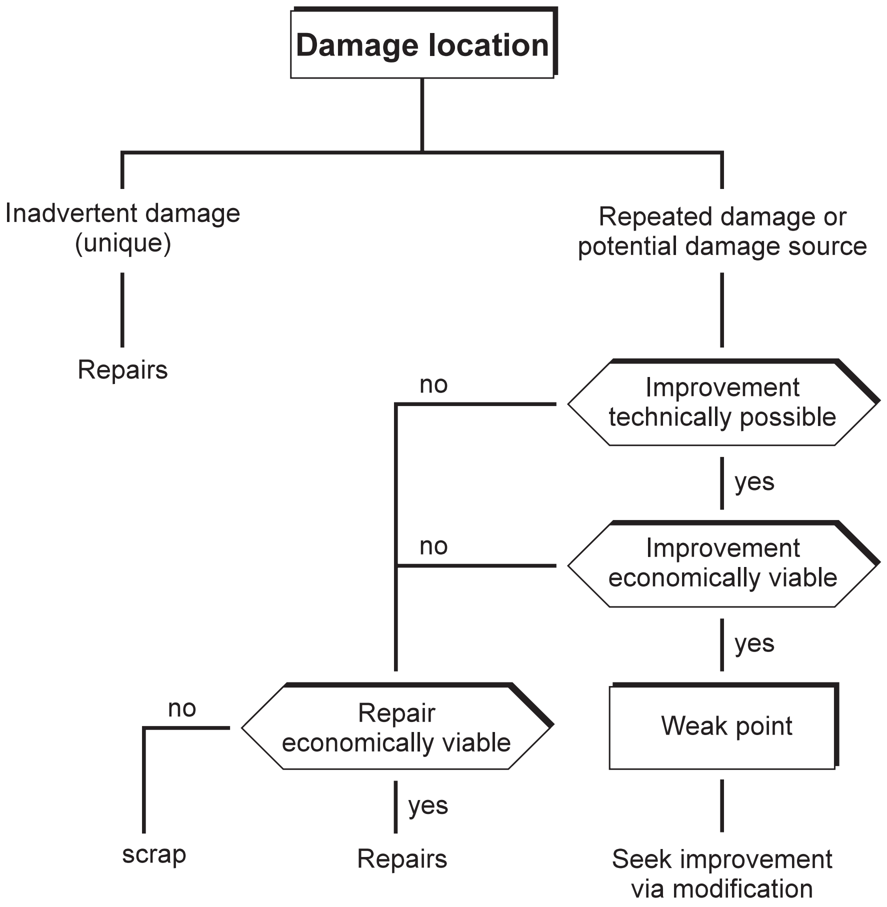

Fig. B4-8: Fault analysis

4.4 Final analysis

Fault finding and elimination means not just to render the system operational again, but also to identify and improve weak areas in the system.

The basic prerequisite for this is a knowledge of all control technology aspects and understanding of the function and interaction of hybrid systems.

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Part C

Solutions

Title

Overview of project design process

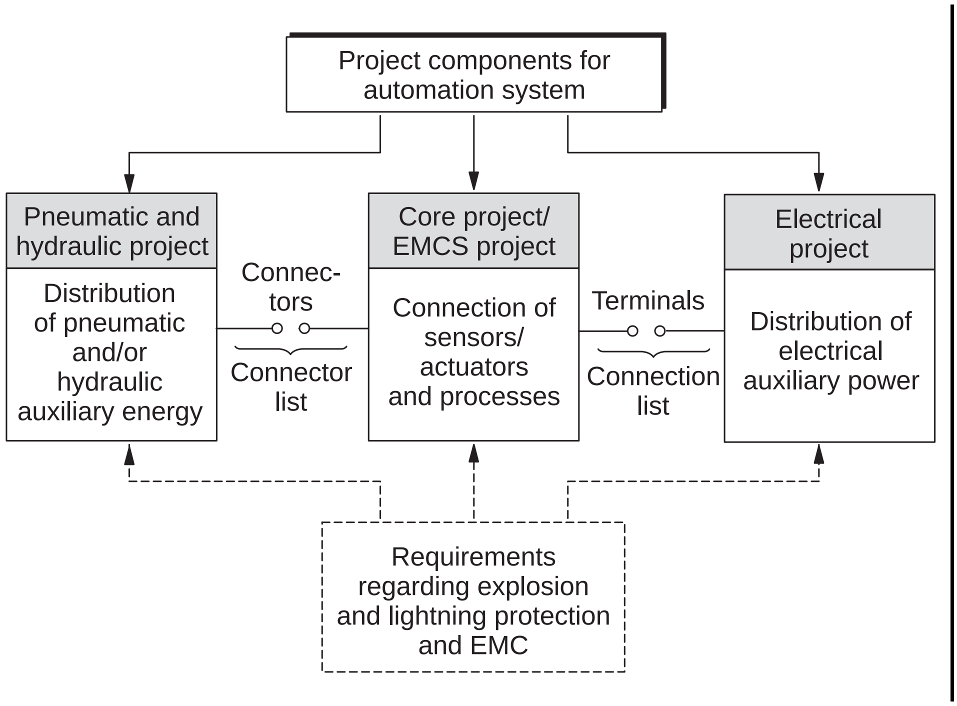
Solution to part exercise 1-1

Name (in brief) the main areas involved in core project design!

- Project configuration
- Tender specification/performance specification
- PI flow diagram
- Preliminary EMCS block diagram
- Final EMCS block diagram
- Wiring lists

Solution to part exercise 1-2

Explain, in principle, the procedure for the combining of the core, electrical and pneumatic projects!



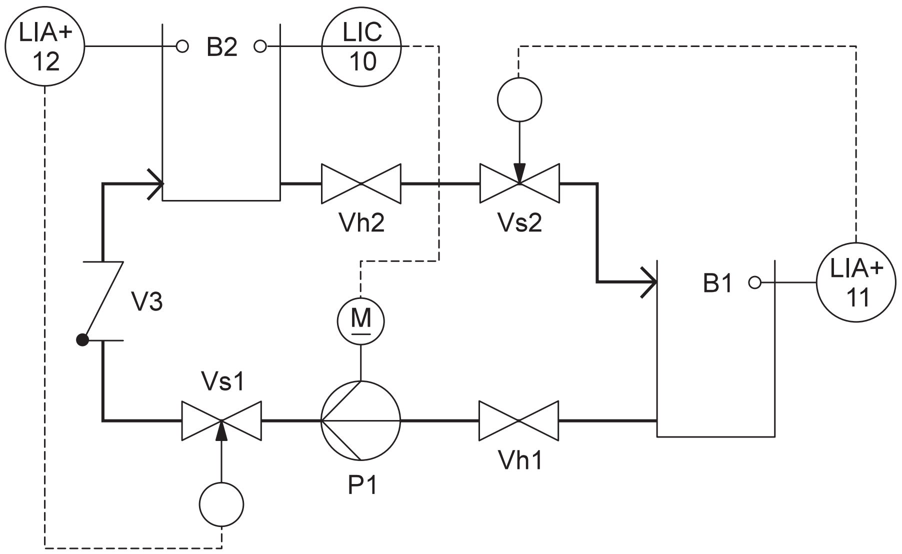
Title

Core project design – Fundamental methodology for the project design of automation systems

Solution to part exercise 2-1

Develop the PI flow diagram for the specified process flow diagram (requirements: control of filling level in container 2 [B2]; monitoring of filling levels in containers B2 and B1).

Complete the PI flow diagram.

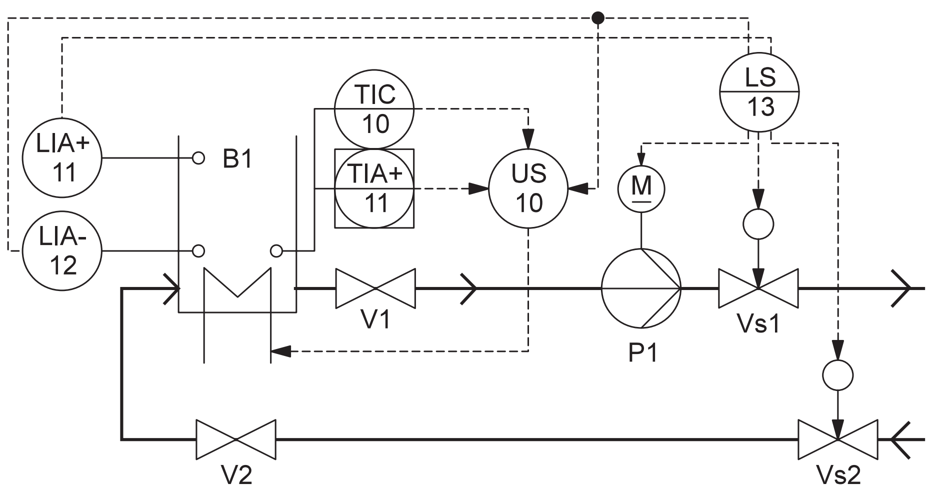


Filling level control system – PI flow diagram

Solution to part exercise 2-2

Develop the PI flow diagram for the specified process flow diagram (requirements: control of temperature in container B1; monitoring of filling level and temperature in container B1).

Complete the PI flow diagram.

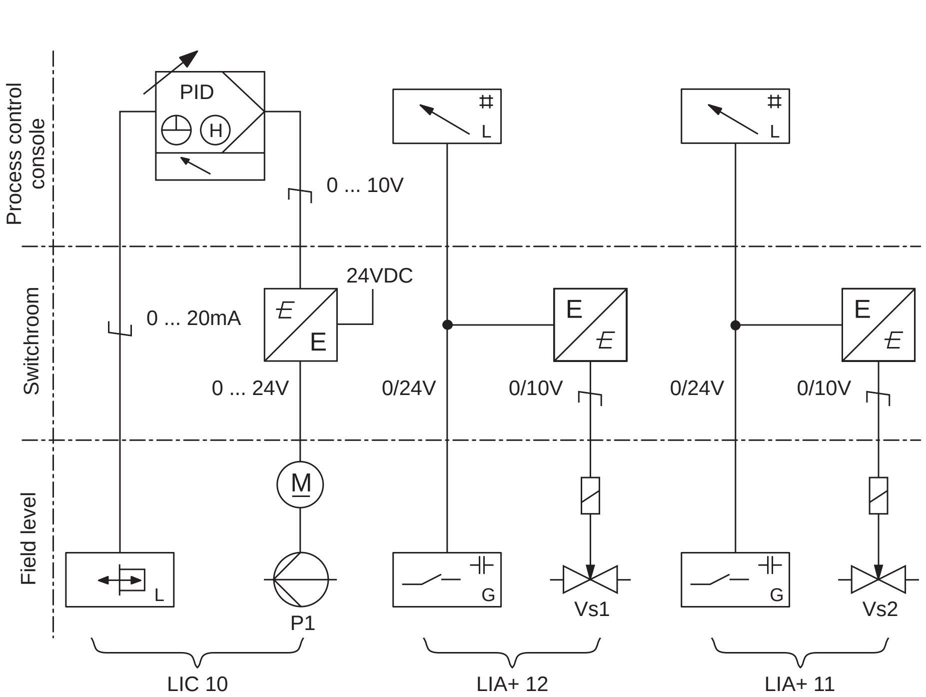


Temperature control system – PI flow diagram

Solution to part exercise 2-3

Draft the preliminary EMCS block diagram for the EMCS points of the PI flow diagram created in part exercise 2-1 (see solution, part exercise 2-1).

Complete the preliminary EMCS block diagram.



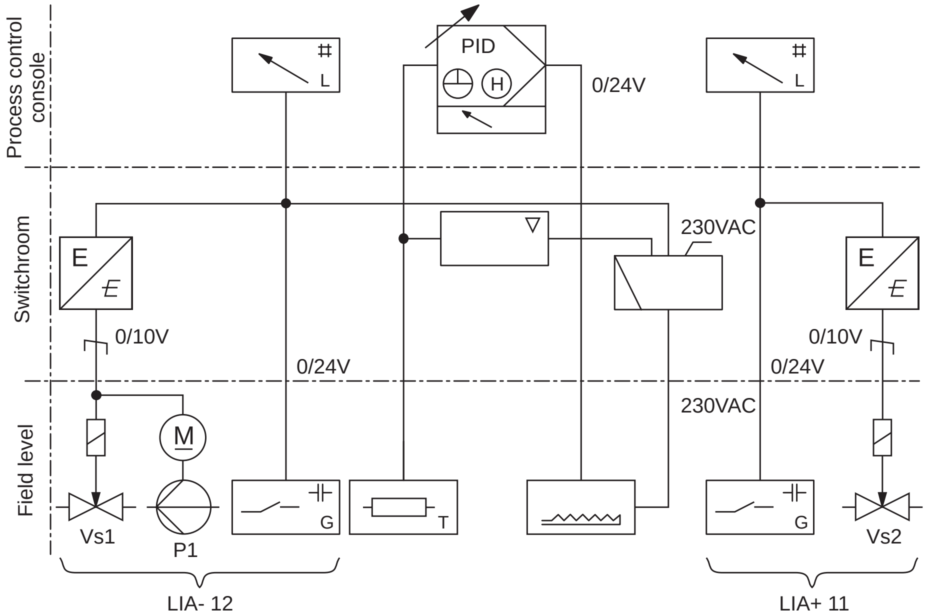
Filling level control system – Preliminary EMCS block diagram

Solution to part exercise 2-4

Draft the preliminary EMCS block diagram for the EMCS points of the PI flow diagram created in part exercise 2-2 (see solution, part exercise 2-2).

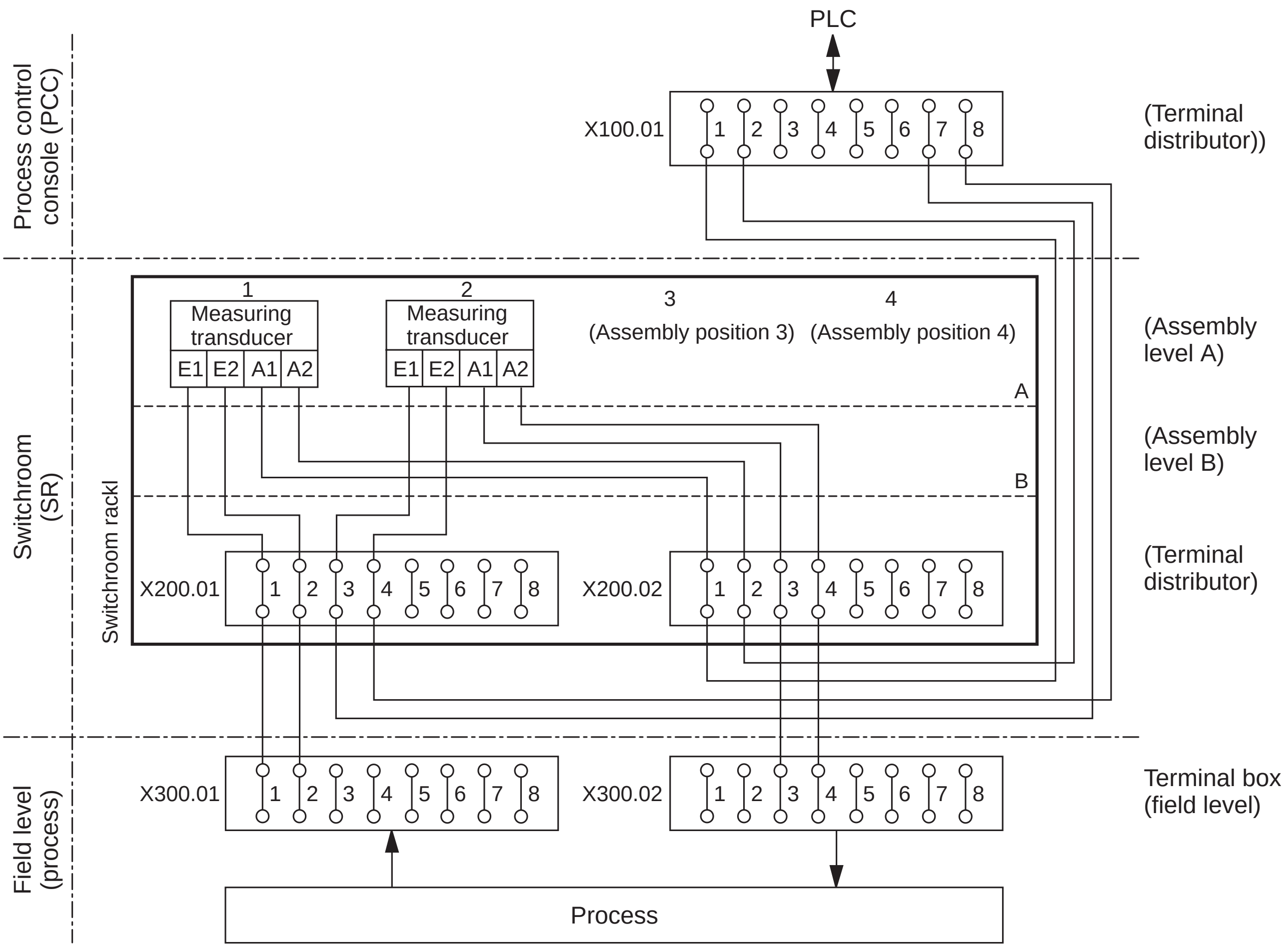
Complete the preliminary EMCS block diagram.

Temperature control system – Preliminary EMCS block diagram

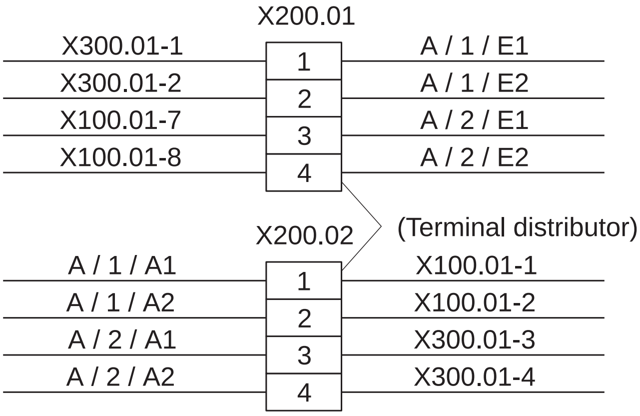


Solution to part exercise 2-5

With the help of the project configuration plan (process control console, switchroom and field level), draw up two examples of wiring (e. g. simple allocation of the switchroom terminal distributors X200.01 and X200.02), whereby the terminal boxes/field level (X300.01 and X300.02), the assembly levels A and B (switchroom rack) and the terminal distributor X100.01 (process control console) are to be used as additional components.



Wiring routing (Part 1) – Project configuration



Wiring routing (Part 2) – Terminal distributor allocation

Title

Closed control loop synthesis and planning of binary control systems

Solution to part exercise 3-1

- Investigate the method of operation of the filling level control loop (closed control loop in manual operation; type of action of sensors and actuators).
- Develop a strategy for computer-aided measured value acquisition.
- Determine the static characteristic curve of the ultrasonic sensor, i.e. the correlation between filling level and the respective current or voltage signal.
  Note: Record a sufficient number of interpolation points.

Investigation of the experimental areas

Regarding communication between computer and process

The first step of the experimental analysis, is the investigation of the available technical resources. These comprise the sensors and actuators of the process to be examined and the auxiliary hardware and software equipment required for data acquisition and evaluation.

In the case of computer assisted data acquisition, the communication between the process and computer is effected via *PC cards* or via a bus system (e. g. PROFIBUS). Here, it should be taken into account that the majority of PC cards can only read an output of 0 to 10 V as analogue signals, which necessitates a signal conversion. The analogue ultrasonic sensor used in this system supplies a current signal of 6 to 20 mA analogue to the measured distance. This can be converted into a voltage signal via a load resistance. From the description of the sensor it can be seen, that the load resistance R_L must be less than 400 Ω. For instance, if $R_L = 390\Omega$ is selected, this creates a voltage signal of 2.34 to 7.80 V, which can then be recorded via a PC-card (fig. C3-1a).

If the measured data is recorded via a bus system, then a suitable device is required for converting the signal (fig. C3-1b). A bus-compatible digital controller can for instance be used for this. The bus transfer rate is crucial with regard to the recording of step responses.

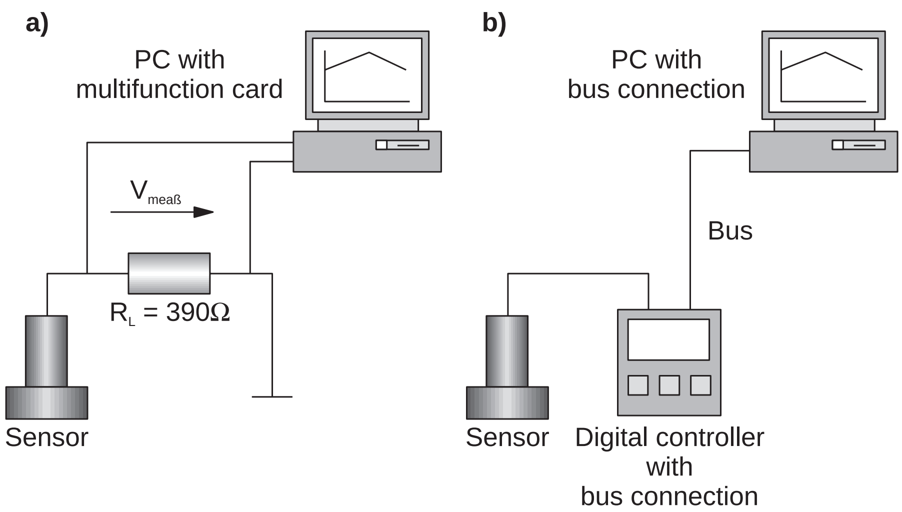


*Fig. C3-1:
Communication between
Computer and process
a) via PC card
b) via bus*

Determining the characteristic sensor curve

The technical description of analogue sensors generally indicates the characteristic sensor curve (graphically or in the form of an equation with tolerances). If this characteristic curve is missing, then it must be determined by experimental means. This may also be necessary in cases where the operating conditions affect the characteristic curve.

In the case of the controlled system for the filling level, the position of the sensor, i. e. its location/height above the container, is of major importance. It is used to measure the distance between the sensor head and the water surface and not the actual filling level directly (fig. C3-2).

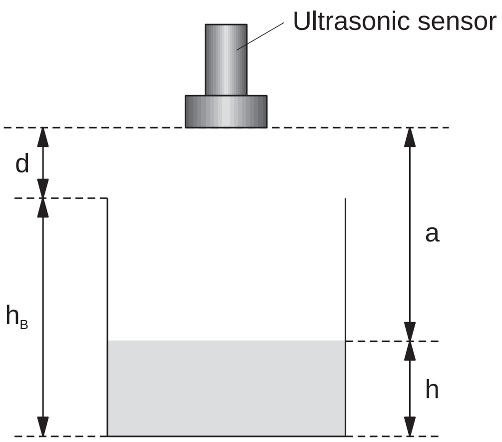


Fig. C3-2: Configuration of ultrasonic sensor

The filling level *h* can thus be calculated as follows:

$$h = d + h_B - a$$

Distance mm	Signal mA	Filling level mm
310	9.98	35
290	10.48	55
270	11.15	75
250	11.73	95
230	12.37	115
210	13.02	135
190	13.64	155
170	14.25	175
150	15.00	195
130	15.57	215

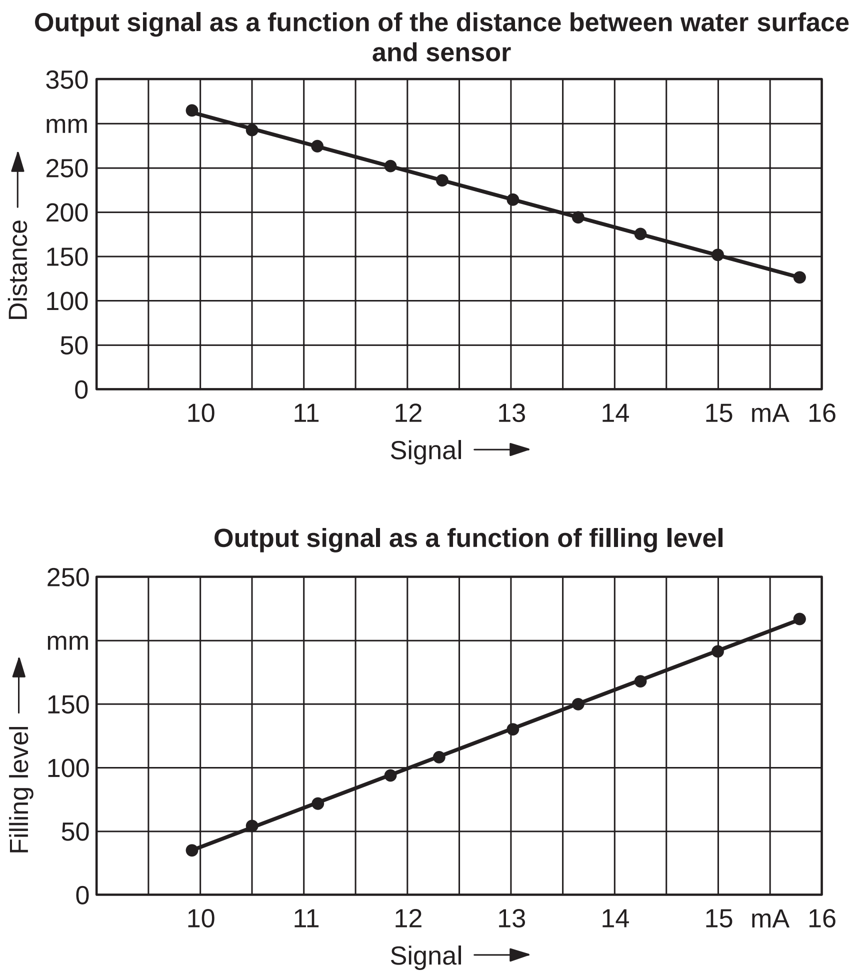


Fig. C3-3: Representation of sensor characteristic

Mathematical evaluation

Correlation coefficient:		-0.99966045
Slope:		-31.76112
Y-section:	Mean value	623.970
	Deviation	1.234

Explanation regarding measuring process

The measurement of data is effected manually by means of a digital multimeter. Starting with a full container the filling level was read in steps of 20 mm. The value table obtained was noted and subsequently evaluated in Microsoft Excel.
The value table does not take into consideration the filling level, but the actual distance between the ultrasonic sensor and the water surface.

Solution to part exercise 3-2

- Determine the static behaviour of the controlled system for the filling level.
  Note: Record the corresponding controlled variable for each correcting variable in the steady-state condition.
- Represent the results in a diagram in the form of a static characteristic.
- Evaluate the static characteristic determined (e. g. linear/non-linear) and compare the results with those determined in the theoretical process analysis.
- Define the operating point for the dynamic analysis (identification) of the controlled system.

Determining the static behaviour of the controlled system

As calculated in the course of the theoretical analysis of the controlled system for the filling level, the filling level in the upper container in the stationary status also depends on the volume of water in the total system. This is expressed via the variable H_W. The parameters and characteristic values determined subsequently therefore only apply for one setting. The results specified were determined at H_W = 40 cm.

The static behaviour of a controlled system is the relationship between input and output variable in the steady-state condition /stationary state. In the case of the controlled system for the filling level, the voltage becomes the correcting variable for the changing of the pump speed (input signal) and the filling level becomes the controlled system output variable. Fig. C3-4 represents the static characteristic curve of the controlled system with open and closed outflow.

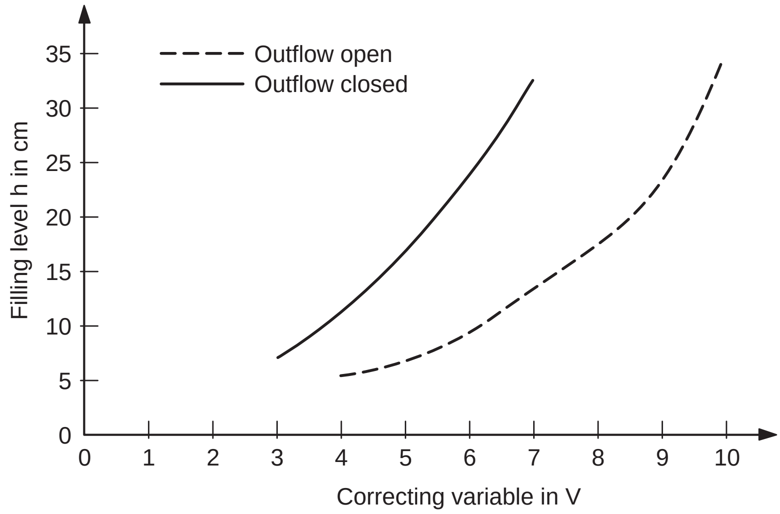


Fig. C3-4: Static characteristic curve of filling level system with open and closed outflow

A comparison of the theoretically determined, qualitative pattern of the static characteristic curve is to be made to check that it conforms to the experiment.

The form of the characteristic curve indicates that the controlled system for the filling level is a *static non-linear system.* Hence the subsequently determined parameters merely apply to a sufficiently small area around the operating point.

The operating point selected for open outflow is a 50% correcting variable (5V) and a filling level of (6.72 cm).

Comment

From the static characteristic curve of this controlled system, it is possible to determine the delivery head of the centrifugal pump with closed outflow in relation to the correcting variable (voltage) and not immediately in relation to the speed (fig. C3-5).

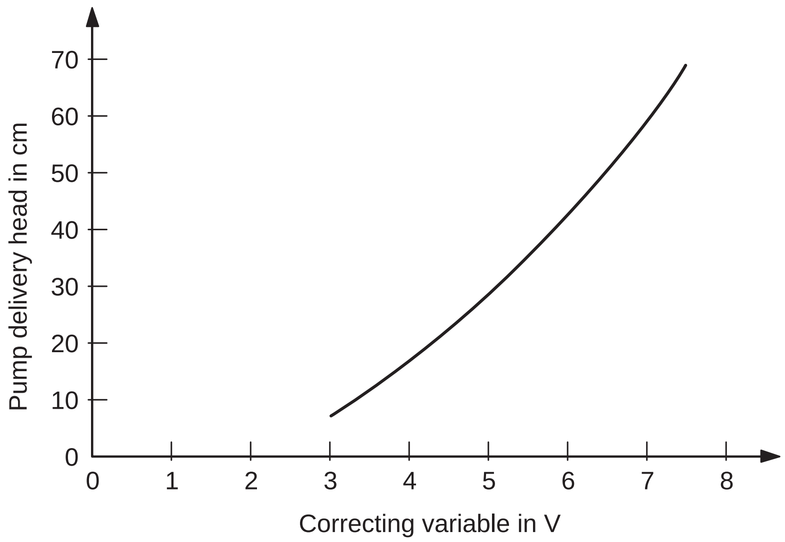


Fig. C3-5: Delivery head of centrifugal pump

Solution to part exercise 3-3

- Determine the dynamic behaviour of the controlled system (identification) for the selected operating point.
  Note: Carry out the step-change experiments around the operating point selected; observe the form of the static characteristic curve to determine the height of the step-change. Also, try to record the correcting variable in parallel with the controlled variable.
- Determine the characteristic values (proportional coefficient, time delay, transient time) of the controlled system, using the inflectional tangent method.
  Note: If necessary, also establish an average of the measured values. Use a sampling interval of 0.2 to 0.5 s for the data acquisition.

Determining the dynamic behaviour of the controlled system

The dynamic analysis is carried out around the selected operating point. Because of the static non-linearity of the controlled system for the filling level, the step-change height must be selected so that the newly obtained operating point (as per step-change height) is not far removed from the original operating point. As such, a linear correlation can be assumed within this range. The step-change height is to be 10% of the maximum possible correcting variable.

Fig. C3-6 illustrates the correcting variable step-change (50% to 60%, i. e. from 5 V to 6 V) and the step response (filling level in cm). The measured voltage signal (6.337 V to 5.915 V) has been converted into the corresponding filling level values (cm).

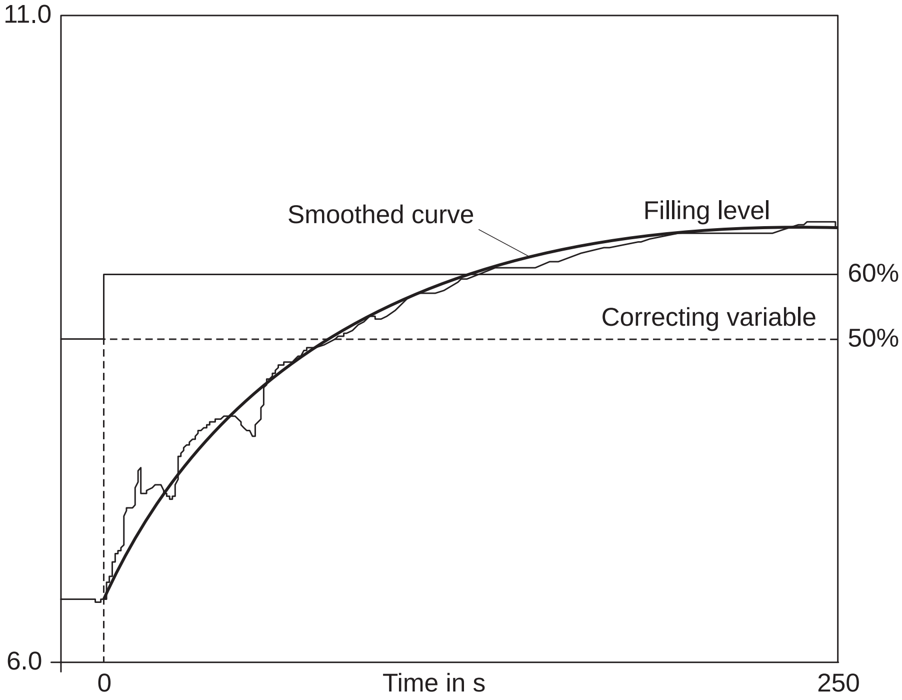


Fig. C3-6: Step response

The filling level step response has been averaged out and evaluated by computer. As a result of this evaluation, the following controlled system parameters have been determined:

Proportional coefficient	K_S	=	2.76 cm/V
Transient time	T_g	=	68.14 s

These two parameters can be derived from fig. C3-6 with the help of the inflectional tangent method. It is however not possible to read a time delay in this way.

It simply needs to be estimated in order to be able to apply the setting rules in accordance with Chien, Hrones and Reswick, i. e. when estimating T_u, a considerably reduced time delay is selected compared to the transient time, e. g. T_u= 0.5 s.

Solution to part exercise 3-4

- Determine a favourable controller configuration for the controlledsystem behaviour.
- Parameterise the controller according to the Chien, Hrones and Reswick method.
- Set the controller parameters on the compact controller (Bürkert controller).
  Note: Please note that with the Bürkert compact industrial controller type 1110, the scale range also enters into the proportional coefficient K_R.

Controller configuration and parameterisation

PI controllers are particularly suitable for controlled systems with *proportional behaviour and dead delay time*.

With the setting rules according to Chien, Hrones and Reswick it is possible not just to select the controller configuration, but also to determine the behaviour of the closed control loop after a disturbance or setpoint step-change.

A PI controller for setpoint step-change and without overshoot is selected for the investigated filling level system. The controller parameters can be calculated as follows:

$$K_R \approx \frac{0,35}{K_S} \cdot \frac{T_g}{T_u} = \frac{0.35 \cdot 68,14}{0.422 \cdot 0,5} \approx 113 \text{ (practical setting value 10...20)}$$

with $K_S = \frac{\Delta\, U}{\Delta\, y} = 0.422$

and

$T_n \approx 1.2 \cdot T_g \approx 81.77$ s (setting value 82s).

Comments

- Please note that the calculated value for $K_R \approx 113$ is obtained from the estimated time delay T_u (see fig. C3-6) and therefore is to be replaced by the practical setting value.
- When setting the controller parameters in the digital controller the existing scaling is to be observed (see page 54 of the operating instructions of the digital industrial controller, type 1110 – Bürkert open and closed loop control technology, 1994).

Solution to part exercise 3-5

- Examine the control behaviour of the closed control loop around the operating point (triggering of setpoint step-changes).
- Evaluate the results obtained in accordance with the following criteria:
  – How are the dynamics of the correcting variable to be evaluated?
  – Does the controlled variable reach the new setpoint value after a finite time?
  – Is it necessary to correct the set controller parameters?

Controller test

The pre-configured controller is to be used to control the filling level system using setpoint step-changes (control behaviour). The same scaling is to be selected for the controlled variable acquisition and the setpoint specification.

Fig. C3-7 illustrates the step-change from 6.5 V to 6 V.

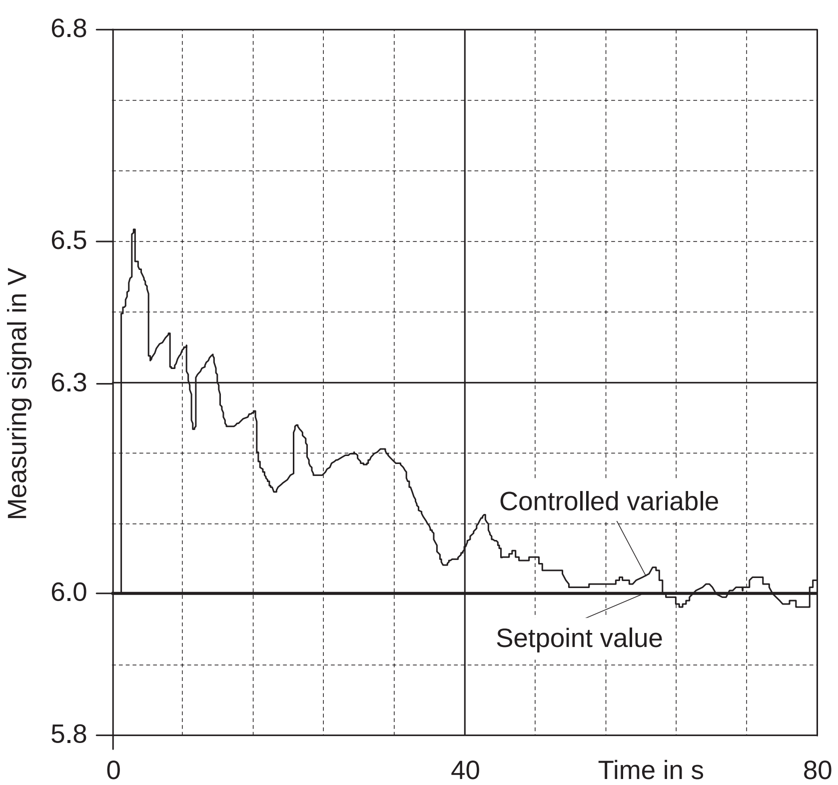


Fig. C3-7:
Setpoint step-change
(Voltage in V)

This process is to be converted back to filling level values in accordance with equation 2.2. (fig. C3-8).

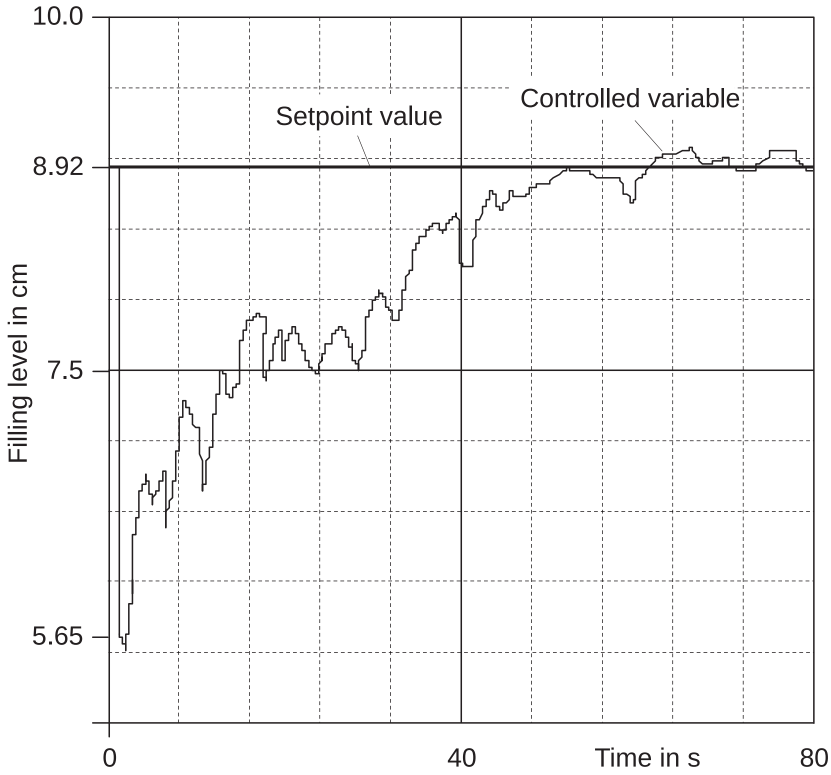


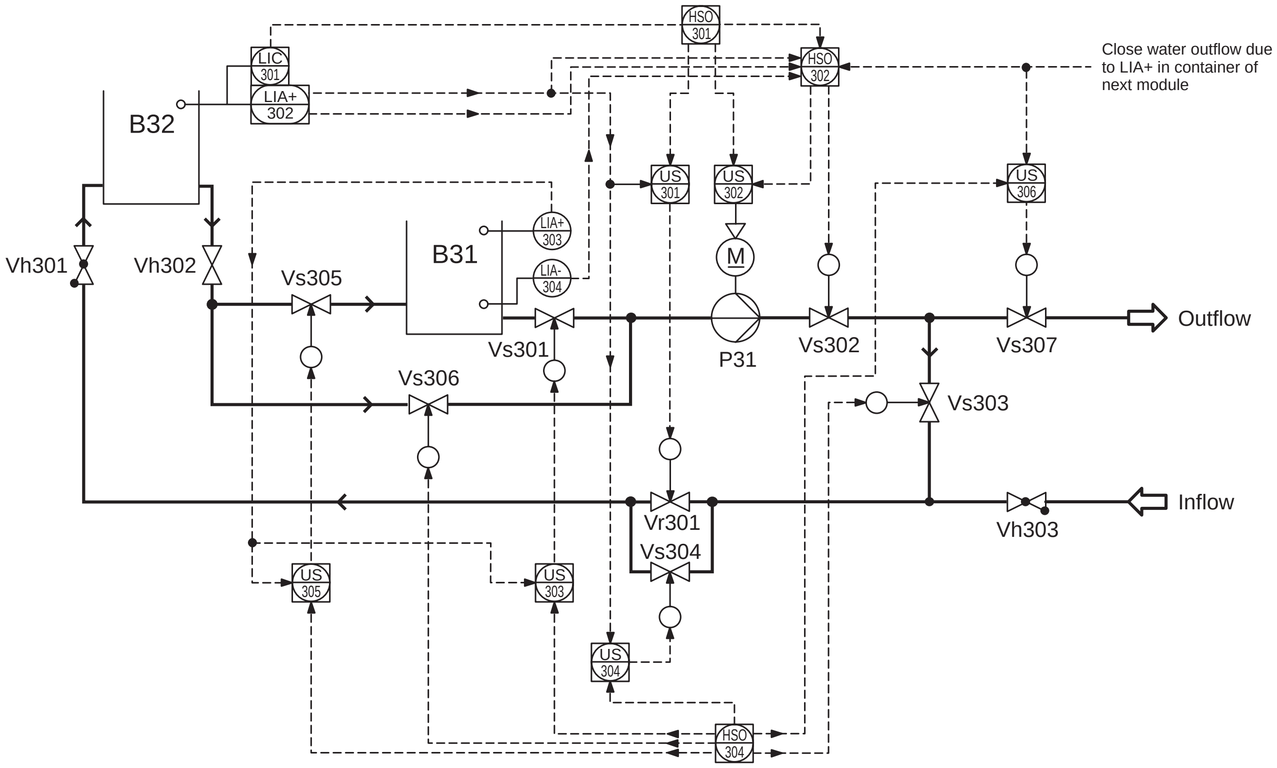
*Fig. C3-8:
Setpoint step-change
(Filling level cm)*

Title

Process protection measures

Solution to part exercise 4-1

Draft the PI flow diagram, whereby the EMCS functions for process protection are to be integrated into the process flow diagram in complete form.



PI flow diagram for filling level control (open and closed loop control and process protection)

Solution to part exercise 4-2

Compile the EMCS points drawn up in part exercise 4-1 in a table (EMCS points list), providing an explanation of the function of the individual EMCS points.

EMCS point	Function	Closed loop control	Open loop control	Process protection
LIC 301	Filling level control	Filling level	–	–
LIA +- 302	Limit-value monitoring in B32	–	–	–
LIA + 303	Limit-value monitoring in B31	–	–	–
LIA - 304	Limit-value monitoring in B31	–	–	–
HSO 301	Select control mode (Pump/regulating valve)	–	Switch through the control signal to selected actuators	–
HSO 302	Pump on/off Vs302 open/closed	–	B: Pump on (binary signal), Valve open	LIA+302 and A
HSO 303	Select type of operation (A/B)	–	A: Vs301, 303, 304, 305 B: Vs306, 307	–
US 301	Signal switching for Vr301	–	–	LIA + 302
US 302	Signal switching for P31	–	–	
US 303	Signal switching for Vs301	–	–	LIA+ 303
US 304	Signal switching for Vs304	–	–	LIA + 302
US 305	Signal switching for Vs305	–	–	LIA + 303 then off
US 306	Signal switching for Vs307	–	–	next module LIA+ then off

Table: Regarding function of the EMCS points of the PI flow diagram – Filling level control

Title

Connection of Pt100 temperature sensors

No sample solution is provided in this instance.

The results of the resistance or temperature measurements are highly dependent on the individual experimental design.

Title

Closed loop control technology

The controller parameters for the individual control systems can be found in the following table. The specified parameters are to be determined during test measurements. Your experimentally determined values may vary from the values in the table.

Temperature control system		Flow control system		Filling level control system	
Kp	4.00	Kp	3.50	Kp	28
Tn	2500	Tn	0.40	Tn	5.00
Tv	0.00	Tv	0.00	Tv	0.00

Controller parameters

Part D

Appendix

Chapter 1 ProVis – Process visualisation software

Chapter 1

ProVis – Software for process visualisation

1.1 System prerequisites

The ProVis software is a graphic operating system extension operating in Windows. Your computer must fulfil the following requirements in order to ensure a satisfactory program execution:

CPU:
486 or higher

Main memory:
at least 8 MB, 16 MB recommended

Hard disc:
at least 100 MB available hard disc capacity

Disc drive:
3.5", 1.4 MB memory capacity

Graphic card:
Graphic card with Windows 3.x driver, type according to desired image resolution, recommended resolution 800 x 600

Screen:
Colour monitor

Interfaces:
parallel for one printer, serial for process connections, possibly a second serial interface for a mouse connection, if no system mouse is used

DOS:
Version 3.3 or higher

Windows:
Microsoft Windows Version 3.x or higher

Software:
InTouch software package must be installed on your computer in order to execute ProVis.
(Order No. of english version: 167 019).

1.2 Installation of ProVis in Windows

You have started Windows and are now in the Program Manager. Insert the ProVis diskette in your disc drive. Select *File-Run* in the Pull-Down menu of the program manager. Enter the command line A:\PCS_GB. ProVis is then installed.

1.3 Starting the program

To start ProVis, proceed as follows:

- Set the controller of your system to *Remote*.
- Start the EZDDE program and set the interfaces COM1 and COM2.
- Start the InTouch program.
- Select ProVis in the application directory.
- Start the InTouch Window Viewer,
  The initial display of ProVis is loaded.

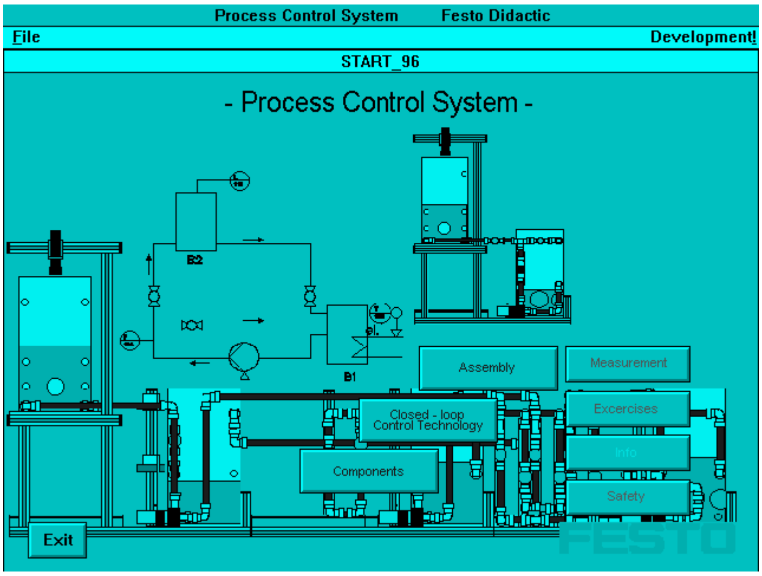


Fig. D1-1:
Initial display of ProVis

Components of process automation	Contains detailed and general information about components, which are used in process automation.
Closed-loop control technology	Provides information about methods of controller setting.
Configuration and commissioning	Information is given regarding configuration
Metrology facility	The metrology facility enables you to carry out controller settings and read and evaluate measured values.
Course overview	Contains predefined interactive exercises
Info	Provides general information for Process Control System.
Safety	Displays notes regarding safety.

Table D1-1:
Description of
control buttons on
initial display of ProVis

D1 – 4

Software