Practical mastery of closed-loops I

C46003

FESTO

Workbook
for MPS®PA
Compact Workstation

With CD-Rom

Including learning module:
- Energy intelligence

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1.1 The Revolution of Instrumentation and Control

Improved management, new production processes and the introduction of new machinery and equipment has brought about a distinct rapid growth in output and productivity in manufacturing industries since the 1920's.
The mass production and demand of standard products required has increased dramatically. Managers believed that close control at all stages of production was too important to be left to workers.

From the turn of the century onwards, recorders were developed to assist supervisors and managers to secure and maintain consistent and reliable operating conditions and as instrument manufacturers claimed, to "give an absolute check on the efficiency of employees". Recorders were used to measure the performance of machinery, to check the hours worked and also to ensure that working practices were carried out to the correct standard.

One instrument manufacturer, The Bristol Company (today: Emerson), in its 1912 Catalogue, gave an example, where a recorder was used to ensuring that the men keep the furnace evenly full and not stop filling for longer than twenty minutes. The men were not allowed to rest too long and it was a better plan for the men to fill for a short time and then rest for a short time. The chart would show whether they did this or not.

The standardization of products, companies and procedures not only made it easier to observe and control what workers were doing, but also encouraged managers to consider automatic operation in the work place to optimize work efficiency and mass productivity. The uncertainty involved in human operations could also be removed.

The change to mass production and the use of assembly line and continuous production techniques was accompanied by a change in the social organization of work. The semi-skilled worker began to be replaced by semi-skilled and unskilled factory hands that operated the automatic and semi-automatic machinery.

At the beginning of the 1920s, control was, with a few exceptions, was seen as simply switching on or off devices – motors, valves, pumps etc. The switching was done either directly by push buttons or levers or through relays. The common characteristic of all control devices during this time was that the measuring instrument/element and controlling actuator were combined to form a single unit. By the end of the decade, it became clear that in order to improve control, the measurement and actuation would have to be separated by a unit that could either amplify or even modify (convert) the signal being produced by the measuring device.

Prior to the World War (1914 – 1918), European instrument manufacturers held an important position in the field of Industrial Instrumentation. To apply automatic control to industrial processes at that time was a daring procedure.

The use of automatic controllers in process industries did not become widespread until the mid-1920s. A survey was carried out by the United States government towards the end of the 1930s. It was found that the sales of industrial instruments has grown quickly, in both absolute terms and relative to other forms of machinery produced between 1919 and 1929. Americas industry spent over $300 million on instrumentation between 1920 and 1936. The survey covered controllers, indicators and recorders and found a steady increase in the proportion of controllers sold. From 8% of total sales in 1923, to between 40% and 50% from about 1932 onwards. It was estimated that over 75000 automatic controllers were sold by American instrument companies between 1925 and 1935.

In the USA, several industrial instrument manufacturing companies were formed around the turn of the century and a number of scientific instrument makers began to produce instruments suitable for industrial use. In England and also in Germany, similar instrument companies were developing. In the early years of the century, they concentrated on improving the measuring elements of indicators and recorders. By mid 1920s accurate, reliable and cheap indicators and recorders were readily available for the most common measurements:

- Flow
- Pressure
- Temperature
- Level

During the 1920s design leadership in industrial instrumentation passed from Europe to USA and by the mid-1930s there were over 600 companies in the USA manufacturing and selling industrial instruments. Of these companies, seven dominated the market with a combined sales amounting to 65% of total sales.

Early users of instruments were the:

- Power generation companies , seeking to improve the efficiency of steam generation and lessen CO2 emissions
- Automobile industry for heat treatment of parts
- Chemical industry for a wide range of activates.
- Dairy industry for pasteurization of milk
- Paper manufacturing for the measurement of relative humidity.

The need to measure levels, pressure, temperatures and flow was common to a wide variety of industries, temperature measurement being the biggest requirement. The ability to measure a specific quantity is essential to controlling it. Before we understand the way in which controllers were developed, we need to first briefly examine the development of measuring (recording) instruments during the earlier years.

For installations with a large number of instruments, central instrument or control rooms became popular in the 1920's. One operator or supervisor would decide on the basis of the instrument reading, if a valve or actuator should be opened or closed. Someone was either sent to adjust the valve or actuator, or the supervisor changed the color of a light to indicate to the furnace operator or another worker that a change was required.

The heat treating systems sold by the Leeds & Northrup Company during the early 1920s, adopted this similar concept. A supervisor in a central room would observe the temperature records of the heat treatment furnaces and would pass the commands to the furnace operator to increase or decrease the heat in the furnace by placing pegs into a switch board. This would illuminate different colored lights situated by the furnace. The furnace would be adjusted according to the color of the light:

- Red meant reduce the heat
- Green meant increase the heat
- White meant no change

It was not long before instruments were introduced to operate the lights directly and then to operate the control valves which controlled the supply of heat to the furnace, thus making the furnace operator redundant.

1.2 Process Control Systems

Process - It is a naturally occurring or designed sequence of changes of properties or attributes of an object or system. Industrial and environmental processes relate to the sequence of operations and involved events, taking up time, space, expertise or other resources, which lead/(should lead) to the production of some outcome. The changes they may create in the properties of one or more objects under their influence are especially important for their identification and design.

Control – The technique of making an apparatus, a process, or a system operated without human intervention.

System – An organization of parts that are connected together, real or abstract, where each component interacts with or is related to at least one other component and they all serve a common objective

Within a short period of time, industry has made a transition in manufacturing: from production techniques that were accomplished through manual operation, to sophisticated automatic procedures that need little or no human intervention.
Through this evolution, there have been some drastic changes that have resulted in more economic production and better quality products.

The initial transition to automation was created as a means of improving production through reduced labor costs. In many parts of industry this particular goal has been realized. The savings from a reduced payroll (less staff) compensated for the increase in cost due to acquisition costs. However, with this comes the need for better-trained technical personnel.

Automated production has brought about a number of features that are of far more importance than having a smaller payroll. These features include:

- Reduced waste
- Improved tolerances
- Better product consistency
- Production convenience
- Improved product development techniques

Automation of equipment and improved technology has caused industrial process control to become the fastest growing field in industry today. This has had a tremendous effect on industrial artisans (craftsman), technicians and engineers.
The basic concepts of industrial process control have become an essential tool for those that are pursuing a career in any part of industry.

In the past, industrial process systems were limited to a number of simple motor control applications and the devices used to achieve basic control. Magnetic contactors, gaseous tubes, rheostats and potentiometers were the heart of control field during the beginning of automated process control. Developments in the solid state electronics, micro component design and hence, revolutionary advances in computer technology have brought about important technological changes to process control. Microprocessors, intelligent instrumentation, programmable logic controller (PLC's) and electronic devices may all be combined to control a single or multiple processes. A person, who is working with this kind of equipment, must have an understanding of the complete system, to be able to locate faulty components when a malfunction occurs. The astonishing progress in computer science and hardware technology means that computers have large memory, high speed, lower cost and sophisticated machine interface environments. In addition to modern control technology, the application of intelligent systems and combination of modern control with intelligent systems have been recognized as one of the most important directions in todays digitalization of industrial control.

The main characteristics of production in industry today are large scale, high speed, highly continues and flexible manufacturing.

Process control is a unique part of industry that deals with the control of variables that influence materials and equipment during the development of a product. It may range from a relatively simple operation, such as filling a bottle to maintaining the level in an analytical procedure or a complex chemical process. In both cases, there is always some kind of control. Control can range from a simple ON/OFF function or a PID closed loop.

Processes are manufacturing processes or operations performed on a product that brings it one step closer to becoming a finished product. Manufacturing processes depend on:

- The type of material being manufactured
- The equipment performing the operation
- The quality of the finished product
- The quantity that is being produced

Manufacturing processes are grouped into areas that respond to changes in pressure, level, flow and temperature. Processes are continually monitored and changed during the manufacturing of a product.

1.3 Modern Day Instrumentation

Instrumentation is one of the fastest growing disciplines in industry and a wide variety can be found in the international market. From bio-medical to process control and from chemical analysis to aviation, almost all the industries are being increasingly based on sophisticated instruments. Simple applications of instrumentation can be found in equipment we rely on, every day of our lives:

- Tire Pressure
- Speedometer
- Car Fuel Gage
- Car Temperature Gage
- Stove
- Fridge and Freezer
- Geyser
- Toilet Cistern Water Level
- Iron
- Football Ball Pressure

1.4 What is Instrumentation?

Instrumentation is defined as "the art and science of measurement and control". Instrumentation can be used to refer to the field in which Instrument technicians and engineers work, or it can refer to the available methods of measurement and control and the instruments which facilitate this. Over the last few years, instrumentation technology has advanced dramatically. New and more efficient ways to measure, control and monitor industrial processes are being developed every year.

Here are just some of the well-known companies that require instrumentation to control their processes:

- Power generation company
- Automobile industry
- Chemical industry
- Dairy industry
- Paper manufacturing
- Metal Industry
- Food and Beverage
- Textile industry
- Mining
- etc.

Module 2 - Commissioning a basic closed-loop control system

2.1 Work and safety instructions

General

- Trainees should only work with the circuits under the supervision of an instructor.
- Electrical devices (e.g. power packs, compressors and hydraulic units) may only be operated in training rooms that are equipped with residual current devices (RCDs).
- Observe the specifications included in the technical data for the individual components and in particular all safety instructions!
- Malfunctions which might impair safety must not be generated when the device is operated for training purposes.
- Wear personal safety equipment (safety glasses, safety shoes) when working on circuits.

Mechanical safety

- Switch off the power supply.
  - Switch off the working and control power before working on the circuit.
  - Only reach into the setup when it’s at a complete standstill.
  - Be aware of potential overtravel times for the drives.
- Mount all of the components securely on the profile plate.
- Make sure that limit switches are not actuated from the front.
- Risk of injury during troubleshooting.
  Use a tool such as a screwdriver to actuate limit switches.
- Set all components up so that it’s easy to activate the switches and interrupters.
- Follow the instructions about positioning the components.

Electrical safety

- Disconnect from all sources of electrical power.
  - Switch off the power supply before working on the circuit.
  - Please note that electrical energy may be stored in individual components. Further information on this issue is available in the data sheets and operating instructions included with the components.
- Use protective extra-low voltage only: max. 24 V DC.
- Establishing and disconnecting electrical connections
  - Electrical connections may only be established in the absence of voltage.
  - Electrical connections may only be disconnected in the absence of voltage.
- Maximum permissible current loads for cables and devices must not be exceeded.
  - Always compare the current ratings of the device, the cable and the fuse.
  - If these are not the same, use a separate upstream fuse in order to provide appropriate overcurrent protection.
- Use only connecting cables with safety plugs for electrical connections.
- When laying connecting cables, make sure they are not kinked or pinched.
- Do not lay cables over hot surfaces.
  - Hot surfaces are identified with a corresponding warning symbol.
- Make sure that connecting cables are not subjected to continuous tensile loads.

- Devices with an earth terminal must always be grounded.
  - If an earth connection (green-yellow laboratory socket) is available, it must always be connected to protective earth. Protective earth must always be connected first (before voltage), and must always be disconnected last (after voltage).
  - Some devices have high leakage current. These devices must be additionally grounded with a protective earth conductor.
- The device is not equipped with an integrated fuse unless specified otherwise in the technical data.
- Always pull on the plug when disconnecting connecting cables – never pull the cable.

Pneumatic safety

- Depressurize the system.
  - Switch off the compressed air supply before working on the circuit.
  - Check the system using pressure gauges to make sure that the entire circuit is fully depressurized.
  - Please note that energy may be stored in reservoirs.
    Further information on this issue is available in the data sheets and operating instructions included with the components.
- Do not exceed the maximum permissible pressure of 600 kPa (6 bar).
- Do not switch on the compressed air until all tubing connections have been established and secured.
- Do not disconnect tubing while under pressure.
- Do not attempt to connect tubing or push-in connectors with your hands or fingers.
- Risk of injury when switching compressed air on.
  Cylinders may advance and retract automatically.
- Risk of accident due to advancing cylinders.
  - Always position pneumatic cylinders so that the piston rod's working space is unobstructed over the entire stroke range.
  - Make sure that the piston rod cannot collide with any rigid components of the setup.
- Risk of accident due to tubing slipping off.
  - Use shortest possible tubing connections.
  - In the event that tubing slips off:
    Switch off the compressed air supply immediately.
- Pneumatic circuit setup:
  Connect the devices with plastic tubing with an outside diameter of 4 or 6 mm. Push the tubing into the push-in connector as far as it will go.
- Switch off the compressed air supply before dismantling the circuit.
- Dismantling the pneumatic circuit
  Press the blue release ring down so that the tubing can be pulled out.
- Noise due to escaping compressed air
  - Noise caused by escaping compressed air may damage your hearing. Reduce noise by using silencers, or wear hearing protection if noise cannot be avoided.
  - All of the exhaust ports for the components included in the equipment set are equipped with silencers. Do not remove these silencers.

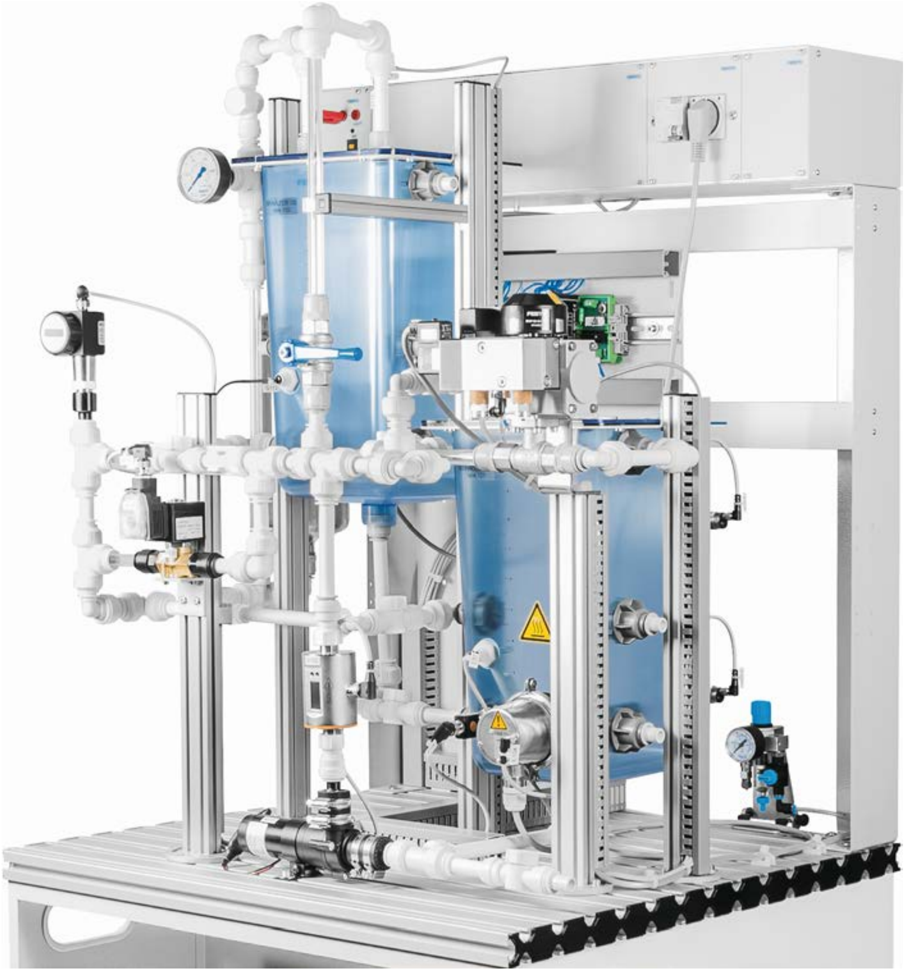
Process engineering safety

- Before filling the tanks with water switch of power supply!
- Switch of power supply 24 VDC and 230 VAC (110 VAC)!
- The use of tap water in quality of drinking water (recommended), ensures a prolonged maintenance-free operation of the system (proportional valve and pump).
- The maximum operating temperature of the tanks must not exceed +65 °C.
- Do not operate the heating unit unless the heating element is fully immersed in fluid.
- Do not operate the piping system with a system pressure higher than 0.5 bar.
- Do not operate the pump without fluid, running dry or used for sea water or contaminated fluids.
- Please empty fluids from the system (tanks, piping, close valves) before you make changes at the piping system.
- It is possible to drain the fluids inside the MPS® PA Compact Workstation by opening hand valve V105
- Do not left the water inside the tanks for a longer time. It is possible, that bacteria as legionella grow up, which can cause diseases.

2.2 Design and function

The MPS® PA Compact Workstation is available in different designs to suit individual training outcomes:

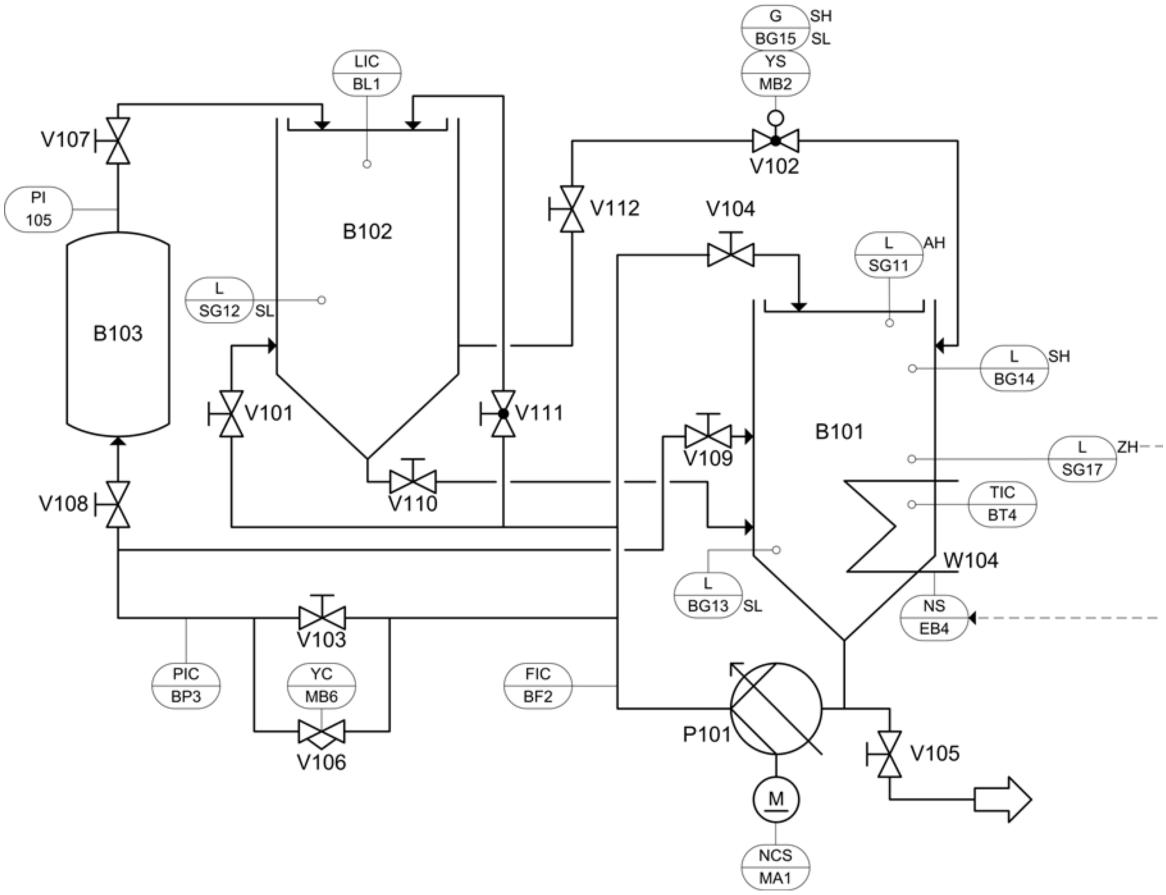
- Basic design
- Process instrumentation (PI)
- Energy
- or many other customized solutions...



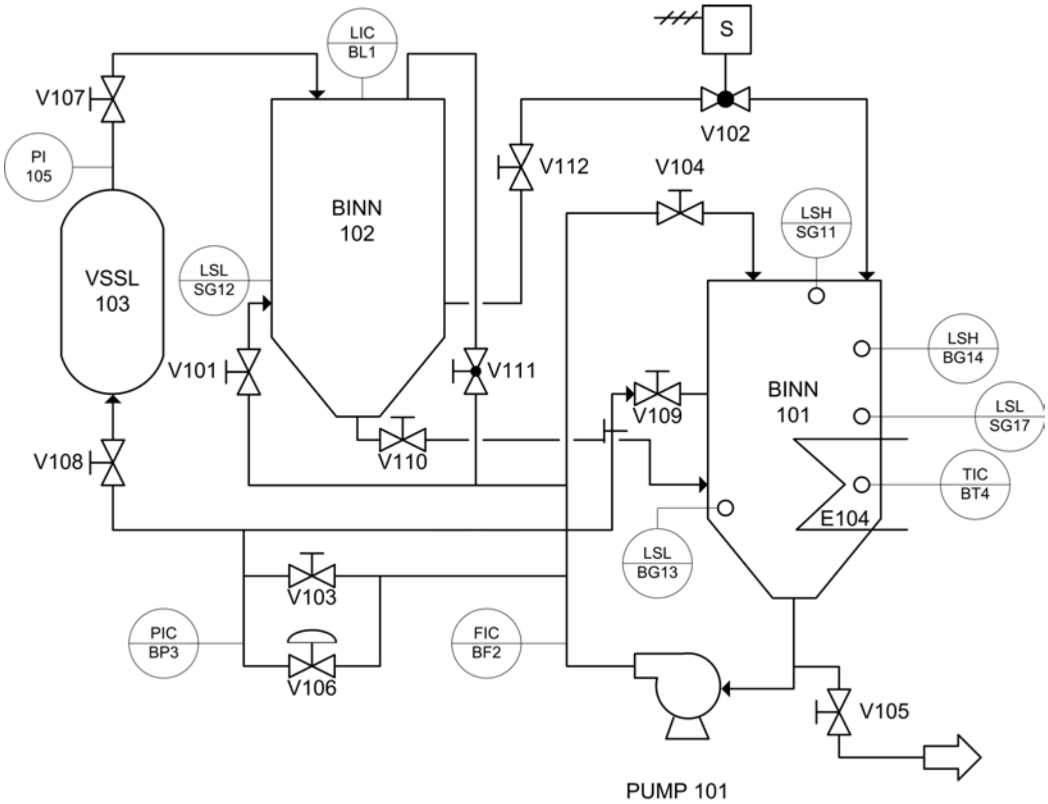
MPS® PA Compact Workstation – basic design

The MPS® PA Compact Workstation combines 4 closed-loops with digital and analog sensors and actuators. With a PLC or a controller it is possible to use them individually or cascaded:

- level controlled system
- flow rate controlled system
- pressure controlled system
- temperature controlled system



P&I diagram MPS® PA Compact Workstation in standards DIN EN 62424 and ISO 10628



PI diagram MPS® PA Compact Workstation in ISA 5.5 / ISA 5.1 Standard

It is possible to work with following functions by using the 4 closed-loop systems:
- two point control of a level control system with an analog standard signal
- continuous control of a level control system with an analog standard signal
- continuous control of a flow rate control system with a pump as controlled system and an impulse signal for frequency measuring
- continuous control of a flow rate control system with a proportional valve (controlled system) and an impulse signal for frequency measuring
- continuous control of a flow rate control system with a pump as controlled system and with an analog standard signal
- continuous control of a flow rate control system with a proportional valve as controlled system and with an analog standard signal
- continuous control of a pressure control system with a pump as controlled system and with an analog standard signal
- continuous control of a pressure control system with a proportional valve as controlled system and with an analog standard signal
- two point control of a temperature control system with an analog standard signal

Advanced control systems can be additionally used with in FluidLab-PA multi-loop:
- Cascade control of flow rate and level
- Override control of flow rate and pressure
- Feedforward of pressure and flow rate

The basic design components of the MPS® PA Compact Workstation are:

- Analog ultrasonic sensor
- Flow sensor, magnetic-inductive (0,1…25 l/min) with integrated measuring convertor and display
- Pressure sensor, piezo resistive with on-site display
- Pressure gauge for 0…1bar
- PT100 temperature sensor –50…+150 °C, with plug-in measuring convertor 0…100 °C with output 0-10V
- 2x Capacitive proximity switch for min/max level in lower tank
- Float switch for threshold function (electromechanical) in upper tank
- Float switch for overflow alarm monitoring in lower tank
- Float switch as a protection for the heating system
- Centrifugal pump
- Motor Controller for pump motor (DC)
- Proportional valve with electronic control module
- Heating system with integrated micro controller
- 2W ball valve with pneumatic rotary drive (COPAR) with 5/2way pilot valve and sensor box with position indicator and dual inductive position sensing
- I/O-board with I/O terminal (Syslink) for binary signals and analogue terminal for analog signals
- Signal converter: current to voltage (rail mount), frequency to voltage (integrated in sensor), PT100 to voltage (plug-in)
- Piping system incl. 4 transparent segments
- Pressure tank (reactor), 2L, stainless steel
- 2x Water tanks, 10L, square
- Manual valves
- Service Unit
- cable ducts
- Aluminum profiles
- Profile plate
- 19’’ mounting frame
- Mounting frame for ER units or A4 Edutrainers

Additional accessories should be used:
- 24 V DC power supply for 19” frame
- PLC or closed-loop controller, e.g. EasyPort USB, EduTrainer Universal with PLC
- trolley
- basic control panel for 19” frame
- touch panel (HMI)

The functions of each closed-loop system result in the specified combination of the (manual-) valves. Also they depend on the programming, configuration or parametrizing of the PLC/ controlling system.
For the usage of the station a control kit and a power supply for 24 V DC is required.

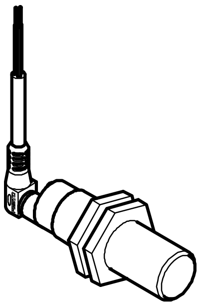
2.2.1 Level monitoring

Following technical examples for level monitoring are integrated into the MPS® PA Compact Workstation:

- proximity switches
- float switch for overflow safety
- float switch for threshold function

2.2.2 Proximity switches

Two capacitive proximity switches BG13 and BG14 are located on the side of the lower tank B101 and mounted on a profile. The proximity switches can be mechanically adjusted. The sensing distance through the tank wall can be adjusted with a screw. The binary 24 V input signals are connected to the I/O-terminal XD1.



Level monitoring with capacitive proximity switches BG13 and BG14

The minimum level of the tank B101 is indicated by the lower sensor BG13. At minimum level the heating element EB4 should be totally immersed into the liquid.
The maximum level of the tank B101 is indicated by the upper sensor BG14.
At reset position of the system both sensors have to be activated.

2.2.3 Overflow safety

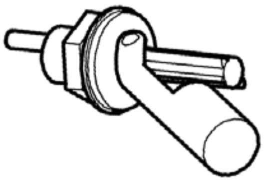
The overflow at tank B101 is monitored with float switch SG11. If the level in the tank exceeds the maximum level the transparent float cylinder is pushed upward. Inside the float cylinder are magnets which activate a reed contact.

Level monitoring with float switch for overflow safety SG11

The binary 24 V input signals (no) is connected to the I/O-terminal XD1. The signal of the overflow switch should activate an alarm function in the PLC-program and has effect on ball valve V102 and pump P101.
If changed electrically the overflow switch also can be used to turn off the pump or valve with a relay circuit or for signal indication to an emergency relay.

2.2.4 Threshold function

The increasing fluid level into the upper tank B102 is monitored at a certain minimum level by float switch SG12. If the mounting position is changed the switch can also indicate the decreasing level.

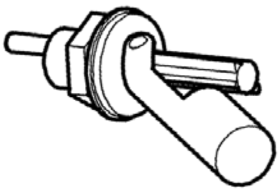


Level monitoring with float switch for threshold function SG12

The binary 24 V input signals (NC) is connected to the I/O-terminal XD1. The cable of the switch has a plug connection for easy connect/disconnect on changing the mounting position.

2.2.5 Switch-on protection for heating

The float switch SG17 is monitoring the decreasing filling level in tank. It avoids continuing heating if filling level undershoots the critical point. The heating must be surrounded completely by the fluid.

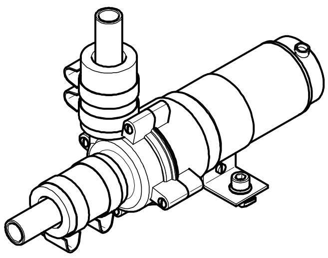


Float switch as switch-on protection for heating

The cable of the switch has a plug connection and is connected directly to the heating and to the connecting cable of the I/O- connecting board.

2.2.6 Pump

The centrifugal pump P101 is the controlling equipment used in all controlled systems. The pump is delivering fluid from a reservoir tank B101 through the piping system.



Controlling equipment - Pump P101

The pump must not be operated running dry. Before commissioning the reservoir tank or piping system to/from the pump should be filled with fluid.
The pump is driven by the motor controller QA1 and relay KF1. With a digital output

(Q2 at XD1) it is possible to switch from digital binary control to analog control variable from 0 to 24 V. At digital binary control (Q2 = 0) the pump is turn on/off with an additional output (Q3 at XD1). At analog control (Q2 = 1) the drive voltage from analog output signal channel 0 (UA1 at XD3) is setting the speed of the pump from 0 to 10 V.

Please also see the data sheet of the pump for further safety instructions!

2.2.7 Proportional valve

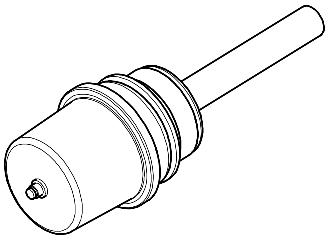
The proportional valve V106 is a directly actuated 2/2-way valve for flow control of fluids. It can be used as an adjustable remote element in open- or closed-loops. The valve piston is lifted of its seat as a function of the solenoid coil current and releases the flow through the valve.

Controlling element proportional valve V106

The control electronic of the proportional valve is activated with a binary output
(Q4 at XD1). An analog signal from channel 1 (UA2 at XD3) is driving the signal input of the proportional valve with a standard analog signal from 0 to 10 V.
The standard analog signal is transformed into a pulse-width modulation (PWM) and the opening of the valve is infinitely adjustable. The frequency of the PWM can be adapted for different valve types.

2.2.8 Heating

The heating element is controlled by an internal micro controller, on activation of a binary output (Q1 at XD1).



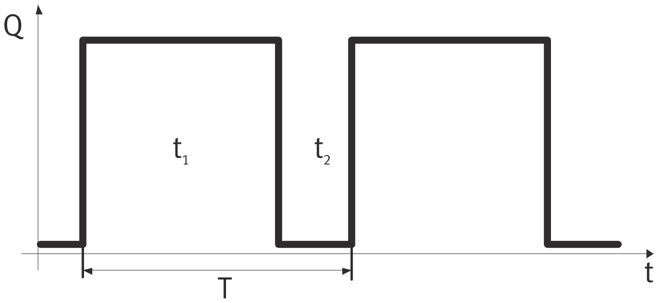
Heating

Notes on safety:

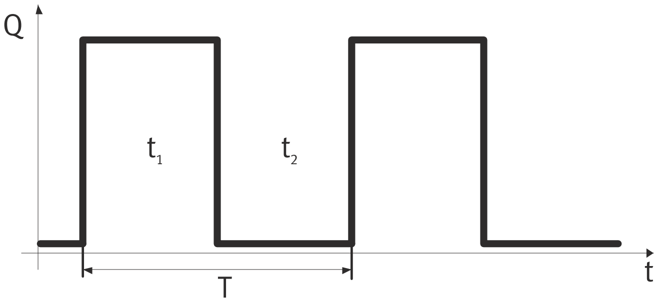
- The maximum operating temperature of the tanks must not exceed +65 °C.
- Do not operate the heating unit unless the heating element is fully immersed in fluid.
- Critical temperature at the heat element: at temperature around 50-60 °C the heating is internal automatically switched off. If the temperature value drops below 45 °C the heating is switched on again.
- Critical temperature at the micro controller of the heating: at a semiconductor temperature of around 90°C the heating is internal automatically switched off. If the temperature value drops below 85 °C the heating is switched on again.

Controlling the heat element

The heating can be controlled binary as well as analogue (continuous). For the MPS®PA Compact Workstation the heating is controlled **binary only**. To use the heating as a continuous output element a pulse-width-modulation (PWM) is used. The control is clocking the ON- and OFF- time of the heating. The time period T is constant (e.g. 10s). By changing the ON-time t1 of the heating the thermal power Q is manipulated. If the ON-time is raised, also the thermal power is.



PWM with a puls-width ration of 75%



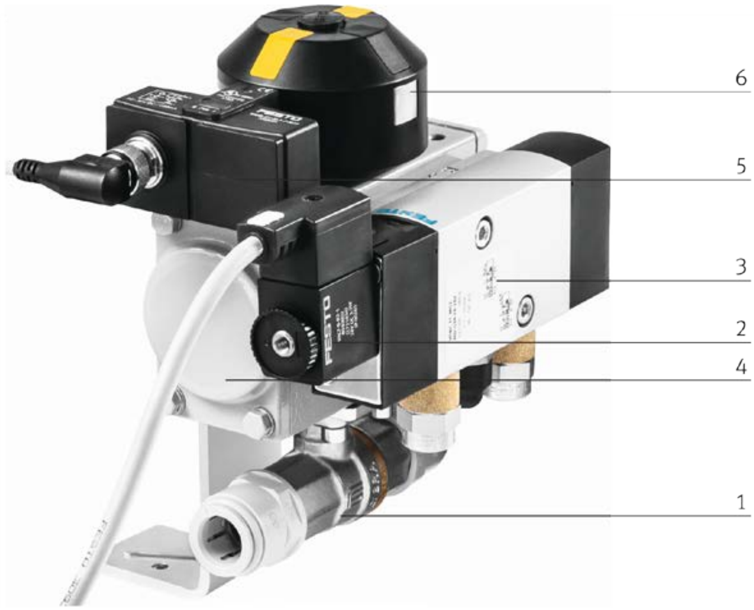
PWM with a puls-width ration of 50%

Key

t1	OFF-time
t2	ON-time
T	time period
Q	thermal power

2.2.9 2W ball valve with pneumatic rotary drive

The 2-way ball valve V102 is opened and closed by a pneumatic rotary drive. The controlled equipment consists of a brass ball valve (1) with rotary drive type COPAR (4), using rack-pinion principle. A solenoid (2) 5/2 way valve (3) with port pattern to NAMUR and sensor box with inductive dual sensor (5) with position indicator (6) are flange mounted onto the rotary drive. The flow of the fluid from upper tank B102 into the lower tank B101 is controlled with the ball valve of the rotary drive.



2-way ball valve V102 with pneumatic rotary drive

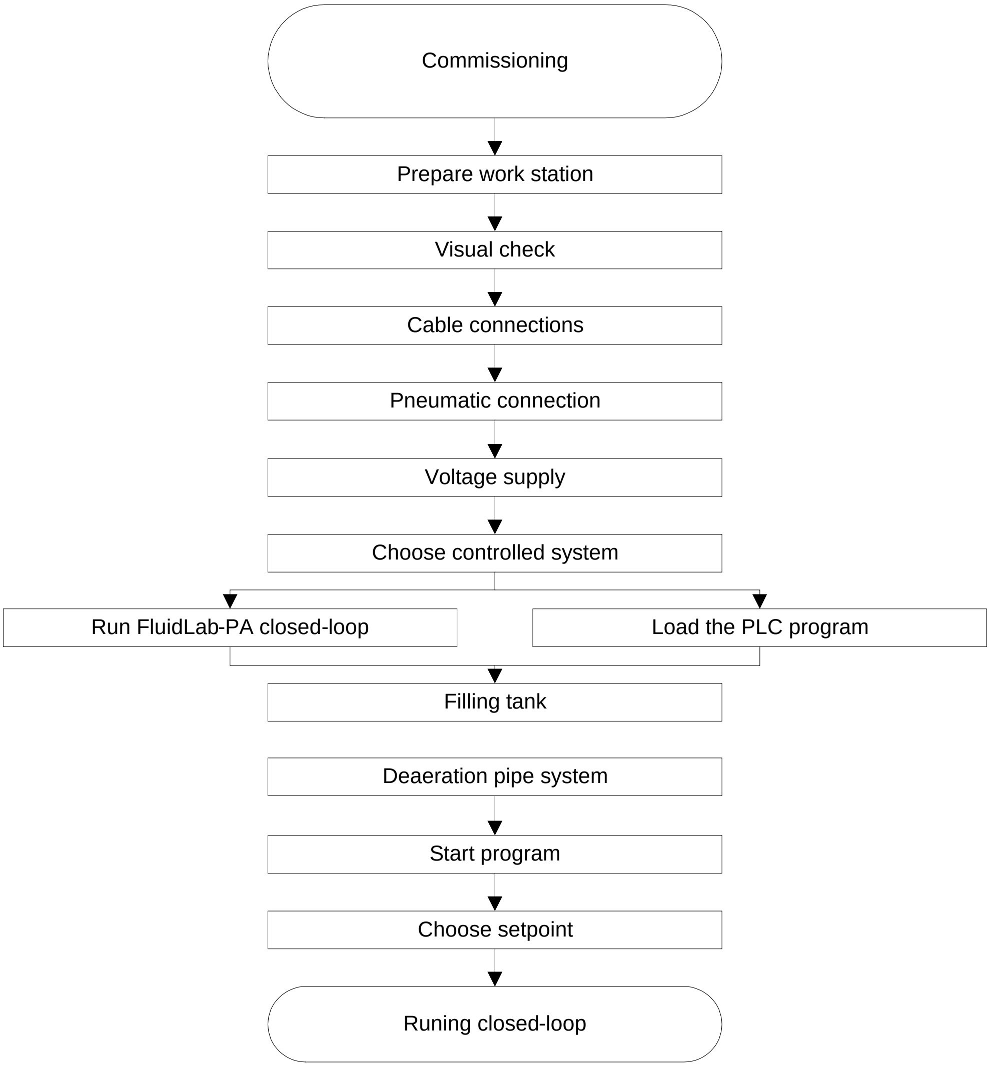
Key

1 brass ball valve
2 solenoid 24 V DC
3 5/2 way pilot valve with port pattern to NAMUR
4 quarter turn actuators, type rack-and-pinion principle
5 sensor box with inductive dual sensor
6 position indicator

The end position sensing attachment (5) consists of a contact-free inductive dual sensor. The two binary 24 VDC signals (BG15) are connected as inputs to the I/O-terminal XD1. There is also a visual indication of the drive position for the operator.

2.3 Commissioning

For running the MPS® PA Compact Workstation all commissioning steps have to be obeyed according to the rules of operation:



Flow chart for commissioning the MPS® PA Compact Workstation

The MPS® PA Compact Workstation is generally delivered

- completely assembled,
- operationally adjusted,
- commissioned and
- tested.

⚠

The commissioning is normally limited to a visual check to ensure correct tubing connections / pipe connections / wiring and supply of operating voltage.
All components, tubing and wiring are clearly marked so that all connections can be easily reestablished.

2.3.1 Workstation

The following is required to commission MPS® PA Compact Workstation:

- The assembled and adjusted MPS® PA Compact Workstation
- A control console
- A EduTrainer with PLC, EasyPort USB or industrial controller
- A power supply unit 24 V DC, 4.5 A
- A compressed air supply of 6 bar (600 kPA), approx. suction capacity of 50 l/min
- A PC with installed PLC programming or FluidLab-PA closed-loop software

2.3.2 Visual check

A visual check must be carried out before each commissioning!
Prior to starting up the station, you will need to check:

- The electrical connections
- The correct installation and condition of the pipes and pipe connections
- The correct installation and condition of the compressed air connections
- The mechanical components for visual defects (tears, loose connections etc.)

Eliminate any damage detected prior to starting up the station!

2.3.3 Cable connections

The MPS® PA Compact Workstation can be controlled in different ways. In the following chapters the different control variants will be described.

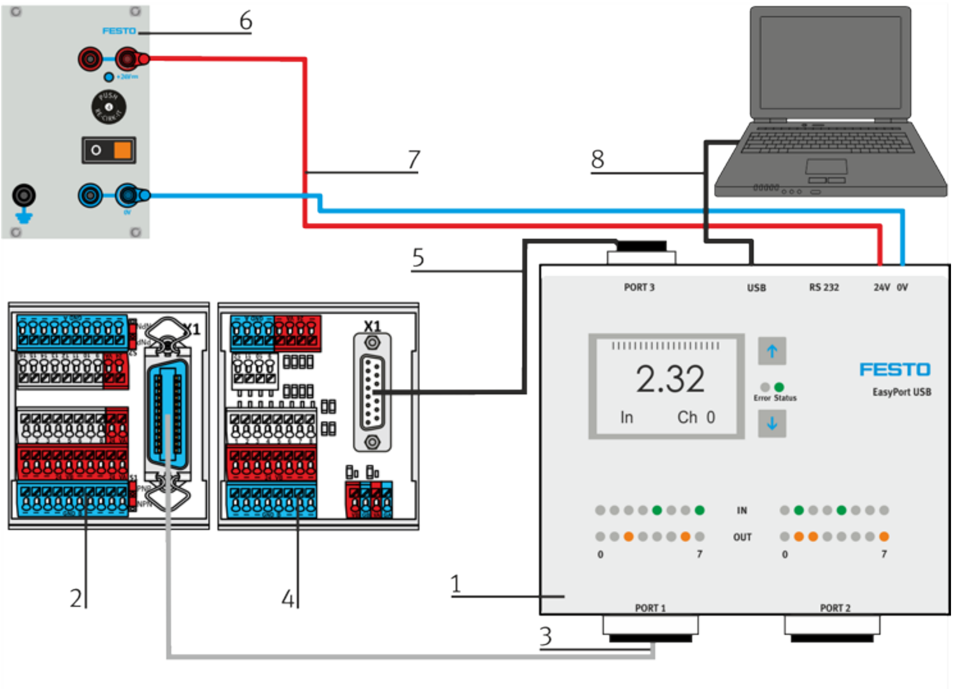
The overall cable connections are:

- Connect the pneumatic hose to the service unit of the station
- Connect an IEC power supply cable (C14, male) to the back side of the 19” frame of the station to the IEC connector (C13, female). The female connector also uses a fuse.

2.3.4 EasyPort USB and MPS® PA Compact Workstation

All cable connections are described as an example for a MPS® PA Compact Workstation with the EasyPort USB.

- Connect 4 mm safety plugs cable (7, red and blue) to the EasyPort USB screw terminals (24V/0V)
- Connect port 1 (Digital I/O) of the EasyPort USB with the XD1 socket of the I/O terminal (2) of the station with a Syslink cable (3).
- Connect port 3 (Analog I/O) of the EasyPort USB with the XD3 socket of the analog terminal (4) of the station with analog cable (5).
- Connect your PC to the EasyPort USB by means of a USB data cable (8).
- Connect EasyPort USB to 24 V DC power supply unit with 4 mm safety plugs cable (red = + / blue = —).



Cable connections MPS® PA Compact Workstation – EasyPort USB

Key

1	EasyPort USB
2	I/O terminal Syslink
3	Syslink cable, I/O- data cable with Syslink, 20 pol (grey endings, Order No. 034031)
4	Analog terminal
5	Analog cable, 15-polig, parallel (Order-No. 529141)
6	24 V DC power supply
7	universal cable set with 4 mm safety plugs (red/blue)
8	USB-cable

2.3.5 Choosing controlled system

For using a specific controlled system integrated in the MPS® PA Compact Workstation see to following table for setup of the manual valves and actuators. Programming, configuration or parameterizing of the PLC or closed-loop controller depends on the chosen controlled system and used signal type. E.g. at controlled level system the ultrasonic sensor is used with a signal range of 4 to 20 mA. This signal is converted into a standard voltage signal of 0 to 10 V. Therefore the signal input at the controlling system has to be configured. Configuration of the PLC or closed-loop controller is depending on the used device. For the Compact Workstation following control types can be used:

- PLC, e.g. Simatic S7-1500 CPU 1512C
- EasyPort USB with educational software Fluid Lab®-PA closed-loop
- Simulation box digital/analog

Component	Level controlled system fill from top	Level controlled system fill from bottom	Flow controlled system with actuator Pump P101	Flow controlled system with actuator Prop. Valve V106	Pressure controlled system with actuator Pump P101	Pressure controlled system with actuator Prop. Valve V106	Temperature controlled system
PCE task Sensor	LIC BL1		FIC BF2		PIC BP3		TIC BT4
Pump P101	controlling element		controlling element	binary On	controlling element	binary On	binary On
Prop. valve V106	Off	Off	Off	controlling element	Off	controlling element	Off
Heating element	Off	Off	Off	Off	Off	Off	controlling element
Hand valve V101	open	closed	closed	closed	closed	closed	closed
Ball valve V102	open/closed	open/closed	closed	closed	closed	closed	closed
Hand valve V103	closed	closed	closed	closed	open	closed	open
Hand valve V104	closed	closed	open	closed	closed	closed	closed
Drainage valve V105	closed	closed	closed	closed	closed	closed	closed
Hand valve V107	closed	closed	closed	closed	closed	closed	closed
Hand valve V108	closed	closed	closed	closed	open	open	closed
Hand valve V109	closed	closed	closed	open	open/closed	open/closed	open
Hand valve V110	closed	open	closed	closed	closed	closed	closed
Ball valve V111	closed	closed	closed	closed	closed	closed	closed
Hand valve V112	open/closed	closed	closed	closed	closed	closed	closed

Choosing the controlled system of MPS® PA Compact Workstation

2.3.6 Allocation list of inputs and outputs

Symbol	PIN assignment	EasyPort/ Simbox address	PLC address	Description
Binary inputs (XD1)				
-	1 (I 0)	I 0	%I0.0	Not used
SG11	2 (I 1)	I 1	%I0.1	Float switch tank B101 level high alarm
SG12	3 (I 2)	I 2	%I0.2	Float switch tank B102 level lower limit
BG13	4 (I 3)	I 3	%I0.3	Sensor, capacitive tank B101 level lower limit
BG14	5 (I 4)	I 4	%I0.4	Sensor, capacitive tank B101 level higher limit
BG15c	6 (I 5)	I 5	%I0.5	Position indicator 2way ball valve V102 position closed
BG15o	7 (I 6)	I 6	%I0.6	Position indicator 2way ball valve V102 position opened
-	8 (I 7)	I 7	%I0.7	Not used
Binary outputs (XD1)				
MB2	9 (Q 0)	Q 0	%Q0.0	Solenoid valve 2way ball-valve V102 open
EB4	10 (Q 1)	Q 1	%Q0.1	Heating ON, binary, in tank B101
KF1	11 (Q 2)	Q 2	%Q0.2	Relay, Preselection of pump P101 0=binary/1=analogue
MA1	12 (Q 3)	Q 3	%Q0.3	Motor controller Pump P101 binary ON
KF6	13 (Q 4)	Q 4	%Q0.4	Load relay for proportional valve V106 drive electronic KK6
(KF5)	14 (Q 5)	Q 5	%Q0.5	Optional: Switch-over relay K2 water-air cooler
-	15 (Q 6)	Q 6	%Q0.6	Not used
(M121)	16 (Q 7)	Q 7	%Q0.7	Optional: 2way solenoid valve V121 open cooling circuit
Analogue inputs (XD3)				
LIC BL1	1 (UE1)	AE 0	IW4	Process value PV, level in tank B102
FIC BF2	2 (UE2)	AE 1	IW6	Process value PV, flow rate in pipe system
PIC BP3	3 (UE3)	AE 2	IW8	Process value PV, pressure in pipe system optional: with water-air-cooler, rotation of fan motor
TIC BT4	4 (UE4)	AE 3	IW10	Process value PV, temperature in tank B101
Analogue outputs (XD3)				
MA1	9 (UA1)	AO 0	QW4	Manipulated output CO, pump P101
MB6	10 (UA2)	AO 1	(QW6	Manipulated output CO, proportional valve V106 optional: with water-air-cooler, speed of fan motor

Module 3 - Read and design a technical drawings for process engineering

3.1 Project planning

Project planning of a process plant should include the following documents:

- Specifications
- Process description, associated conditions such as environmental protection
- Start of scheduling and schedule monitoring
- Planning of flow diagrams
- Basic flow diagram
- Process flow diagram
- Piping and instrumentation diagram (PI diagram)
- Function diagrams
- Design of process plant
- Environmental protection requirements
- Specification of all equipment, Instrumentation and Control (EMCS) point list
- EMCS point plan – outline
- EMCS point plan – detailed
- Wiring and terminal diagrams
- Assembly plans
- Installation planning
- Acquisition
- Assembly, commissioning and acceptance of the system

The planning of a process-engineering project should be practiced using a PI diagram, an EMCS point list and an EMCS point plan for a controlled system.

Project planning for control systems

The experimental unit MPS-PA Compact Workstation consist of the control systems:

- Level
- Flow
- Pressure
- Temperature

The experimental unit EduKit-PA consist of the control systems:

- Level
- Flow
- Pressure

Please see the manuals for setup of the manual valves when choosing a control system.

3.2 Designation of equipment

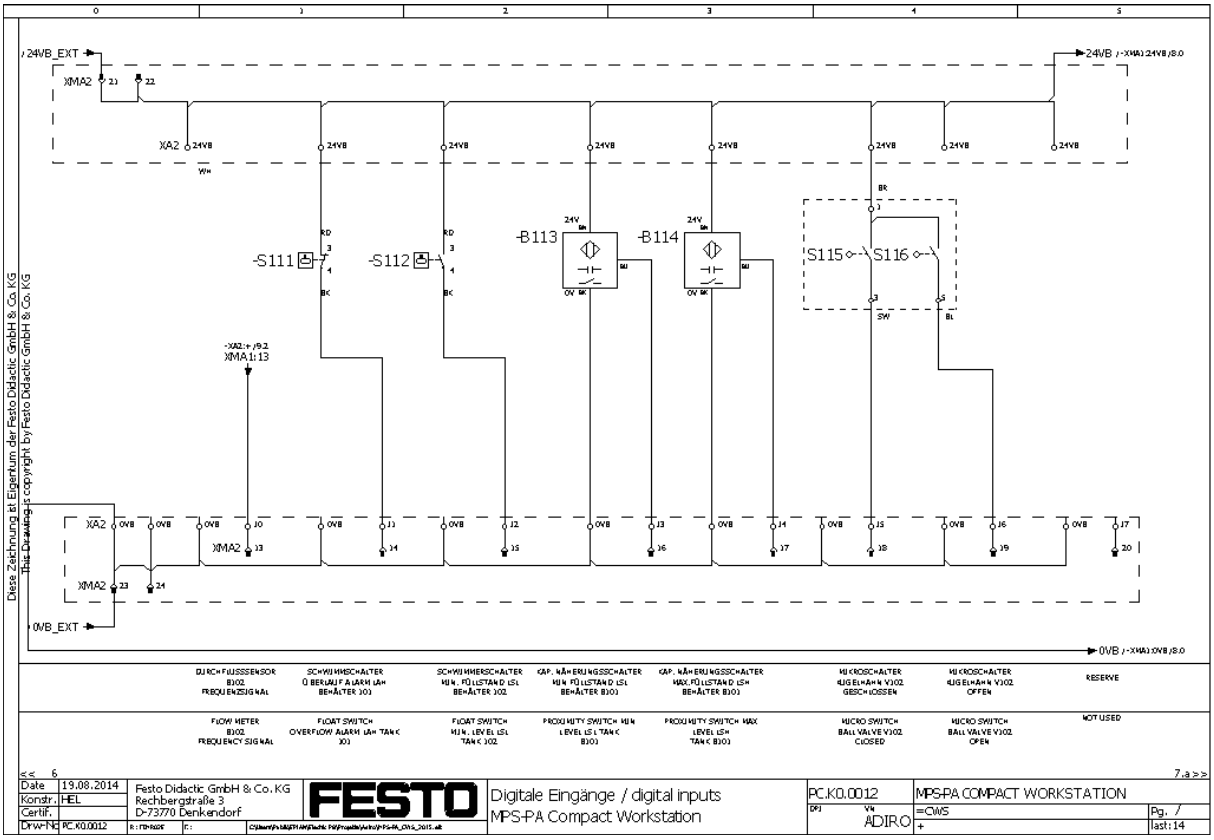
3.2.1 Basic definition

All electrical equipment of an MPS®PA station is labelled with equipment codes according to the electrical circuit diagram. Equipment without electrical function, such as hand operated valves, is labelled according to the P&I diagram.

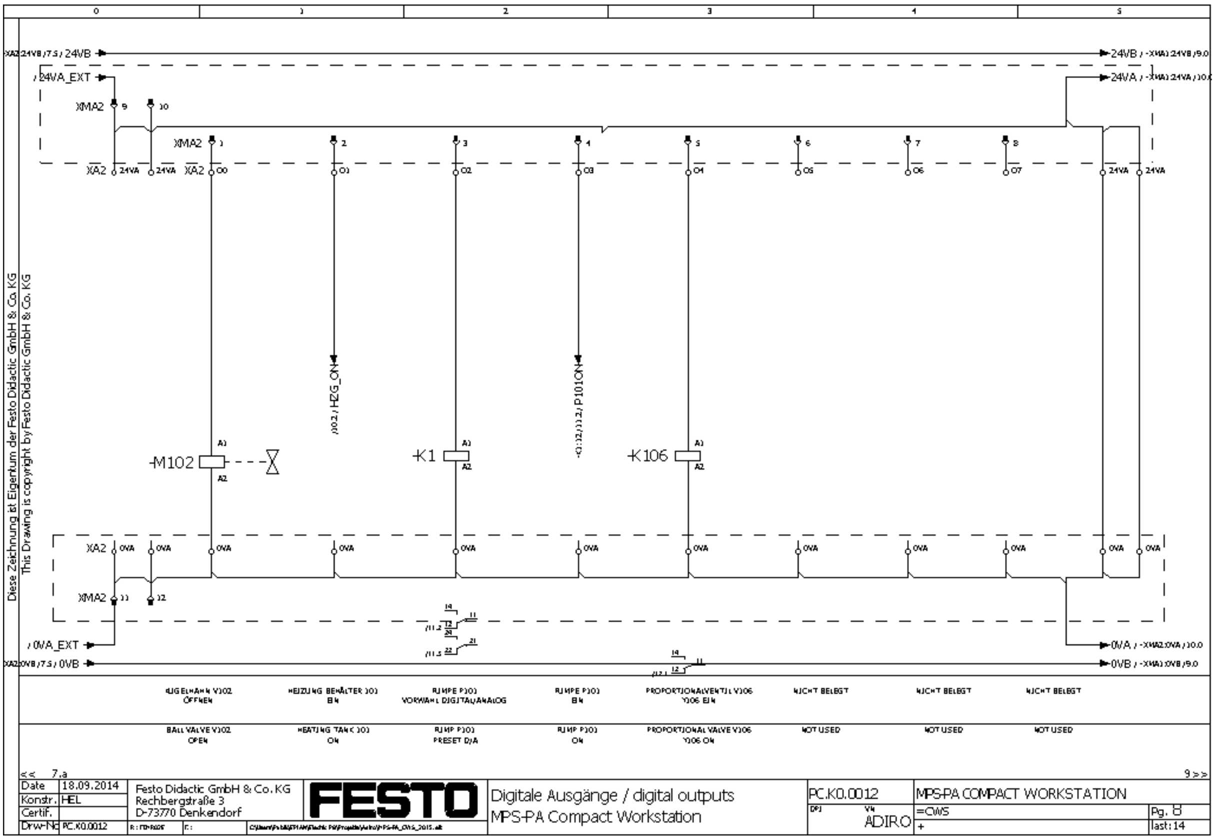
3.2.2 Electrical components

The designation of equipment in the electrical circuit diagrams is effected according to the standard IEC81346-2. The standard describes general principles for structuring systems, including structuring information about systems. Based on these principles, rules and instructions for creating unique reference identifiers for objects in arbitrary systems are given. The reference indicator identifies objects with the purpose of generating and recovering information about an object and, if it was realized, the corresponding component. A reference tag that labels a component is the key to finding information about that object, which can be divided into different types of documents. The principles set out are generally valid and applicable in all technical areas (e.g. mechanical engineering, Electrical engineering, construction and process engineering). They can be applied to systems based on different technologies, and also to systems in which multiple technologies are combined.

Type of equipment	Code letter
Drives (servo drive, actuating coil, electric motor, linear motor)	MA
Diode	RA
Auxiliary contactor	KF
Terminal, terminal block, terminal strip (> 1000V AC oder > 1500V DC)	XD
Capacitor	CA
Circuit breaker	QA
Power transistor	QA
Disconnector	QB
Indicator (mechanical, optic, acoustic)	PJ
Relay	KF
Tube, semiconductor	KF
Contactor (for load)	QA
Sensors general, position switch, proximity switch, proximity sensor, etc.	BG
Fuse	FC



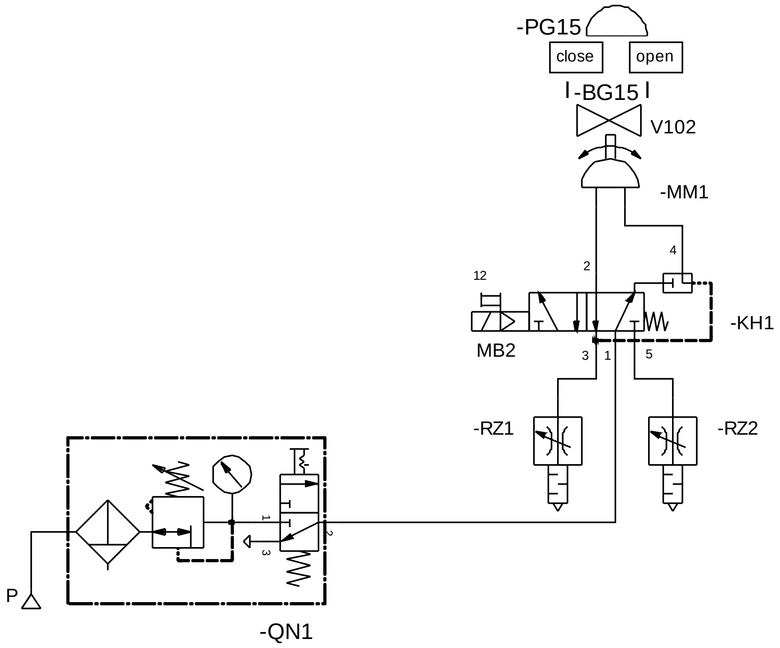
Example of electrical circuit diagram – MPS® PA Compact Workstation, inputs



Example of electrical circuit diagram – MPS® PA Comapct Workstation, outputs

3.2.3 Pneumatic components

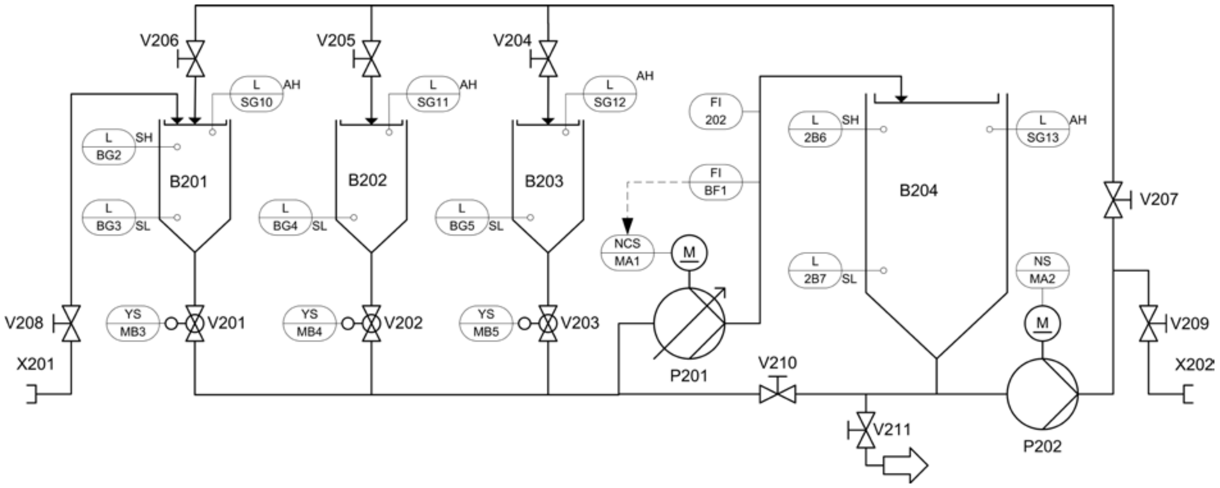
The designation of the elements has so far been carried out in the schematics according to standard DIN ISO 1219 2. Unfortunately, different labels are used in the before mentioned standards. Sensors and valve coils must be represented both in the pneumatic circuit diagram and in the electrical circuit diagram. To ensure uniqueness and ease of readability, the graphic symbols in both plans should be labeled and numbered in the same way



Example of pneumatic circuit diagram in reference designation DIN EN 81346-2 – MPS® PA Compact Workstation

3.2.4 Process engineering components

The designation of components in the P&I diagrams is effected according to
the standard ISO 10 628 and IEC 62 424 (since 2010). The development of a PI diagram is a significant part of the project work.



Example of PI diagram – MPS® PA Compact Workstation

ISO 10 628 standard

The design and function of a process engineering system is described in the piping and instrumentation flow diagram (P&I diagram). Peripheral components such as containers, pumps, heat exchangers, etc. are defined in the standard ISO 10 628.

Code letters for Valves and Fittings

Valves and fittings	Code letter
Shut-off valve	B
Filter, strainer, dirt trap, sieve (piping)	F
Sight glass	G
Control valve	H
Steam trap	K
Check valve	R
Valve/fitting with safety function (e.g. rupture disk)	S
Valve, general	V
Other valves/fittings by definition	X
Other valves/fittings with safety function by definition	Y
Orifice plate, blind disk	Z

Code letters for apparatus and machines

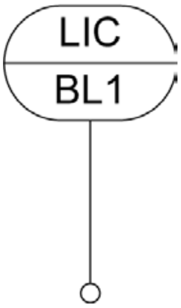
Apparatus and machines	Code letter
System component or machine unless classified under one of the groups below	A
Container, tank, hopper, silo	B
Chemical reactor	C
Steam generator, gas generator, furnace	D
Filtration device, liquid filter, sieving device, separator	F
Gear unit	G
Lifting, handling and transport equipment	H
Fractionating column	K
Electric motor	M
Pump	P
Stirrer, container with stirrer, mixer, kneader	R
Centrifuge	S
Dryer	T
Compressor, vacuum pump, ventilator	V
Heat exchanger	W
Metering, separating device, other devices	X
Drive motor, other than electric motor	Y
Pulverising machine	Z

Code letters for piping

Piping	Code letter
Pipe, pipline, duct	P, Q
Item of piping	R
Hose	S
Conduit (open), trench	T
Canal (underground)	U

IEC62 424 standard

In addition to the technical equipment, PCE-tasks are entered in a P&I diagram (PCE = Process Control Engineering). The process related functions of the measured variables are described by means of PCE-requests in accordance with the standard IEC 62 424. The measured variables or another input variable, its processing, direction and position should be apparent from the designation.
A **PCE- tasks** consists of an oval and is defined with code letters (A-Z) for a PCE-category and a **code number or designation**. The code letters are entered in the upper section a PCE-oval and the number or designation is entered in the bottom section. The order of the code letters can be derived from the table overleaf which lists the "PCE tasks according IEC 62 424".



PCE-request for level: measure, indicate and control

PCE category	PCE processing function	PCE processing functions	Graphical symbol
L	I	C	Oval with separator line
Level	Display/indication	Automatic control	Utilization in process control system

The designation system for PCE tasks is freely selectable. A consecutive number is advisable since a PCE task designation must only occur once if there are several measuring points with identical measured variables. The designation in the learning system is derived from the reference designations of IEC 81346-2 so there is an overall link between the standards for Electrical and Process Engineering.

For further information, please refer to standard IEC 62 424.

Designation and representation of PCE tasks of a process control system

PCE tasks according to IEC 62 424

Code letter	First letter PCE category	Supplementary letter(s) PCE processing function
A	Analysis	Alarm, Message
B	Burner combustion	Restriction, Limit
C	(User defined)	Automatic control
D	Density	Difference
E	Voltage, electrical	
F	Flow, throughput	Ratio
G	Distance, length, position	
H	Manual input, manual intervention	Upper limit value (high)
I	Current, electrical	Analog display
J	Electrical Power	
K	Timebased function	
L	Level	Lower limit value (low), OFF, closed
M	Humidity	
N	Motor	
O	(User defined)	Local or visual binary signal,
P	Pressure	
Q	Material properties, quality variables	Integral, total
R	Radiation variables	Registration
S	Speed, velocity, frequency	Binary control or switch-on function (not safety related)
T	Temperature	
U	PCE control function	
V	Oscillation	
W	Weight, mass, force	
X	Other variables	
Y	Control valve	Arithmetic operation
Z	(User defined)	Safety related binary control or switch-on function

The PCE-processing functions A, H, L, O, S and Z have to be represented only outside of the PCE oval!

Order of the combination of PCE processing functions

1	F	D	Y	C
2	B	Q	X	

Processing functions of Actuators of a process control system

Actuator code letter	Description
YS	ON/OFF valve
YC	Control valve
YCS	Control valve with ON/OFF-function
YZ	ON/OFF valve (safety relevant)
YIC	Control valve with continuous display
NS	ON/OFF motor
NC	Motor continuous controlled

3.3 Exercise - Equipment list

An equipment list provides a first indication which controlled system should be used for the measurement and which components are relevant to it.

Information

Draw up an equipment list for the level controlled system based on the information given. Consider which of the items of equipment and elements listed in the worksheet you need for setup of the system or controlled system and mark these in the worksheet.

Information

View the individual components and the data sheets and acquaint yourself with the variables used in the system.

Task

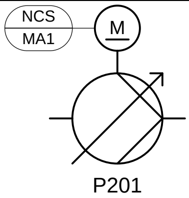
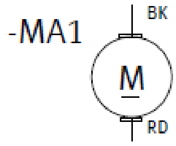
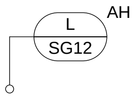
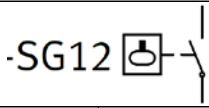
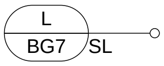
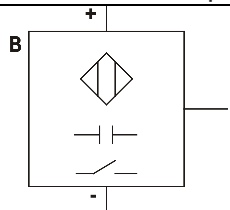
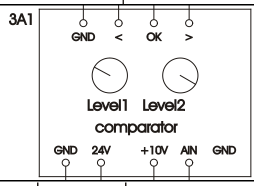
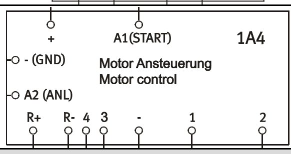
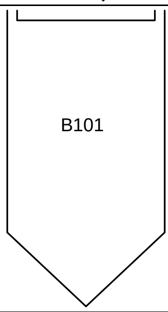
Control system							
Level		Flow rate		Pressure		Temperature	

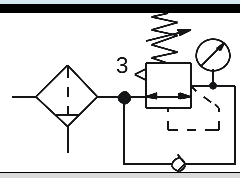
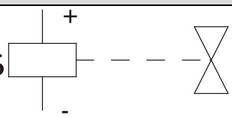
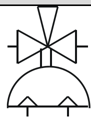
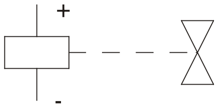
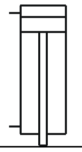
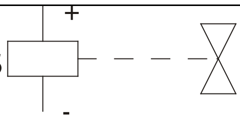
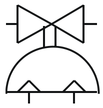
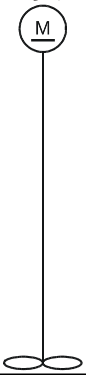
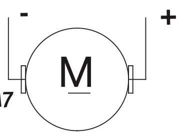
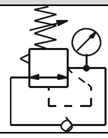
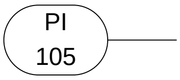
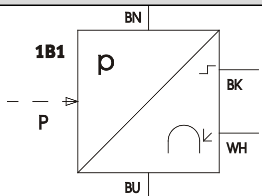
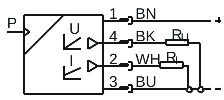
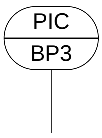
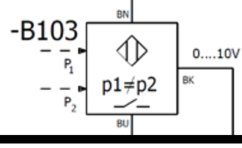
Komponenten	**PCE-task**	**Used**
Service unit, pneumatic	-	
Tank, rectangular, lower	B101	
Pump P101	NCS-MA1	
Proportional valve V106	YC-MM6	
Ultrasonic sensor	LIC-BL1	
Flow sensor	FIC-BF2	
Pressure sensor	PIC-BP3	
Temperature sensor	TIC-BT4	
Capacitive proximity switch, tank B101, lower limit	LSL-BG13	
Capacitive proximity switch, tank B101, upper limit	LSH-BG14	
Float switch, overflow, tank B101	LAH-SG11	
Float switch for raising level, tank B102	LSL-SG12	
Tank, rectangular, upper	B102	
Pressure tank	B103	
Heating unit	NS-EB4	
Operator interface (HMI) or process control engineering software	-	
Control: Easyport, PLC, etc.	-	

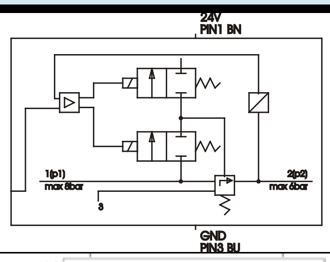
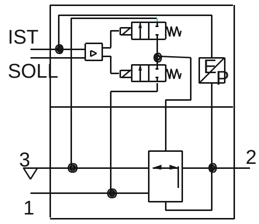
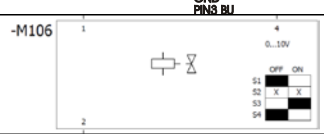
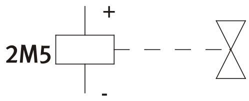
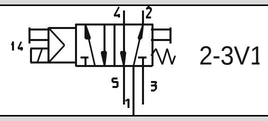
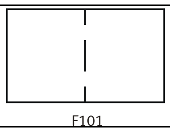
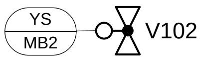
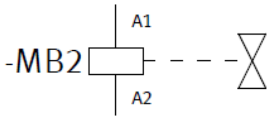
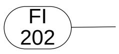
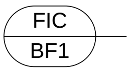
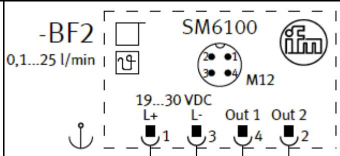
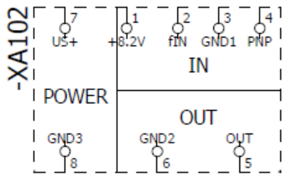
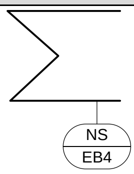
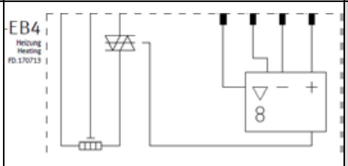
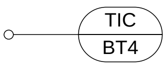
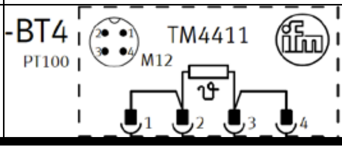
3.4 MPS® PA components

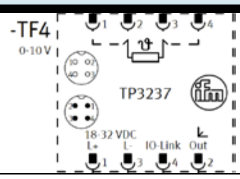
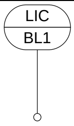
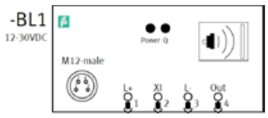
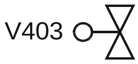
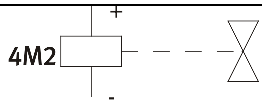
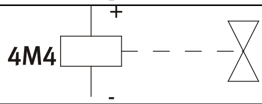
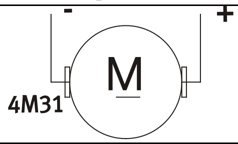
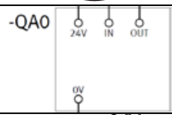
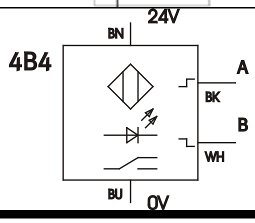
The component symbols of the MPS® PA stations in the documentation for the various circuits.

Not all components perform functions in every technology and these fields are therefore shown grey shaded

Component	Symbol ISO 10628 / IEC 62424 P&I diagram/ PCE task	Symbol IEC 81364-2 Electrical	Symbol ISO 1219 2 Pneumatic
Pump			
Float switch			
Capacitive proximity sensor			
Comparator			
Motor actuation			
Tank, round			
Tank, square			

Component	Symbol ISO 10628 / IEC 62424 P&I diagram/ PCE task	Symbol IEC 81364-2 Electrical	Symbol ISO 1219 2 Pneumatic
Filter regulator with on/off valve			 3
Hand operated valve	V402 		
Double non-return valve	V112 		
3-way ball valve with pneumatic swivel actuator	V106 	1M6  + -	 1-4A1
Slide valve with pneumatic linear actuator	 V102	1M4  + -	1-2A1 
Butterfly valve with pneumatic swivel actuator	 V103	1M5  + -	 1-3A1
Stirrer module	R304  M	 - + M 1M7	
Pressure regulator			
Pressure sensor, air	 PI 105	 BN 1B1 p P BK WH BU	 P U I 1 BN 4 BK 2 WH 3 BU
Pressure sensor, water	 PIC BP3	-B103  BN P_1 P_2 p1≠p2 0....10V BK BU	

Component	**Symbol ISO 10628 / IEC 62424 P&I diagram/ PCE task**	**Symbol IEC 81364-2 Electrical**	**Symbol ISO 1219 2 Pneumatic**
Proportional pressure regulator			
Proportional valve			
Solenoid valve 5/2-way			
Filter			
2-way ball valve with pneumatic swivel actuator			
Flow sensor with float (mechanical)			
Flow sensor Type2 (electrical)			
Frequency-voltage converter			
Heater			
Temperature sensor			

Component	Symbol ISO 10628 / IEC 62424 P&I diagram/ PCE task	Symbol IEC 81364-2 Electrical	Symbol ISO 1219 2 Pneumatic
Temperature-voltage converter			
Ultrasonic sensor, analogue			
2/2-way solenoid valve			
Stopper			
Conveyor belt			
Starting current limiter for conveyor motor			
Diffuse sensor			

3.5 Exercise – drawing a P&I diagram

Introduction

Draw up a P&I diagram for a level controlled system using the main P&I diagram of your training unit.

Resources

- P&I diagram, Compact Workstation or EduKit-PA
- Standard ISO 10628 "Flow diagrams for process plants – general rules" (replacement for DIN 28004)
- Standard IEC 62424 "Representation of process control engineering (IEC 62424:2008)

Task

3.6 Exercise – drawing a PLT loop list for PCE-tasks

Introduction

Draw up a P&I diagram for a level controlled system. In the older standard DIN 19227-2, which is still used, the overall designation of the task is described and the operating data for process engineering: description, place, material data, used devices.

Resources

- P&I diagram, Compact Workstation or EduKit-PA
- Standard DIN 19227-2 "Control technology; graphical symbols and identifying letters for process control engineering; representation of details"

Task

Specification forms for process measurement and control					
PCE task	**Amount**	**Device designation**	**PCE description**	**Place**	**Range**

(This table is an extract of a bigger form!)

3.7 Exercise – drawing a instrumentation loop diagram

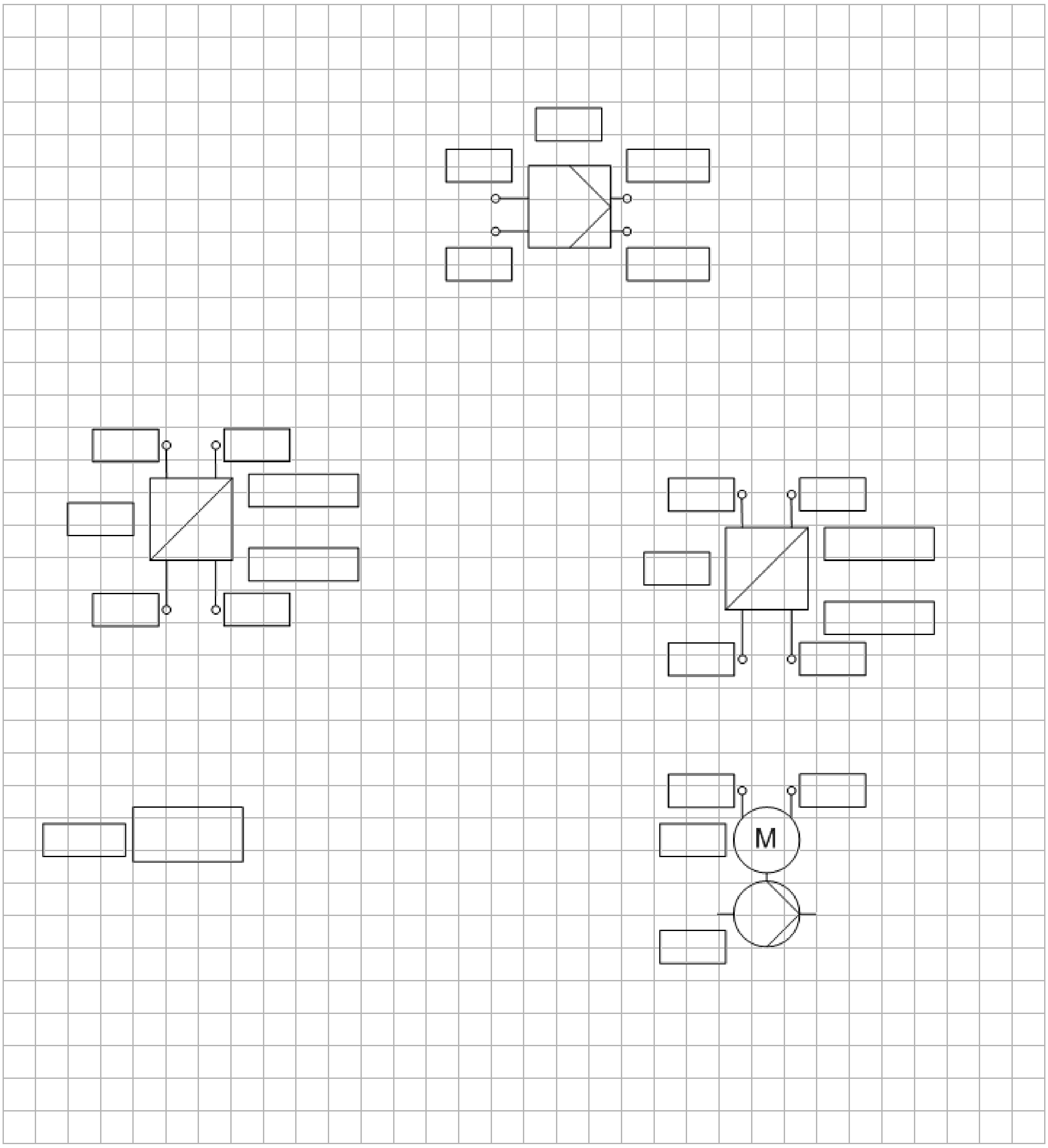
Introduction

Draw up a instrumentation loop diagram for a level controlled system.

Resources

- Electrical circuit diagram, Compact Workstation or EduKit-PA
- P&I diagram, Compact Workstation or EduKit-PA
- Standard DIN 19227-2 "Control technology; graphical symbols and identifying letters for process control engineering; representation of details”

Task



Module 4 - Analogue Signal Processing

4.1 Introduction

Measured variables, which may vary flexibly (using any intermediate values), are known as analogue measured variables. Examples: Temperature, pressure, brightness, etc.

Analogue variables need to be digitalised for acquisition by a PLC or a computer. To this end, they may be compared with a specified threshold or a tolerance band and converted into a digital signal. However, the actual digitalisation consists of a comparison with considerably shorter intervals. A (typical) 12 bit analogue/digital converter divides the range of measurement into 4096 (= 212) consecutive, intervals of identical size and determines, into which interval the measured value falls. The interval number represents the digitalised measured value.

Hence, digitalisation means the conversion of the analogue measured value into a computer compatible digital number notation. The number of intervals and the range of measurement result in the resolution of the analogue/digital converter.

4.2 Analogue-Digital-Convertors

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Analogue variables need to be digitalised for acquisition by a PLC or a computer. To this end, they may be compared with a specified threshold or a tolerance band and converted into a digital signal. However, the actual digitalisation consists of a comparison with considerably shorter intervals. A (typical) 12 bit analogue/digital converter divides the range of measurement into 4096 (= 212) consecutive, intervals of identical size and determines, into which interval the measured value falls. The interval number represents the digitalised measured value.

Hence, digitalisation means the conversion of the analogue measured value into a computer compatible digital number notation. The number of intervals and the range of measurement result in the resolution of the analogue/digital converter:

$\Delta V = V_{max} / 2^n$

V_{max} = Measuring range, typical 0 ... 10 V

n = Word length

Changes of the analogue value within an interval width of ΔV do not alter the digital value. Contrary to common belief, the digital value is therefore less accurate in principle than the analogue value. The significance of digital measured data processing is in the fact that a digital value can be converted, stored and transmitted in any way.

The characteristic curve of digitalisation is a stepped curve. The deviation from the linear influence is known as a quantisation error. In practice, quantisation errors are kept smaller than other measuring inaccuracies (due to the selection of a suitable word length).

4.2.1 Calculation of resolution

The following data applies for the calculation of the resolution of analogue sensor signals in a controller:

- Measuring range of voltage inputs: -10 V to +10 V
- Measuring range of current inputs: 0 to 20 mA
- Digital word length: 10 bit

The resolution of analogue signals in a controller is calculated as follows:

$$\text{Resolution} = \frac{\text{Measuring range of sensor}}{\text{Number digital values}}$$

Voltage signal:

$$\frac{20\ \text{V}}{1022} = 0.01957\ \text{V}\ \ (\text{ca. } 0.02\ \text{V})$$

Current signal:

$$\frac{20\ \text{mA}}{1022} = 0.01957\ \text{mA}\ \ (\text{ca. } 0.02\ \text{mA})$$

Calculation example

Resolution of voltage signal of a linear potentiometer in the controller:

The following are known:

- Measuring range of sensor:
  200 mm, output voltage 0 ... 10 V
- Effective range of voltage input:
  Digital values 511 ... 1022

To be inserted in the calculation formula:

$$\text{Resolution} = \frac{200\ \text{mm}}{1022 - 511} = 0.39\ \text{mm}$$

Note

It should be noted that for the digital resolution of the controller only the effective range for the analogue sensor is taken into account. With some characteristic curves, the range of the sensor signal and the measuring range of the controller are not identical.

4.2.2 Calculation of a digital value

Each analogue value measured is assigned a digital value (step). The following variables must be known for the calculation of a digital value:

- Initial and end value of characteristic curve:
  S_{min}, S_{max} in mm
- Initial and end value of characteristic curve in the controller:
  Digital $value_{min}$, Digital $value_{max}$
- Measured value S_{actual} in mm

$$\text{Digital value} = \frac{\text{Digital value}_{max} - \text{Digital value}_{min}}{S_{max} - S_{min}} \cdot S_{actual} + \text{Digital value}_{min}$$

Calculation example

Digital value of the measured value 100 mm of a linear potentiometer in a controller:

The following are known:

- Measuring range of sensor:
  200 mm, output voltage 0 ... 10 V
- Effective range of voltage input:
  Digital values 511 ... 1022

To be inserted in the calculation formula:

$$\text{Digital value} = \frac{1022 - 511}{200\text{ mm} - 0\text{ mm}} \cdot 100\text{ mm} + 511 = 766(.5)$$

Notice:
The place after the decimal point cut off in the controller.

4.3 Basic principles: Binary numbering system and floating-point numbers

In addition to binary signals (on/off), there is a multitude of variables with continuous curves, for example:
- Temperature
- Speed
- Light intensity
- Filling levels

These cannot be represented in binary mode. The microcontroller, however, can only work with binary signals. The technical solution is called a binary numbering system.

A decimal number such as 4379 can also be represented as follows:

4379 = 4 x 1000 + 3 x 100 + 7 x 10 + 9 x 1

The structure of the places and the value of these places are characteristic of the decimal numbering system used as a rule.

The decimal numbering system is based on the existence of 10 different digits (decimal: from decem (lat.) = 10). These 10 different numbers can be used to count from 0 to 9. To count past 9, we carry over to the next place. This place has the value 10; once 99 is reached, we carry over to the next place again.

If you restrict yourself to exactly 2 digits per place in a number, then the structure of the numbering system is as follows:

$2^7 = 128$	$2^6 = 64$	$2^5 = 32$	$2^4 = 16$	$2^3 = 8$	$2^2 = 4$	$2^1 = 2$	$2^0 = 1$
1	0	1	1	0	0	0	1

The principle is exactly the same as the method used to form a decimal number. However, there are only two digits available, which is why the value of a place is calculated as 2x rather than 10x. In other words the lowest-value place on the far right has the value $2^0 = 1$, the next place $2^1 = 2$, etc. This numbering system is called the binary or dual numbering system because of the fact that only two digits are used.

With eight places, you can only count to max. $2^8 – 1 = 256 – 1 = 255$, this would be the number 11111111 in the dual system. A dual number with 8 places is called a byte. A byte therefore consists of 8 bits. Since dual numbers can initially only represent whole numbers, they are also called integers (int for short).

Dual numbers are used with algebraic signs within microcontrollers. The first place then stands for the sign (1 means minus), so an integer then has the value range -127 to +127. If you use two bytes (i.e. 16 places) for the representation, the value range increases to -32,768 to +32,768 for an integer16 (for short: int16) and to 0 to 65,536 for an unsigned integer 16 (for short: uint16).

If arithmetic operations lead to results that are outside the data type's value range, there will be an overflow and the result will be incorrect:

Example
Two numerical values with the value range uint8 are to be added:
Binary: 11111111 + 00000001 = 00000000
Decimal: 255 + 1 = 0

The same happens when a uint8 is incremented. The number after 255 is 0, not 256!
It is important to note this when working with different value ranges.

Floating-point numbers are used to represent decimals. These consist of a mantissa and exponent in the format: mantissa multiplied by base to the power of exponent. Examples of floating-point numbers are:

$3.5 = 3.5*10^0$
$3{,}500 = 3.5*10^3$
$35.7 = 3.57*10^1$

Floating-point numbers are referred to as single or double precision depending on how many bits are used to represent the mantissa and exponent. The overflow problem does not occur with floating-point numbers; however, arithmetic inaccuracies can occur.

The "smallest" data type sufficient for the task should generally be selected because this reduces the memory requirement and increases the execution speed of the program.

Type	Explanation	Value range
bool	Logical values	True, false
Int8	Integer with 8-bit precision	Integers between -128 and 127
Int16	Integer with 16-bit precision	Integers between -32,768 and 32,768
uint8	Unsigned integer with 8-bit precision	Integers between 0 and 255
uint16	Unsigned integer with 16-bit precision	Integers between 0 and 65,535
float	Floating-point number (32-bit)	-3.14
double	Floating-point number (64-bit)	-3.14

4.4 Linear scaling of measured values

Linear conversion for scaling of values is based upon a straight line equation:

$Y = a \cdot x + b$

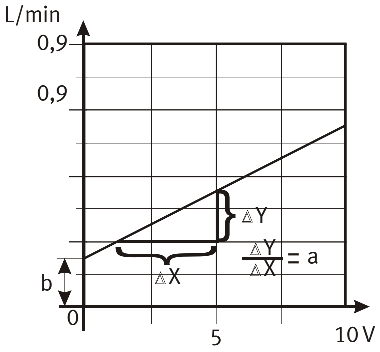
Where:

a = factor;

b = Offset;

x = measure value and

y = physical value



Graph of straight line equation

Example

A flow sensor with a measure transmitter reads out a voltage signal within a range of 0 to 10 V for a measuring range of 0.3 to 7.5 litres per minute.

In this case, factor "a" for a full scale value of 7.5 l/min calculates as follow:

$$a = \frac{y-b}{x} = \frac{7.5-0.3}{10} = 0.72$$

The offset is found by shifting of the line's initial point to the origin :

at y_0 = 0,3 and x_0 = 0:

$$b = y_0 - a \cdot x_0 = 0.3 - 0.72 \cdot 0 = \underline{\underline{0.3}}$$

Example for factor

Sensor: 0…200 bar

Signal: 0…10V

so the factor has to be = 20

Example for offset

Sensor: 0…100 bar

Signal: 0…10V, for measurement 5 bar should be = 0V.

55 bar should be 5 Volt

so the offset has to be = -5.

Eventually the factor has to be adjusted, too.

4.5 Read process values and write control outputs with FluidLab®-PA closed-loop

Using FluidLab®-PA closed-loop step by step to teach and demonstrate the fundamentals of control technology. The EasyPort is used to connect the PC and real hardware, e.g. the EduKit PA, the MPS® PA compact workstation or the MPS® PA filtration station, mixing, reactor, filling.

- **Settings**

Parametrisation of sensor values with factor and offset to represent the physical quantities as well as signal attenuation per median filter for the analogue input signals. Display of the physical value in the variable units field. Other possible settings are the inversion of the controller direction, Y offset in the continuous rules and the selection of the simulation mode.

- **Menu: Measurement**

All binary and analogue process data, for example the signal statuses of the sensors, process fittings and pump, can be displayed graphically and evaluated directly. To record the sensor characteristic and determining a step response, functions are available such as selection of measuring channels, adjusting the test time or cursor evaluation with zoom function.

- **Menu: Characteristic curve**

The characteristics of a final control element (e.g. pump or proportional valve) is investigated in various perspectives (voltage for flow, flow for pressure, pressure for voltage).

- **Menu: 2-point controller**

Typical applications are level and temperature controlled systems.

- **Menu: Continuous regulation**

Experimentation, configuration and optimisation of the control processes (P, PI, PD or PID controller) with immediate effect in the process. Controlled systems can be operated via mouse click. Trouble-free documentation of the control parameter is possible. The measured values and curve profiles can be documented comprehensively. The block diagram can be displayed as a function menu for all continuous controllers with current numerical values.

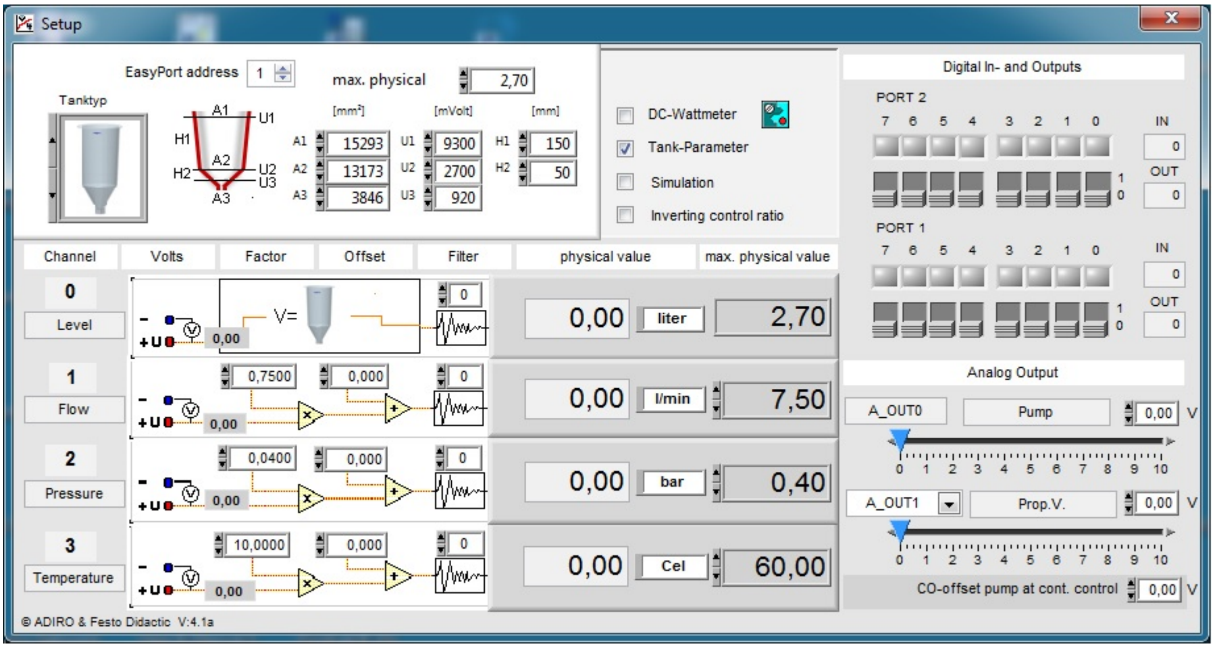
- **Industrial controller functions**

System operation like in a process control system. It is possible to specify nominal values and switch the controller between manual and automatic.

- **Simulation**

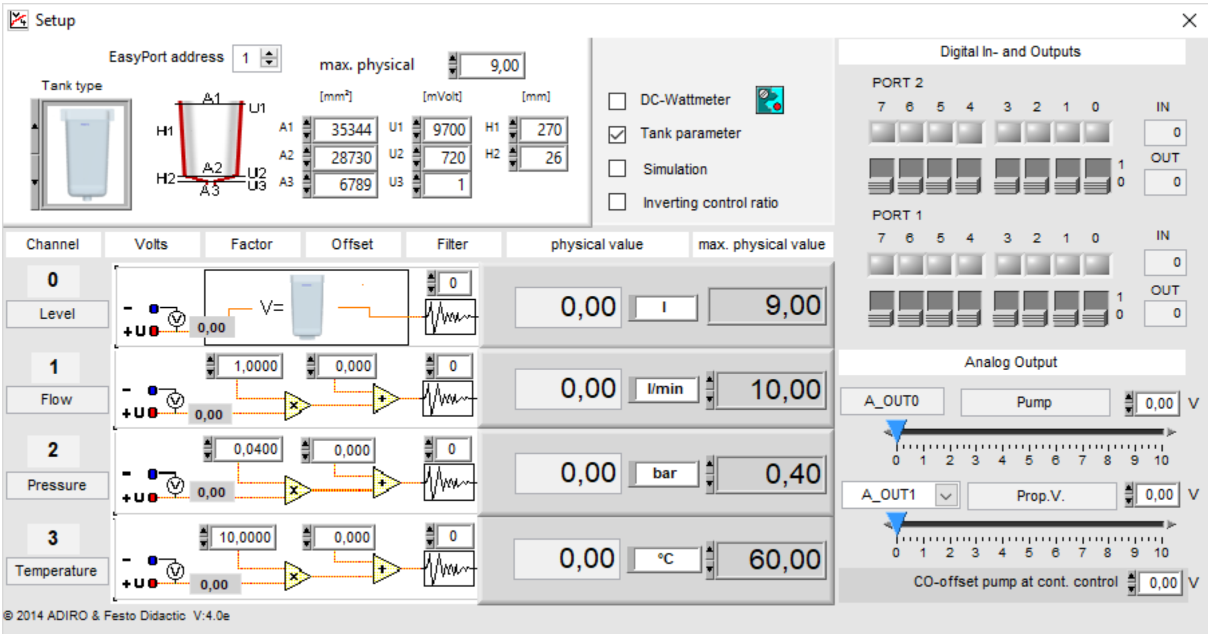
A simulated process model illustrates the sequence identically to the operation of the real hardware.

4.5.1 Settings for EduKit-PA Advanced



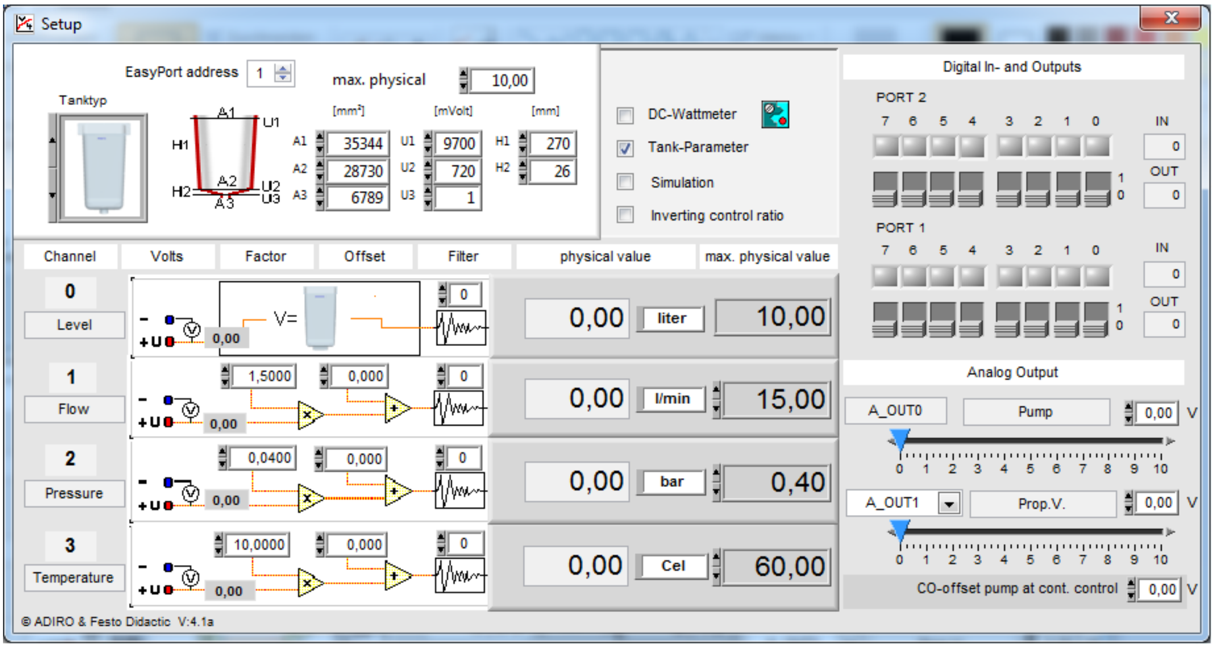
Adapt tank parameters U1, U2 and U3 individually.

4.5.2 Settings for MPS-PA Compact Workstation Basic and Energy



Adapt tank parameters U1, U2 and U3 individually.

4.5.3 Settings for MPS-PA Compact Workstation Process Instrumentation

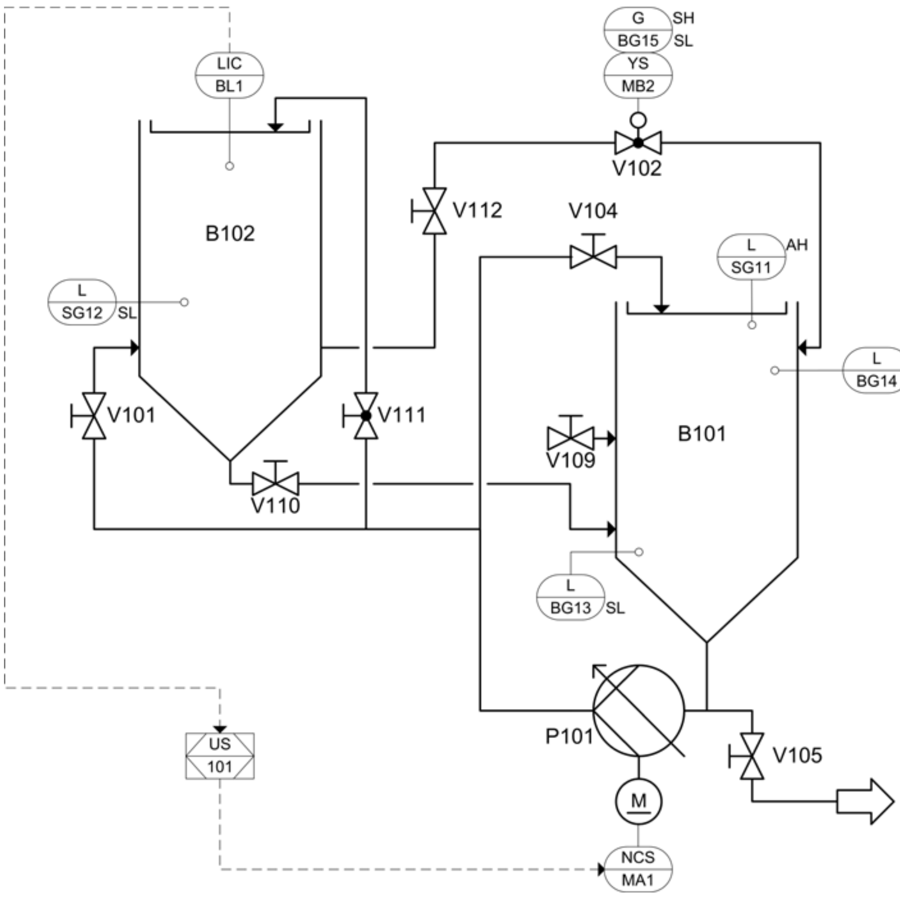


Adapt tank parameters U1, U2 and U3 individually.

Module 6 – Operating, identifying and analyzing a level control system

6.1 Introduction

The function of the level controlled system is to regulate the filling level of a fluid in a reservoir tank.
The controlled filling level system can be used as I- or PT1 controlled system.



PI-diagram of the close loop level control system (EN62424/ISO10628)

The pump P101 delivers a fluid from a storage tank B101 to a reservoir tank B102 via a piping system. The level of the fluid inside tank B102 is monitored with a analog sensor BL1 at measuring point 'LIC BL1' and read as actual value. The actual value should be kept on a certain level also if disturbances or set point changes occur.

The reservoir tank B102 can be filled from the bottom through manual valve V101 and from the top through ball-valve V111. The fluid quantity of the pump P101 can be a binary or manipulated value. For controlling system a two-position or a continuous element can be used.
For disturbance is it possible to partly or totally open/close the ball valve V102 to drain the upper into the lower tank or open/close hand valve V104.

All the exercises in the workbook and solutions are done with the usage of EasyPort and FluidLab®-PA closed-loop software.

6.2 Exercise – Analysis of tank parameters

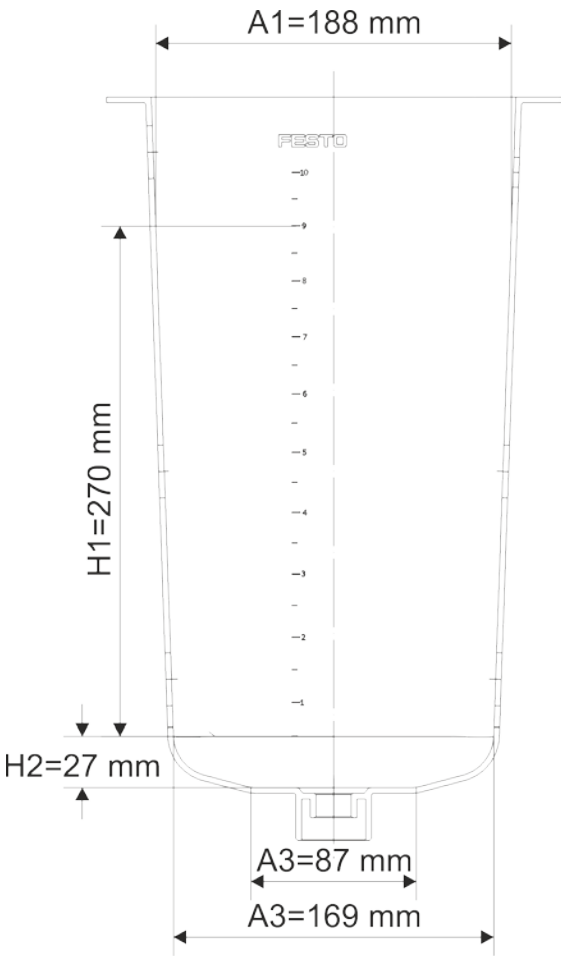
Information

The tank level is measured with an ultrasonic sensor. The 4-20 mA signal of the ultra-sonic sensor is converted with a measuring transducer I/U to 0-10V standard voltage signal. The voltage signal will be displayed in Fluid Lab®-PA closed-loop as a physical value, the water volume in liters. Determine the parameter settings, so that the displayed level value in the software matches with the scaling 0-10l of the tank.

Note:
Documentation:
- Datasheet: Ultrasonic sensor
- Datasheet: 10L Tank
- Tank drawing

Task

Calculate and determine the required information based on the task description. After that, enter the parameters into the software and verify that the calculated values are appropriate.



Tank, 10L with dimensions

Procedure

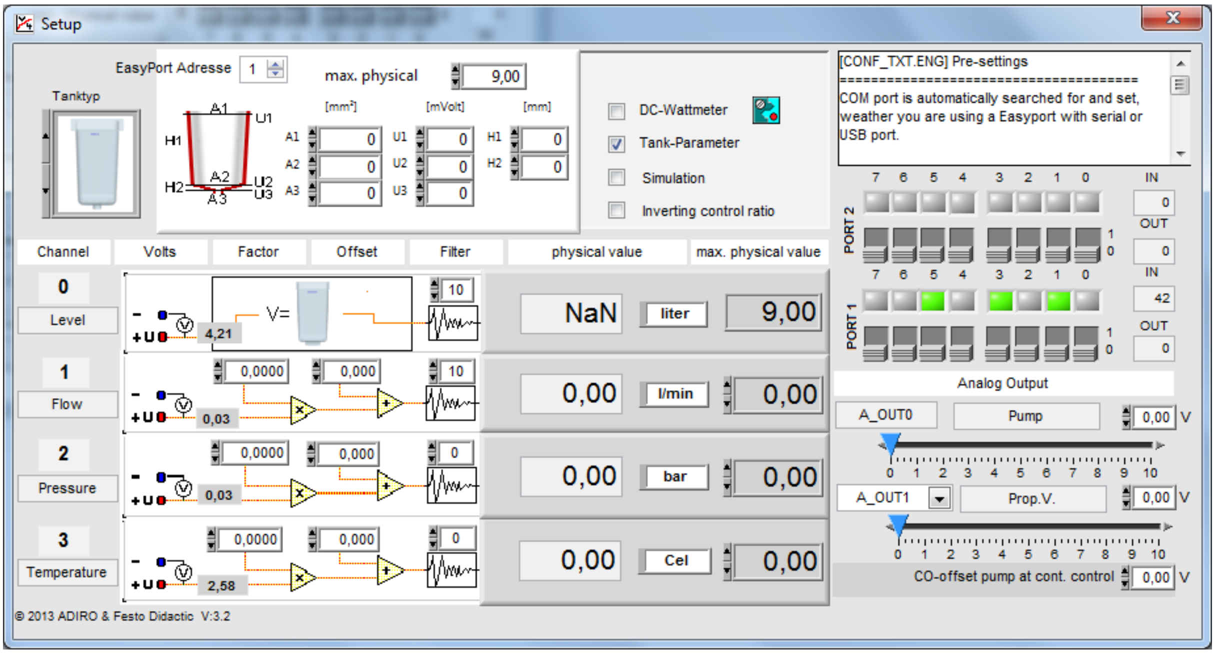
1. Start FluidLab®-PA closed loop – choose menu "Setup".
2. Follow the instructions in the table underneath.

No.	Action	Value
1	**Empty** the tank completely and read the voltage value	Voltage value U3: mV
2	Fill the water level to **0.5L** and read the voltage value	Voltage value U2: mV
3	Fill the tank with **9L** of water and read the voltage value	Voltage value U1: mV
4	Calculate the surface area at 9L	Area at 9L - A1: mm²
5	Calculate the edge area at 0.5L	Area at 0,5L - A2: mm²
6	Calculate the area at voltage value U3	Area at U3 – A3: mm²
7	Determine the height H1 between 9L and 0.5L	Height H1: mm
8	Determine the height H2 between 0.5L and U3	Height H2: mm

Calculations:

3. Tick the Tank-Parameter
4. Fill in the determined values.

Note
Because of the dead range of the ultrasonic sensor, the measuring range works in the range between 0-9L. Therefor the maximum physical value can be determined as 9L.
Using the capacitive probe of the process instrumentation the maximum reading is at 10L!



Fluid Lab®– PA closed-loop – The setup window

Questions

- Does the value displayed match with reality?

6.3 Exercise - Analysis of a pump

Information

Pump data sheet

Task

Answer to the following questions.

Questions

- What type of pump is used in the Compact Workstation?
- How many other different types of pumps there are? Name the main differences and point out the advantages and disadvantages.
- What must be taken into account when using the pump?
- Calculate the rated current of the pump motor.

6.4 Exercise – The delivery rate of a pump

Information

- Collection of data sheets
- Book of tables
- Engineering Handbook

Task

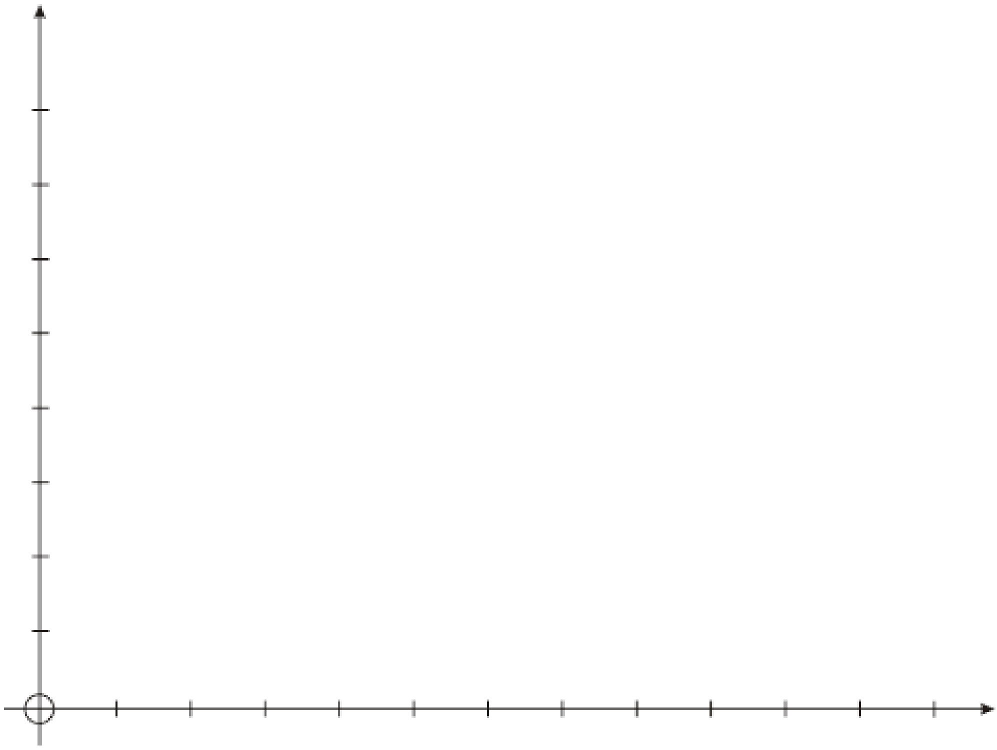
Determine the delivery rate of a pump.

Execution

1. Fill the lower tank with approx. 10l of water.
2. Start FluidLab®-PA closed loop and choose menu "Measuring and Control".
3. Open manual valve V101.
4. Select "Level" and "OUT" as measured values.
5. Select "DOUT3 Pump" as a manipulated value.
6. Start the execution.
7. Turn the "Contr. val." switch ON. The execution time can be 1 minute.

Questions

- Calculate the delivery rate of the pump.
- Analyze your measurements and results. Please also compare results to those of other groups.



6.5 Exercise - System behavior of a tank

Information

In a level control system, the controlled system is the tank. It is therefore essential to know the behaviour of a tank when filled or emptied.

Write down the behavior you expect in the prepared worksheet before starting measurements.

6.5.1 Measure - Behavior of the tank at filling from above without discharge

Measure the behavior for the tank with the pump switched on, outlet valve closed and inlet valve open.

Execution

1. Fill the lower tank with approx. 10l of water.
2. Start FluidLab®PA closed-loop – choose menu "Measuring and Control".
3. Open manual valve V111.
4. Select "Level" and "OUT" as measured values.
5. Select "DOUT3 Pump" as a manipulated value.
6. Start the execution.
7. Turn the "Contr. val." switch ON. Terminate the measure if a level of ~9 l has been reached.

6.5.2 Measure - Behavior of the tank at discharge

Measure the behavior for the tank with the pump switched off, outlet valve open and inlet valve V111 closed.

Execution

1. Fill the upper tank with approx. 9l of water.
2. Start FluidLab®PA closed-loop – choose menu "Measuring and Control".
3. Open manual valve V112.
4. Select "Level" and "OUT" as measured values.
5. Select "DOUT0 2way ball-valve V102" as a manipulated value.
6. Start the execution.
7. Turn the "Contr. val." switch ON. Terminate the measure if the tank is empty ~0.5 l.

6.5.3 Measure - Behavior of the tank at filling from above with discharge

Measure the behavior for the tank with the pump switched on, outlet valve open and inlet valve V111 open.

Execution

1. Fill the lower tank with approx. 10l of water.
2. Start FluidLab®-PA closed-loop – choose menu "Measuring and Control".
3. Open manual valves V101, V112.
4. Open the 2way ball-valve V102.
5. Select "Level" and "OUT" as measured values.
6. Select "DOUT3 Pump" as a manipulated value.
7. Start the execution.
8. Turn the "Contr. val." switch ON. Terminate the measure as the level reaches a steady state.

6.5.4 Measure - Behavior of the tank at filling from below with discharge

Measure the behavior for the tank with the pump switched on, outlet valve open and inlet valve V101 open.

Execution

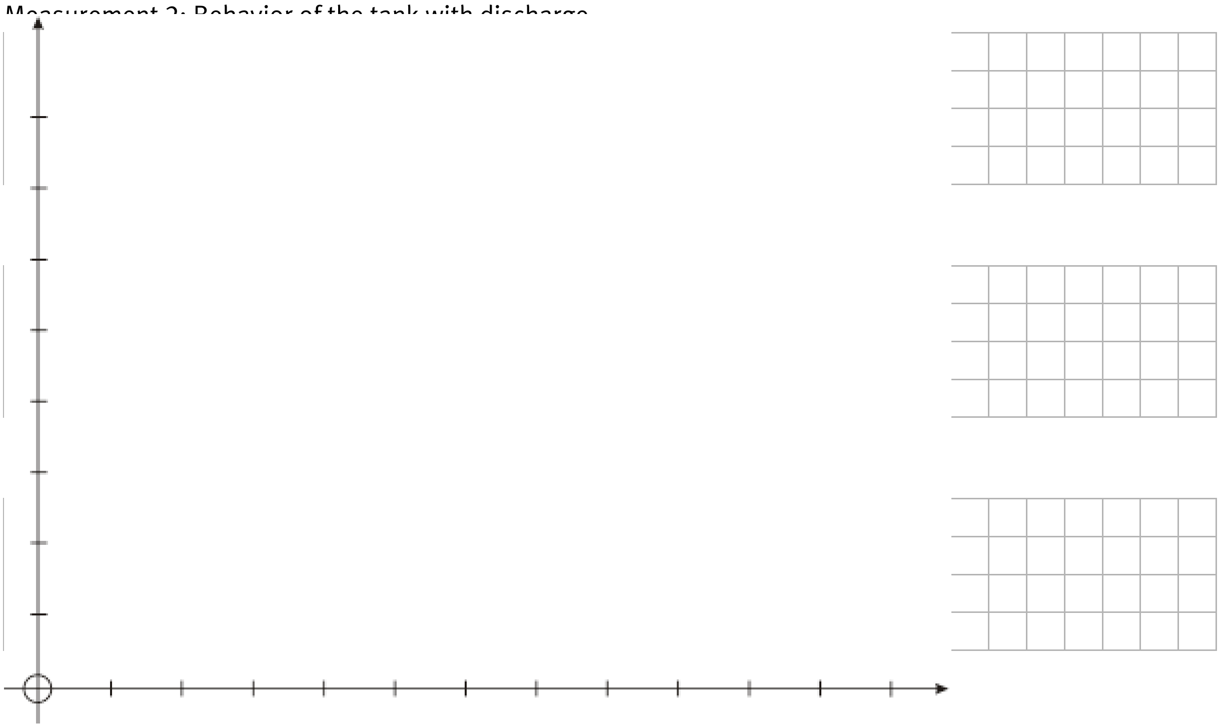
1. Fill the lower tank with approx. 10l of water.
2. Start FluidLab®-PA closed-loop and choose menu "Measuring and Control".
3. Open manual valves V101, V112.
4. Open the 2way ball-valve V102.
5. Select "Level" and "OUT" as measured values.
6. Select "DOUT3 Pump" as a manipulated value.
7. Start the execution.
8. Turn the "Contr. val." switch ON. Terminate the measure as the level reaches a steady state.

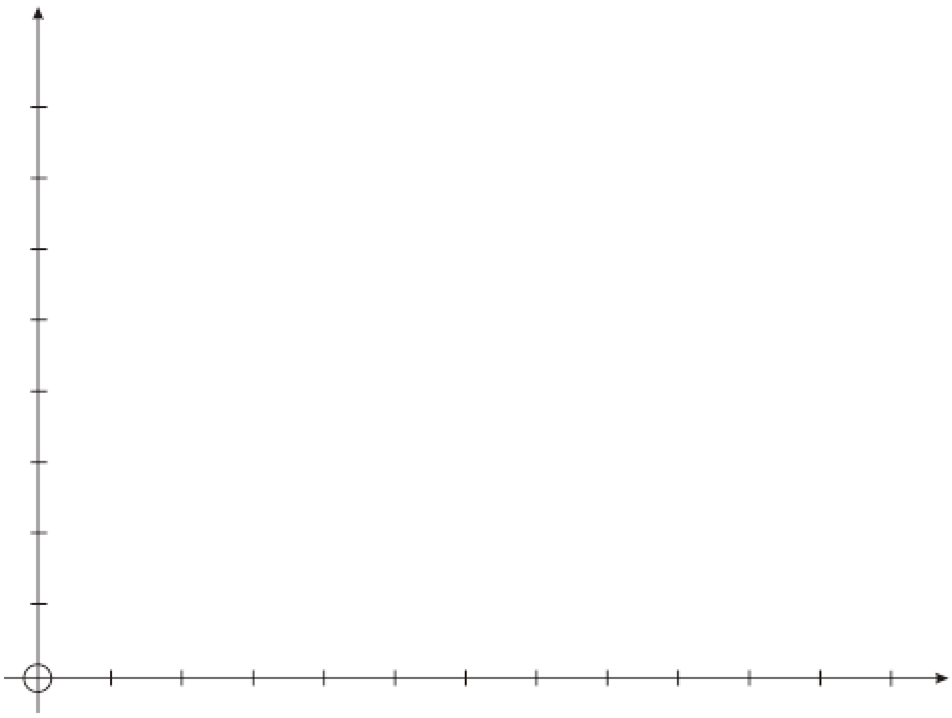
Questions

- What result do you expect to get?
- Print out the 4 curves.
- Label the axes of the diagram and draw all 4 curves into the diagram.
- Compare the characteristics. What do you notice?
- What are the advantages and disadvantages of filling from above or below?

Measurement 1: Behavior of the tank at filling from above without discharge

Measurement 2: Behavior of the tank with discharge





6.6 Conclusions of the tank system behavior

- **Inflow behavior with closed outlet**

The outlet valve V102/V112 is closed. As a result inflow via the inlet valve V101, the increase in the level (h) in the container is steady and linear over time.

The greater the inflow, the more quickly the level in the container increases per unit time.

If the quantity of water in container B101 were not limited, the amount of water would continue to increase until the container overflowed.

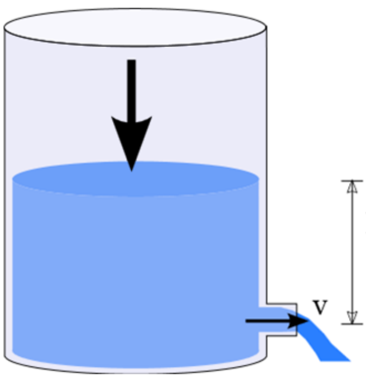
There is no self-stabilization here. For this reason, the closed container B102 is an **uncompensated** controlled system.

These uncompensated controlled systems are also termed integral systems (I systems), because the feed quantities add up.

The level is thus the sum of all water that flows into the system. The time from empty to full level is therefore also called the integration time T_i. Typical integral systems in machine-building are hydraulic cylinders and threaded spindles.

- **Outflow behaviour**

The hydrostatic pressure in the water column ensures a reduction of flow rate at the outlet. The lower the water column is the lower the hydrostatic pressure, the lower the amount of water outflows will be. This results in a non-linear characteristic.



$$v = \sqrt{2 \times g \times h}$$

$$V = 0{,}62 \times A \times \left(\sqrt{2 \times g \times h}\right) \qquad A = \frac{\Pi \times d^2}{4}$$

Formula according to Torricelli for the free discharge from a container

Example: Electrical engineering: discharge of a capacitor.

Inflow behavior with discharge

Controlled systems with compensation are controlled systems whose characteristic reaches equilibrium after a time.

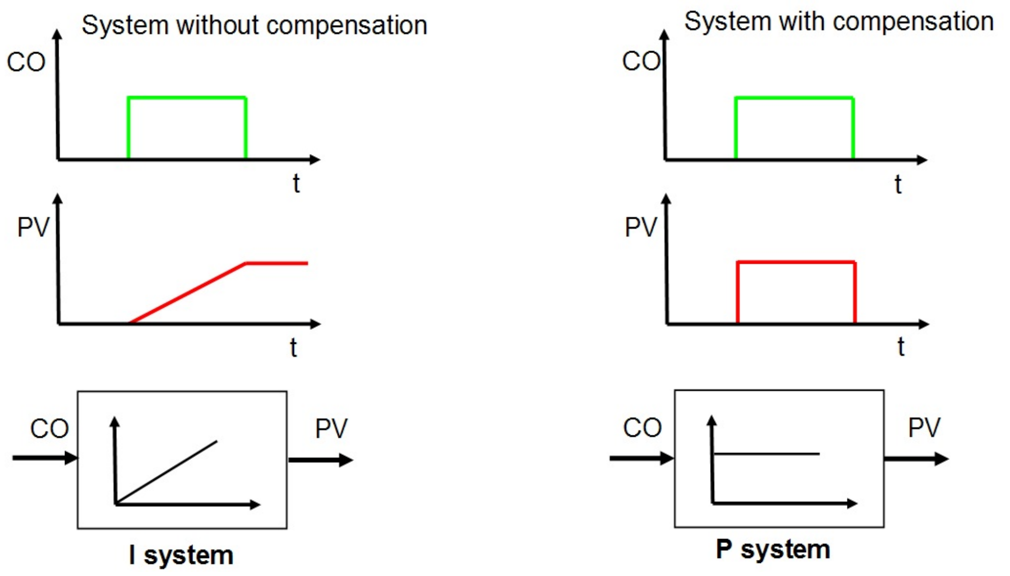
In level control systems, the compensation takes the following physical form:
When filling with a constant flow rate (inflow), the pressure of the water column at the bottom of the container is proportional to the level. Therefore if the incoming amount is always bigger than the discharge the water level will raise until overflow.

A compensation only can happen with a decrease in inflow amount until equilibrium with the outflow is reached. This results in a constant level - that is, it no longer increases. This is called a steady-state value. The system shows a behavior with compensation

The steady state depends on the valve position at the inlet valves V101/V111 and also of the outlet valve V112.

Controlled systems with compensation are also called PT controlled systems:
P – because the **steady-state value** is proportional to the input value.
T – because the **steady-state value** is only reached after delay time T.

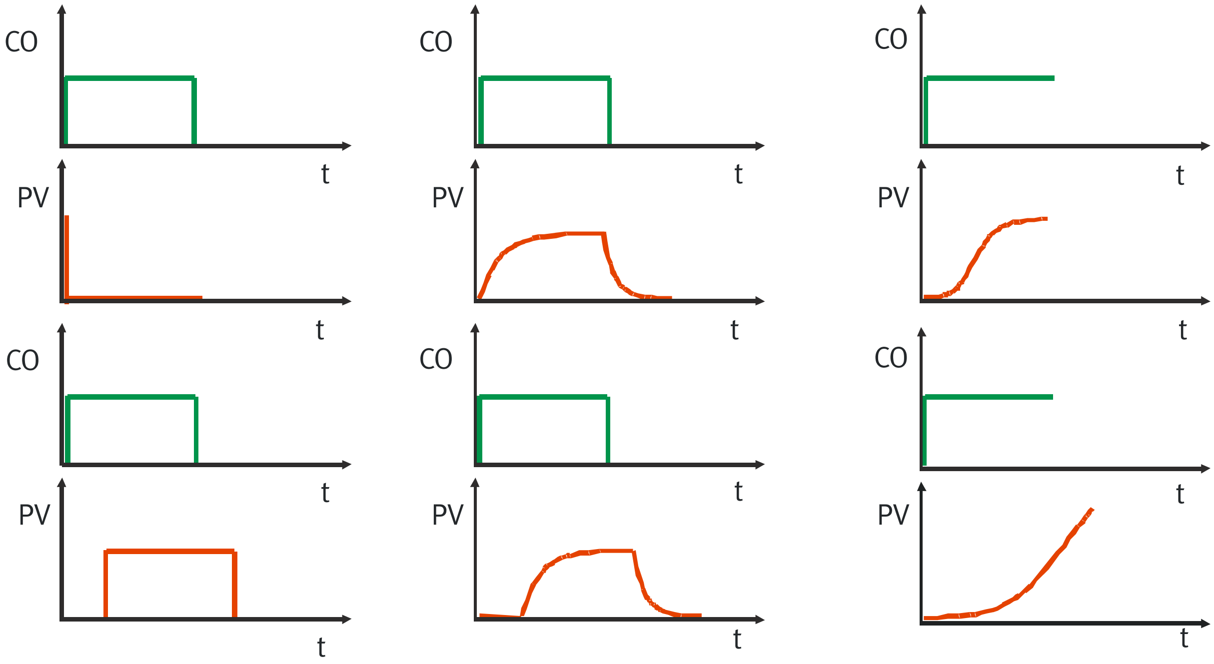
If only one container (controlled system) is present with one time delay, the controlled system is called a PT1 = 1st order controlled system. A controlled system of the 0th order would be a pure P system, for example, a lever: the force is transmitted immediately without any delay.



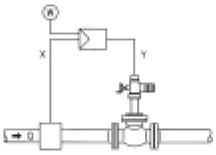
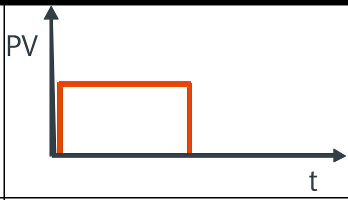
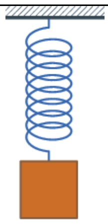
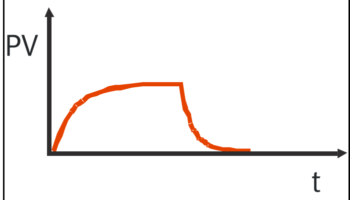
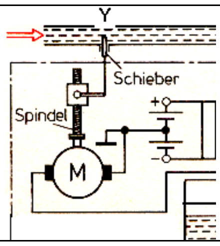
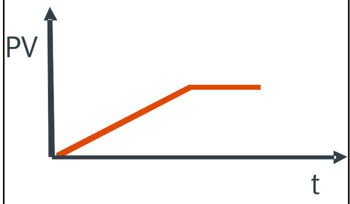
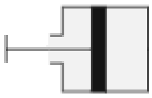
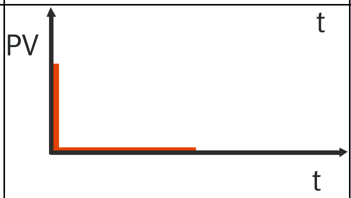
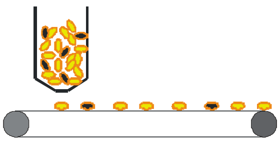
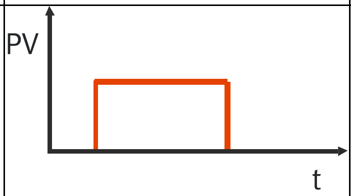
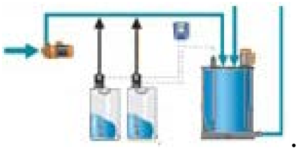
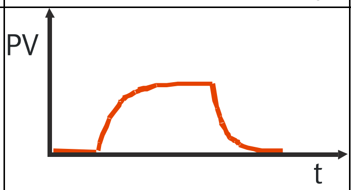
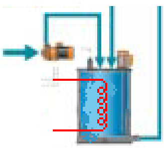
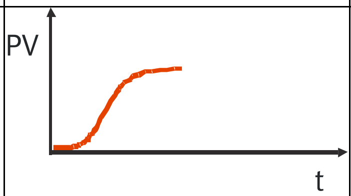
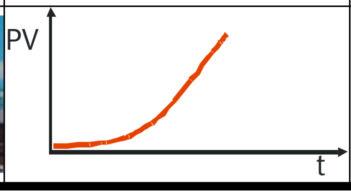
Characteristics of system with or without compensation

Step response and static behavior

'A step response is the time behavior of an output of a system when its input changes from zero to one or a certain value in a very short time.'
A step response shows the dynamic behavior of a system. The output (process value PV) follows the input value which is given by the controller (controller output CO) in a dynamic characteristic.
There are also other system step responses which are important to know about if controlling a system. Here are some examples.



System step responses – what system is it?

Behaviour	System	Step response	Similar behaviour
P			Transformer, P-controller, diaphragm valve, pipe system
PT1			Spring-damper system, level of tank with outlet, electrical capacitor, solenoid coil
I			Motor valve, I-controller, counter, level of closed tank
D			Electric networks, induction coil, D-controller, mechanical damper
T			Conveyor
PT1 with dead time			pH control system
PTn			Heater
Unstable			Magnetic levitation system

6.7 Operating and identifying a level control system

Information

Machines and systems often require variables such as pressure, temperature, flow rate or level to be controlled to a predetermined value. These values should not change in the event of faults. This type of task is undertaken by a controller. Closed-loop control engineering covers all problems associated with this task. The variable to be controlled is measured, converted and supplied to the automatic controller as an electrical signal.

The controller then compares this value (or value curve) with the pre-set value. The corrective action to be taken by the system is then derived.

Finally, a suitable point for corrective action to influence the controlled variable must be determined, for example, the heater’s regulator. Here, system response is important.

Before setting up a closed-loop controller it is important to operate the controller output manually. The following criteria are to be determined manual operation:

- Output range of the final control element (that is, the pump) and its linearity
- Range of the actual value corresponding to the output range and its linearity

The time response of a controlled system must be known for optimum controller selection. This allows conclusions to be drawn regarding the dynamic response of the controlled system the controller settings to be determined.

The time response of a controlled system is determined by recording a transient response of the system. For systems with delay – such as where there is energy storage – the time constant of the controlled system is determined by applying a tangent or, in the case of multiple delays, an inflectional tangent.

6.8 Exercise – Operating manually a level control system

Task

The level of a tank is to be kept constant. Set the manual valves so that the medium can flow directly into the upper tank. Leave the outlet valve closed so that no water can flow out of the tank. Pump water to desired level and open the outlet valve. Try to keep the level constant by switching pump ON and OFF.

Preparation

1. Fill the lower tank with approx. 10l of water.

Note
Please note that the entire system must not contain more water than the capacity of one tank!

2. Vent the pipe system of the level control system.
3. Open manual valve V111.
4. Start FluidLab®-PA closed-loop – choose menu "Setup".
5. Turn the motor binary ON.
6. Pump water to 4,5l and open manual valve V112.
7. Open the 2way ball-valve V102.
8. Try to maintain the level at 4,5l by switching the pump ON and OFF.

Questions

Are you using closed-loop or open-loop control of the level? Give reasons for your answer.

Is it possible to maintain a constant level manually?

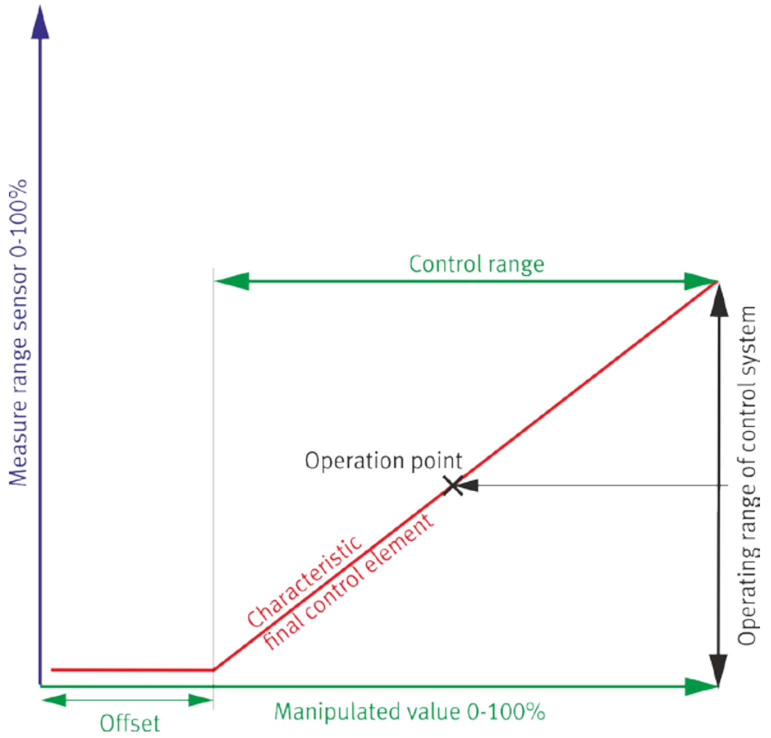
6.9 Exercise - Operating a level control system

Information

Like mentioned in the chapter 6.6 Conclusions about tank system behavior, controlled systems with compensation are controlled systems whose characteristic reaches equilibrium after a time. This means that because of the hydrostatic pressure, at some point the inflow of water to the tank becomes equilibrium with the outflow. At this point the water level stops rising and reaches so called steady-state value.

Because of this behavior, it´s important to determine the flow rate range of the pump in a level controlled system. This can be done by interpreting the Characteristics curve of the final control element.

The following diagram describes the main terms concerning the Characteristics curve analysis.



Analysis of the characteristic of the final control element

Operating range determines the minimum and maximum values possible in the process for the regulated quantity i.e. the flow rate, if the voltage of the pump (see: manipulated value 0-100%) is varied.
Offset of the curve determines the voltage range of the final control element when there is no change in the regulated quantity. The offset can be adjusted for the final control element which results in better reaction of the control system. This is a first step to optimize a control loop, without even thinking about control parameters.
Control range is the range of the final control element without offset. That also equals to the 0-100% output of the controller.
The operating range is the band of the final control element without offset. That equals to 0-100% of the controller output or manipulated range. The given value for the control system derives in practice from process specifications. Having a simulated control system a operating point in the middle of the operation range is useful. Therefore there will be a greater range of the manipulated value changing the process variable.

6.9.1 Determining the control and operating range

Task

Carry out the following series of measurements for determining the operating range of a level control system and the control range of pump.

Preparation

9. Fill the lower tank with approx. 10l water.
10. Open manual valves V111, V110.
11. Start FluidLab®-PA closed-loop – choose menu "Characteristics".
12. Select chart which displays flow rate in relation to pump voltage.
13. Switch the relay K1 ON.
14. Set measure time to 100s, choose "A_OUT0 Pump" as a manipulated output and start the execution.
15. Determine the offset in the beginning of the flow characteristic
16. Determine the control range of the final control element and the operating range of the regulated quantity.
17. Enter the measured values in the tables.

Description	Value [V]
Offset of the final controlling element	

	Control range of pump Manipulated variable [V]	Flow sensor Flow rate [l/min]
Minimum measured value		
Maximum measured value		

6.9.2 Determining the pump voltage at the operating point

Because of the hardware used in the station, the operating range of a level control system works in the range between 0,5 - 9l. Therefor the operating point of the system can be determined to be 4,5l.

Carry out the following measurements for determining the pump voltage at the operating point so the level is constant at 4,5l when the system has an outflow.

Preparation

1. Fill the lower tank with approx. 10l of water.
2. Open manual valves V101, V112.
3. Start FluidLab®-PA closed loop – choose menu “Measuring and Control”.
4. Select “Level”, “A_OUT0 Pump” and “OUT” as measured values.
5. Select “A_OUT0 Pump” as a manipulated value.
6. Switch the relay K1 ON.
7. Open the 2way ball-valve V102.
8. Start the execution.
9. Turn the “Contr. Val.” Switch ON.
10. Determine the pump voltage for the operating point by manipulating the control signal. Fill the voltage reading in the table.

	Control range of pump **Manipulated variable of pump [V]**	**Ultra sonic sensor** **Level [l]**
Operating point		4,5

Questions

- State the system conditions which could influence the level control system.

6.10 Exercise – Identify a level control system

Information

The time response of a controlled system must be known in order to make an optimal controller selection. Information can then be derived regarding the dynamics of the controlled system and the controller setting defined.

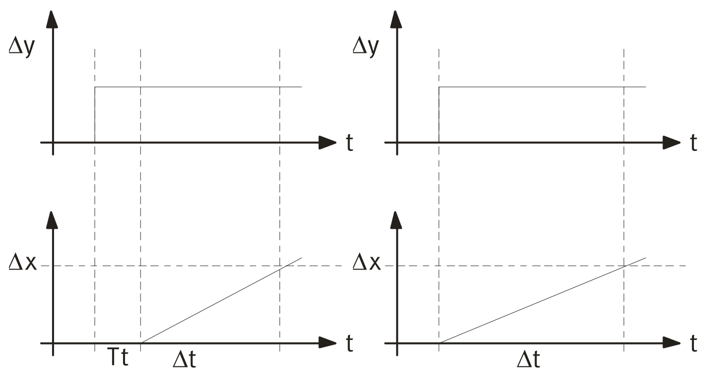
The time response of a controlled system is established by determining the step input response or open-loop response.

Task

Carry out the following series of measurements for determining the step response of the level controlled system when there is no outflow.

Preparation

1. Drain the upper tank completely and fill the lower tank with approx. 10l of water.
2. Open manual valve V101.
3. Start FluidLab®-PA closed loop – choose menu "Measuring and Control".
4. Select "Level", "A_OUT0 Pump" and "OUT" as measured values.
5. Select "A_OUT0 Pump" as a manipulated value.
6. Switch the relay K1 ON.
7. Adjust the pump control voltage to the operating point value
8. Start the execution.
9. Turn the "Contr. val." Switch ON.
10. Define the integral action coefficient K_{IS} with the help of following diagrams and formula



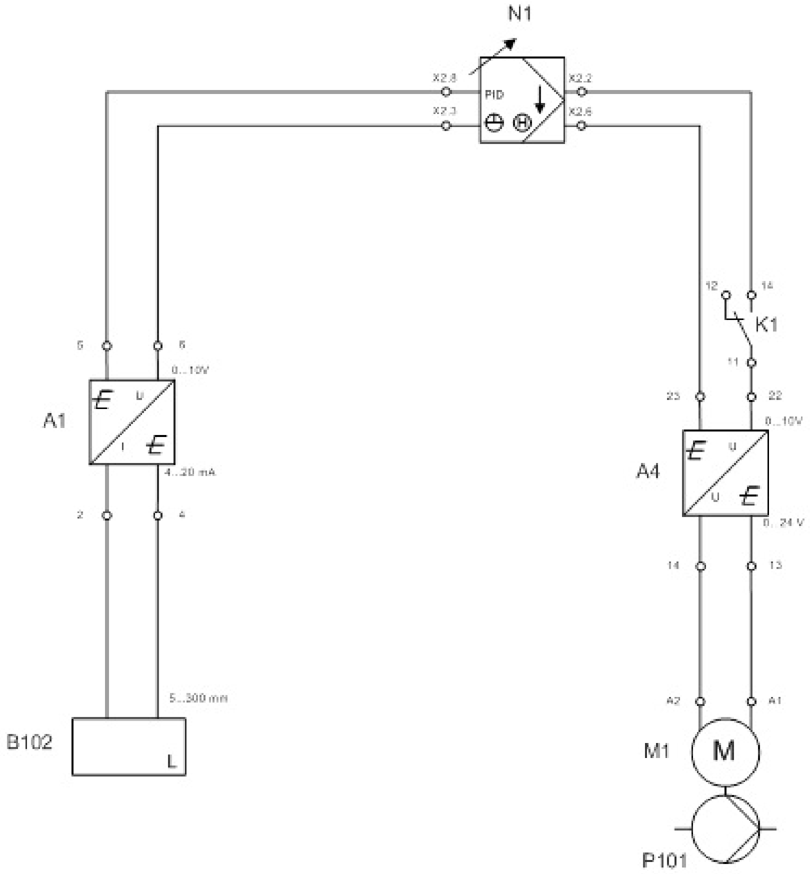
Step response with and without dead time.

$$K_{IS} = \frac{\Delta x}{\Delta y \times \Delta t}$$

Parameter	Dimensionless value	Value [$\frac{l}{Vs}$]
K_{IS}		

6.11 Exercise - Operating a P-I controller for a level control system

Information



Loop diagram of a level control system

A continuous-action controller, in contrast to a two-position controller, has a continuous signal as manipulated variable which is generated in relation to the system deviation.

Task

Familiarize yourself with the mode of operation of different continuous-action controller types.

- Complete the table. The operating point determined in Exercise 6.9 is to be used as the set point value.

Parameter	Dimensionless value	Value [l]
Setpoint value (w) at operating point		

- Check the behavior of the controlled system using different continuous-action controllers.

6.11.1 P-controller

Task

- Control the system by means of a P-controller.
- Consecutively set the gain K_P specified in the table.
- Record the control response for each value.

Preparation

1. Fill the lower tank with approx. 10l of water.
2. Open manual valves V101, V112.
3. Start FluidLab®-PA closed loop – choose menu "Closed-loop Control - continuous".
4. Select "Level" as a controlled system.
5. Switch the relay K1 ON.
6. Open the 2way ball-valve V102.
7. Select "A_OUT0 Pump" as a manipulated output.
8. Set the set point value into the controller.
9. Set the offset of a manipulated value to correspond the measured one in the Exercise 6.9.
10. Use values in the table for the P-controller and start the execution.

Parameter	Value
K_P	2
K_P	5
K_P	10
K_P	50

List of parameters

Questions

- How does the system respond with closed-loop control using a P-controller?
- How does the system respond when you change the set point in small steps around the operating point or close valve V112 or closed valve V102?

6.11.2 I-controller

Task

- Control the system by means of an I-controller.
- Consecutively set the integral time T_I specified in the table.
- Record the control response for each value.

Preparation

1. Fill the lower tank with approx. 10l of water.
2. Open manual valves V101, V112.
3. Start FluidLab®-PA closed loop – choose menu “Closed-loop Control - continuous”.
4. Select “Level” as a controlled system.
5. Switch the relay K1 ON.
6. Open the 2way ball-valve V102.
7. Select “A_OUT0 Pump” as a manipulated output.
8. Set the set point value into the controller.
9. Set the offset of a manipulated value to correspond the measured one in the Exercise 6.9.
10. Use values in the table for the I-controller and start the execution.

Parameter	Value
T_I	50
T_I	10
T_I	5
T_I	2

List of parameters

Note

Because of the value of time for the I-controller is not combined with any other control element we will call it “integral time” T_I .

Questions

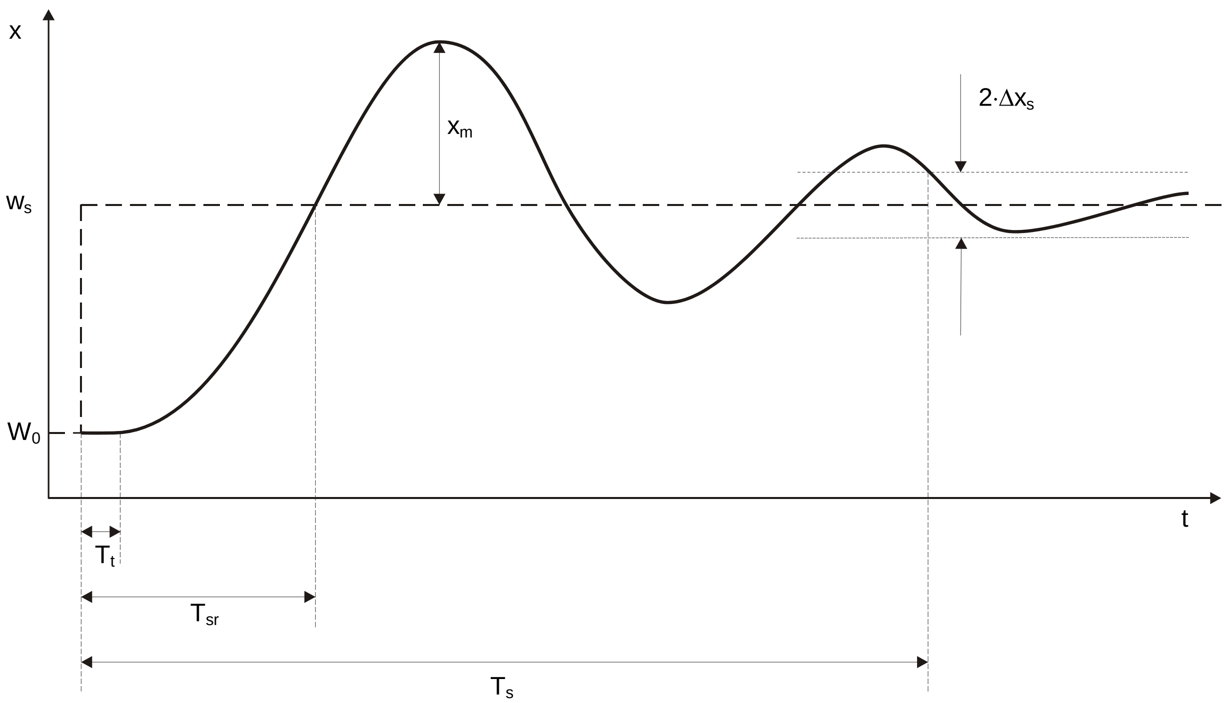
- How does the system respond with closed-loop control using an I-controller?
- How does the system respond when you change the set point in small steps around the operating point or close valve V112 or open valve V104 slightly?

6.11.3 PI-controller

Information

The quality criteria (IEC 60050-351) of a control-loop behavior are:

Overshoot x_m	for a step response, the maximum transient deviation from the final steady-state value of the output variable, usually expressed in percentage of the difference between the final and the initial steady-state values
Dead-time T_t	The dead time indicates the temporal displacement between two values.
control rise time T_{cr}	duration of the time interval after a stepwise change of the reference variable or a disturbance variable beginning, when the controlled variable for the first time leaves a specified tolerance band, placed around the desired value of the controlled variable and ending, when the controlled variable for the first time returns into the tolerance band
control settling time T_{cs}	duration of the time interval after a stepwise change of the reference variable or a stepwise change of the disturbance variable beginning, when the controlled variable for the first time leaves a specified tolerance band, placed around the desired value of the controlled variable, and ending, when the controlled variable returns into the tolerance band and remains within it.
Tolerance Δx_s	specified tolerance limit (preset value: 5% of the setpoint)



Quality criteria of control-loop behavior

Task

- Control the system by means of a PI-controller in parallel structure.
- Consecutively set the gain constant K_P and integral time T_I specified in the table.
- Record the control response for each value.

Preparation

1. Fill the lower tank with approx. 10l of water.
2. Open manual valves V101, V112.
3. Start FluidLab®-PA closed loop – choose menu “Closed-loop Control - continuous”.
4. Select “Level” as a controlled system.
5. Switch the relay K1 ON.
6. Open the 2way ball-valve V102.
7. Select “A_OUT0 Pump” as a manipulated output.
8. Set the set point value into the controller.
9. Set the offset of a manipulated value to correspond the measured one in the Exercise 6.9.
10. Use values in the table for the “PI [math]” controller and start the execution.

Parameter	Value	Parameter	Value
K_P	2	T_I	10
K_P	2	T_I	5
K_P	5	T_I	10
K_P	5	T_I	5

List of parameters

Note

Because of the value of time for the I-controller is not combined with any other control element we will call it “integral time” T_I.

Questions

- How does the system respond with closed-loop control using a PI-controller?
- How does the system respond when you change the set point in small steps around the operating point or close valve V112 or open valve V104 slightly?
- Which PI parameter pair results in the smallest overshoot and/or shortest setting time?
- What happens when changing from the parallel structure PI-controller to the standard PI-controller?

6.12 Exercise – Optimising a PI-controller for a level control system

Information

The fill level control system is an I-controlled system. It is very important to find the optimal controller parameters for the system to be controlled very quickly.

In the course of time, numerous methods have been developed for the calculation of controller parameters. However, it depends on the closed-loop control system whether a method is suitable for the calculation of parameter values.

Task

Calculate the control parameters for a PI-controller using the parameters determined in the Exercise 6.10 and run the level control system with them.

Parameter	K_P	T_i
PI	$K_P = \dfrac{0{,}35}{K_{IS} \times T_t}$	$T_i = 1{,}2 \times T_t$

Parameter	K_P	T_i
PI		

Preparation

1. Fill the lower tank with approx. 10l of water.
2. Open manual valves V101, V112.
3. Start FluidLab®-PA closed loop – choose menu “Closed-loop Control - continuous”.
4. Select “Level” as a controlled system.
5. Switch the relay K1 ON.
6. Open the 2way ball-valve V102.
7. Select “A_OUT0 Pump” as a manipulated output.
8. Set the set point value into the controller.
9. Set the offset of a manipulated value to correspond the measured one in the Exercise 6.9.
10. Use the determined values for the PI controller and start the execution.

Questions

- How does the system respond with the calculated parameters?

6.13 Exercise – Setting a PID controller for a level control system

Information

Before using a loop-tuning method the reaction of a control loop to changes has to be evaluated. There are two main performances:

- Behavior of the process value following a setpoint change.
- Behavior of the process value following a disturbance.

The following criteria are used to specify the two behaviors:

- Rise time – the time between a set point change and the first crossing of the setpoint.
- Overshoot time – the ratio of the magnitude of the first overshoot above set point to the magnitude of the setpoint itself.
- Settling time – the time, following a setpoint change or disturbance, that it takes for an oscillation to become so small that the deviation does not exceed some specified amount.
- Percentage deviation from setpoint specified.

Task

Control the system by means of a PID controller.

Preparation

1. Fill the lower tank with approx. 10l of water.
2. Open manual valves V111, V112.
3. Start FluidLab®-PA closed loop – choose menu “Closed-loop Control - continuous”.
4. Select “Level” as a controlled system.
5. Switch the relay K1 ON.
6. Open the 2way ball-valve V102.
7. Select “A_OUT0 Pump” as a manipulated output.
8. Set the set point value into the controller.
9. Set the offset of a manipulated value to correspond the measured one in the Exercise 6.9.
10. Use the determined values for the PID controller and start the execution.

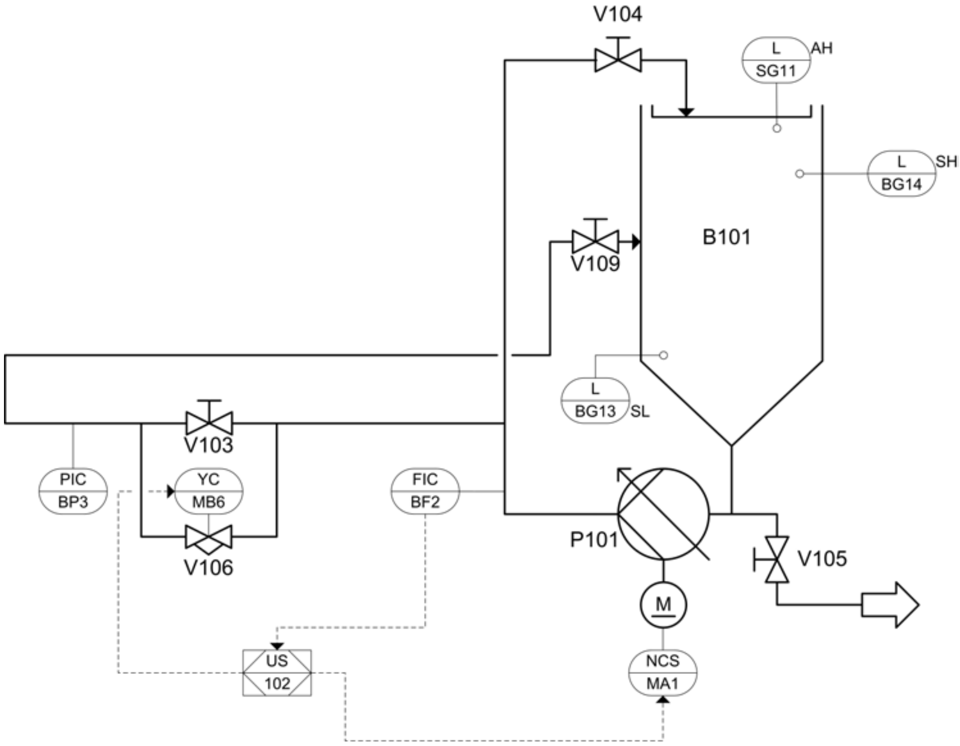
Parameter	Value
K_P	10
T_i	5
T_d	0

Questions

- How does the system respond with the outlet valve open?
- How does the system respond with the outlet valve closed?

Module 7 – Operating, identifying and analyzing a flow control system

7.1 Introduction



PI diagram for a flow rate control system

Information

The function of the flow rate controlled system is to regulate the flow rate of a fluid.

The pump P101 delivers a fluid from a storage tank B101 back to the storage tank B101 via a piping system. The flow of the fluid is measured with a flow sensor at PCE task FIC B102. The actual value should be kept within a certain range even in the event of disturbances or set point changes.

The fluid quantity of the pump P101 is the manipulated value. Disturbances can be simulated by partly or totally closing the manual valve V104.

All the exercises in the workbook and the preparation of solutions are done with the usage of EasyPort and FluidLab®-PA closed-loop software.

7.2 Exercise – Analysis of flow rate parameters

Information

The flow rate of the process is measured with an electro-magnetic flow sensor. The instrumentation is based on the Faraday's induction principle, to measure the flow velocity of an electrically conductive medium in a defined pipe diameter. An integrated measuring transducer converts the voltage difference of the conductive medium into a standard voltage signal. The sensor displays the actual flow value. The voltage signal will be displayed in Fluid Lab®-PA closed-loop as a physical flow rate value. Determine the parameter settings so that the displayed flow rate value in the software matches with the display of the sensor.

Tasks: Setup of the electromagnetic flow sensor

1. Check the settings of the sensor at the display by using the manual:

…\MPS-PA_Compact-Workstation\Technical Documentation\English\Manuals\
8079872_en_flow-sensor_manual.pdf

	Factory setting	User setting
OU2 - Analogue output signal	I	U
AEP - Analogue end value for volumetric flow	25.00	10.00

2. Open manual valve V104 and activate the pump. (Simbix, Easyport, PLC)
3. Change the opening of V104 take 3 of measurements and enter these into the chart.

No.	Volumetric flow (Sensor-display)	Voltage output (Channel 1/CH1)
1		
2		
3		

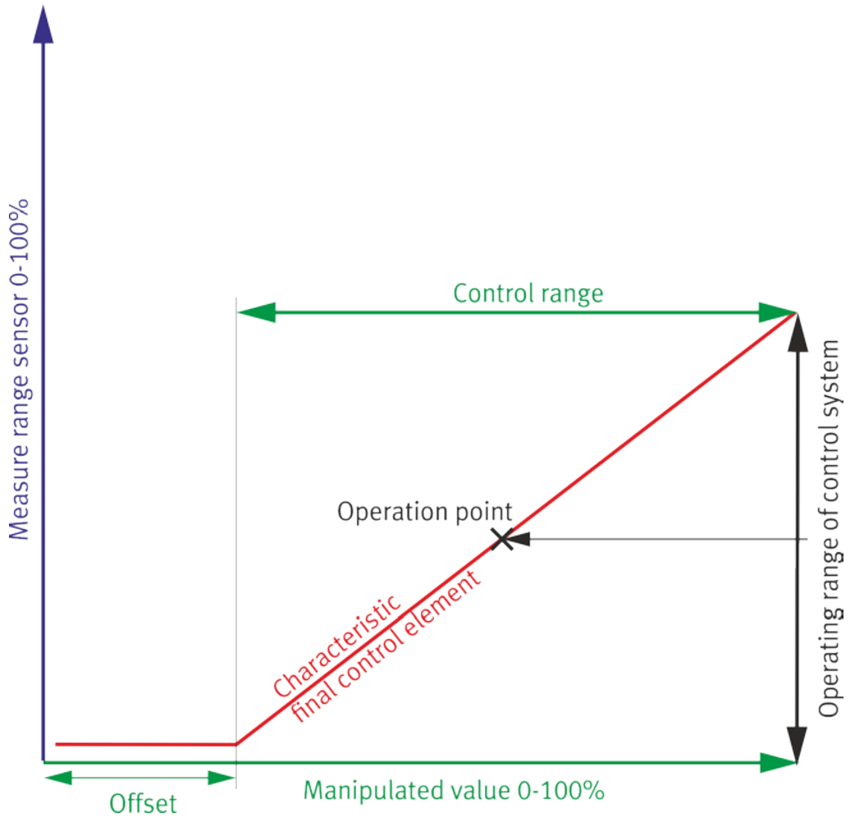
4. Calculate factor and offset

No.	Task	Value	Value
1	Max. phys. Value	MPV	
2	Voltage at max. phys. Value	VMP	
3	Min. phys. Value	LPV	
4	Voltage at min. phys. Value	VLP	
5	Set factor and offset: Factor= (MPV - LPV)/(VMP - VLP) Offset= LPV - Factor • VLP	Factor	Offset
6	Insert calculated factor and offset settings into "Setup" menu at FluidLab-PA closed-loop.		
7	Control task: Measure timing! Fill Tank B102 up to 2 litres.	Time to fill: 1. Volumetric flow in software 2. Volumetric flow on sensor display 3. Calculated volumetric flow	 1. 2. 3.

7.3 Exercise – Identifying the operating range of a flow control system

Information

The goal of the task is to use an automatic loop controller. The reference variable is measured by a sensor.
The control of the pump should be done by means of the loop controller.
To optimize the control behavior, the actuator's existing offset should be compensated.
The following diagram describes the main terms concerning the Characteristics curve analysis.



It is essential to identify the operating range of the controlled system. Operating range determines the minimum and maximum values possible in the process for the regulated quantity, i.e. flow rate. With this information, the operating point can be determined.
In the flow rate controlled system the operating point shall be in the middle of the operating range. Normally the operating point is chosen according to the requirements of the process.
Offset of the curve determines the voltage range of the final control element when there is no change in the regulated quantity. The offset can be adjusted for the final control element which results in more optimised control system.
Control range is the range of the final control element without offset. That also equals to the 0-100% output of the controller.

Problem

Carry out the following series of measurements for determining the operating range of a flow rate control system and the control range of pump.

Preparation

1. Fill/empty the lower tank to approx. 5l of water.
2. Open manual valve V104.
3. Start FluidLab®-PA closed loop – choose menu "Characteristics".
4. Select chart which displays flow rate in relation to pump voltage.
5. Switch the relay K1 ON.
6. Set measure time to 100s, choose "A_OUT0 Pump" as a manipulated output and start the execution.
7. Determine the offset in the beginning of the flow characteristic.
8. Determine the control range of the final control element and the operating range of the regulated quantity.
9. Enter the measured values in the tables.

Task

	Control range of pump **Manipulated variable [V]**	**Flow sensor** **Flow rate [l/min]**	**Messbereich Sensor** **[l/min]**	**Bezugsskala** **Regler**
Maximum measured value				1,0
Minimum measured value	Offset:			0,0

7.4 Exercise – Determining the working point of the controlled system

Information

For the design of the working point of control system the knowledge of the measuring range of the sensor and the working range of the control element or actuator is required.
In practice, the selection of the working point of a control system is based on process specifications. The measuring and actuator elements are then defined and selected.
As a default, the working point of the flow control system should be in the center of the working range of the actuator! The working point shall be in the middle of the working range.

Problem

Carry out the following series of measurements for determining the operating point of a flow rate control system.

Preparation

1. Determine the operating point of a flow rate on the basis of operating range and enter the value in the table.
2. Fill/empty the lower tank to approx. 5l of water.
3. Open manual valve V104.
4. Start FluidLab®-PA closed loop – choose menu “Measuring and Control”.
5. Select “Flow”, “A_OUT0 Pump” and “OUT” as measured values.
6. Select “A_OUT0 Pump” as a manipulated value and set the voltage for the pump.
7. Switch the relay K1 ON.
8. Start the execution and turn the “Contr. val.” Switch ON.
9. Determine the pump voltage for the operating point by manipulating the control signal in the terms of control range. Fill the voltage reading in the table.

Task

	Flow sensor **Flow rate [l/min]**	**Control range of pump** **Manipulated variable [V]**
Operating point		

Questions

- State the system conditions which could influence the flow rate control system.

7.5 Exercise – Identifying the behavior of the controlled system

Information

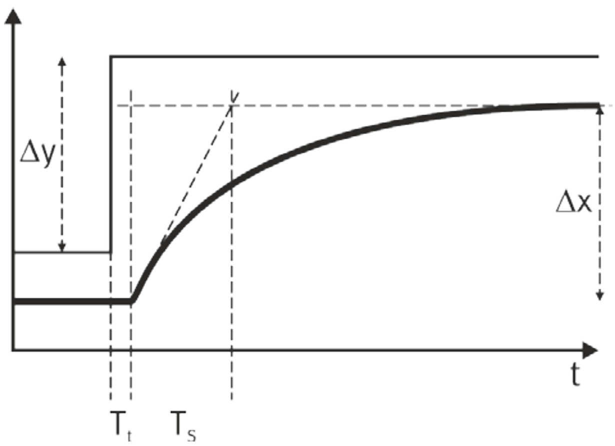
The time response of a controlled system must be known in order to selection and set the controller. The parameters of a controlled system are determined by establishing the step response of the system. In the case of controlled systems with time delay, the time constant is determined by means of applying a tangent or inflectional tangent in the case of higher order systems.

Task

Carry out the following series of measurements for determining the step response and the order of the flow rate controlled system.

Preparation

1. Fill the lower tank with approx. 5l of water.
2. Open manual valve V104.
3. Start FluidLab®-PA closed loop – choose menu "Measuring and Control".
4. Select "Flow", "A_OUT0 Pump" and "OUT" as measured values.
5. Select "A_OUT0 Pump" as a manipulated value.
6. Switch the relay K1 ON.
7. Adjust the pump control voltage to the operating point value.
8. Start the execution.
9. Turn the "Contr. val." Switch ON.
10. Identify the order of the controlled system by means of comparison with the following diagram.



Step response of a controlled systems with time delay and dead time

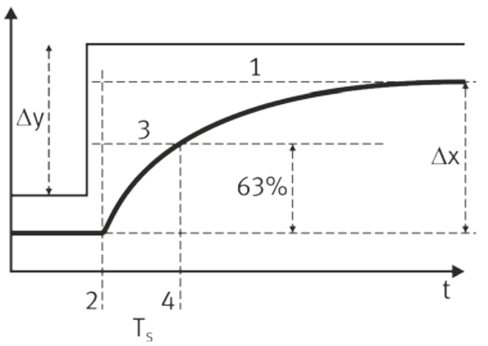
$$K_S = \frac{\Delta x}{\Delta y}$$

Messwert physikalisch	Dimensionslos 0…1
Δx = $\left[\frac{l}{\min}\right]$	Δx =
Δy = $[V]$	Δy =

Parameter	Value	Value without dimension
K_S	$\left[\frac{l/\min}{V}\right]$	
T_S	$[s]$	
T_t	$[s]$	

Please use the value without dimension for further exercises.

Procedure for graphically determining the time constant T_s of



1. Draw the 'maximum value' in the form of a horizontal line (1) at the maximum of curve.
2. Draw a vertical line (2) at the origin of the curve.
3. Draw a horizontal line (3) at 63% of the 'maximal value' of Δx.
4. Draw a vertical line (4) at the intersection of '63% value' and the curve.
5. On the timescale, determine the time period the system requires reaching 63%. This is the time constant Ts.
6. Determine the system gain Ks in the stationary (steady) state after the input step.

7.6 Exercise - Operating a P-I controller for a flow rate control system

Information

A continuous-action controller, in contrast to a two-position controller, has a continuous signal as manipulated variable which is generated in relation to the system deviation.

Task

Familiarize yourself with the mode of operation of different continuous-action controller types. Complete the table. The operating point determined in Exercise 7.4 is to be used as the set point value.

Parameter	Value [l/min]	Dimensionless value
Setpoint value (w) at operating point		

Check the response of the controlled system using different continuous-action controllers.

Disturbance
Close manual valve V104 more or less.

7.6.1 P controller

- Control the system by means of a P controller
- Consecutively set the gain K_P specified in the table.
- Record the control response for each value.

Preparation

1. Fill the lower tank with approx. 5l of water.
2. Open manual valve V104.
3. Start FluidLab®-PA closed loop – choose menu “Closed-loop Control - continuous”.
4. Select “Flow” as a controlled system.
5. Switch the relay K1 ON.
6. Select “A_OUT0” Pump as a manipulated output.
7. Select the P-controller and set the set point value into the controller.
8. Set the offset of a manipulated value to correspond the measured one in the Exercise 7.2.
9. Use values in the table for the P controller and start the execution.

Parameter	Value
K_P	1
K_P	2
K_P	5
K_P	10

List of parameters

Questions

- How does the system respond with closed-loop control using a P controller?
- How does the system respond when you change the set point in small steps around the operating point or close valve V104 slightly?

7.6.2 I controller

- Control the system by means of an I controller.
- Consecutively set the integral time T_I specified in the table.
- Record the control response for each value.

Preparation

1. Fill the lower tank with approx. 5l of water.
2. Open manual valve V104.
3. Start FluidLab®-PA closed loop – choose menu “Closed-loop Control - continuous”.
4. Select “Flow” as a controlled system.
5. Switch the relay K1 ON.
6. Select “A_OUT0 Pump” as a manipulated output.
7. Select I-controller and set the set point value into the controller.
8. Set the offset of a manipulated value to correspond the measured one in the Exercise 7.2.
9. Use values in the table for the I controller and start the execution.

Parameter	Value
T_I	10 s
T_I	5 s
T_I	2 s
T_I	1 s

T_I = Integral time

Note

Because of the value of time for the I controller is not combined with any other control element we will call it “integral time” T_I.

Questions

- How does the system respond with closed-loop control using an I controller?
- How does the system respond when you change the set point in small steps around the operating point or close valve V104 slightly?

7.6.3 PI controller

- Control the system by means of a PI standard controller.
- Consecutively set the gain K_P and the reset time T_i specified in the table.
- Record the control response for each value.

Preparation

1. Fill the lower tank with approx. 5l of water.
2. Open manual valve V104.
3. Start FluidLab®-PA closed loop – choose menu “Closed-loop Control - continuous”.
4. Select “Flow” as a controlled system.
5. Switch the relay K1 ON.
6. Select “A_OUT0 Pump” as a manipulated output.
7. Select PI-controller and set the set point value into the controller.
8. Set the offset of a manipulated value to correspond the measured one in the Exercise 7.2.
9. Use value pair from the table for the PI controller and start the execution.

Parameter	Value	Parameter	Value
K_P	1	T_i	2 s
K_P	1	T_i	1 s
K_P	2	T_i	2 s
K_P	2	T_i	1 s

T_i = reset time

Note

Because the value of time for the I controller is combined with another control element we will call it “reset time” T_i .

Questions

- How does the system respond with closed-loop control using a PI controller?
- How does the system respond when you change the set point in small steps around the operating point or close valve V104 slightly?
- Which PI parameter pair results in the smallest overshoot and/or shortest setting time?

7.7 Manual tuning of a PI controller for a flow rate control system

Information

Manual tuning of control parameter can be done without knowledge of system behavior. Please use a PI controller with series structure (EN 60025-6).

Task

Find the optimal controller parameters for the flow rate control system.

Note
All the changes to the controller parameters have to be done in "Manual" mode. Always set the "CO" that the control error is "0" before switching to "Automatic". To check the result, switch the controller to "AUTO" mode.

Preparation

1. Fill the lower tank with approx. 5l of water and open manual valve V104.
2. Start FluidLab®-PA closed loop – choose menu "Closed-loop Control - continuous".
3. Select "Flow" as a controlled system. Switch the relay K1 ON
4. Select "A_OUT0 Pump" as a manipulated output.
5. Set the offset of a manipulated value to correspond the measured one in the Exercise 7.3.
6. Tick the "bumpless" operation ON. Select the "Control values" window. Choose "Manual" operation and adjust the reference variable to correspond the operating point value.
7. The PI controller parameters for optimal closed-loop control of the system are not yet known in this case. To keep the control-loop steady, the following initial settings are to be carried out:

Controller	Parameter	Value
P component	Proportional coefficient	$K_P = 0{,}1$
I component	Reset time	$T_i = 500s$

Procedure

1. Start the execution.
2. In MANUAL-mode change the manipulated output so the control error is "0".
3. Switch to AUTO-mode and change reference variable in small steps around working point.
4. Gradually increase K_P (in MANUAL) until the control loop (in AUTO) tends to oscillate at small changes of the reference variable.
5. Slightly reduce K_P until the oscillations are eliminated.
6. Reduce T_i until the control-loop tends to oscillate again.
7. Increase T_i until the tendency to oscillate is eliminated.

Questions

- What are the values determined for K_P and T_i?
- What criteria do you use to evaluate your result?

•

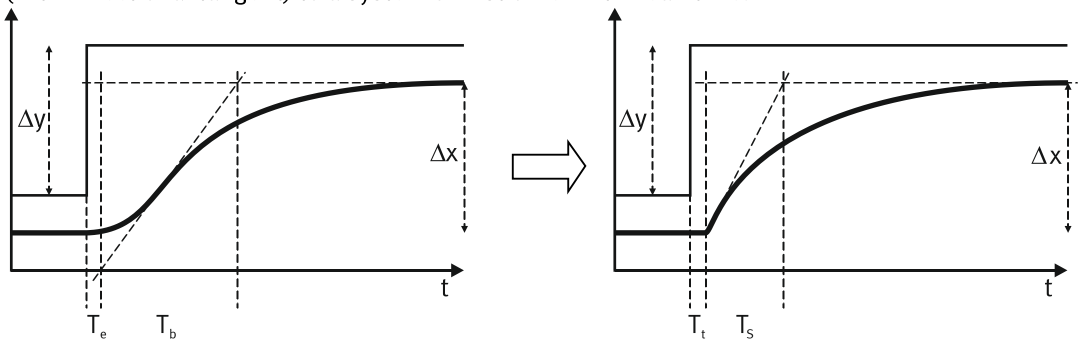
7.8 Loop tuning with step response method

Information

In the initial phase of modern closed-loop control technology J. G. Ziegler and N.B. Nichols established tuning rules which are still frequently used today. They are based on the following idea: Make a simple experiment, extract some features of process dynamics from the experimental data, and determine controller parameters from the features.
This second method is based on the open-loop step response, which is characterized by three parameters:

- system stationary gain: K_s
- system time constant: T_s
- dead time: T_t

Requirement for this method is a stabile control system. The method transfers a system with higher order (with inflectional tangent) to a system of first order with dead time.



Δy = step of control voltage (in % of full range) / Δx= response of system (in % of full scale)

Procedure

1. Carry out the step response by changing the controller output to the obtained output value at operating point of the flow controlled system.
2. Document the step response and identify graphically dead time T_t and time constant T_s.
3. Calculate the system gain K_s.
4. Calculate from the obtained parameters the controller values for proportional gain Kp and reset time Ti with the given formulas.

Control parameter	K_P	T_i
PI-Regler	$K_p = \frac{0{,}9}{K_s} \cdot \frac{T_S}{T_t}$	$T_i = 3{,}3 \cdot T_t$

Document your calculation in your logbook!

7.9 Exercise – Setting a PID controller for a flow rate control system

Task

Commission the flow rate controlled system with a PID controller with given parameter values.

Preparation

1. Fill the lower tank with approx. 5l of water.
2. Open manual valve V104.
3. Start FluidLab®-PA closed loop – choose menu “Closed-loop Control - continuous”.
4. Select “Flow” as a controlled system.
5. Switch the relay K1 ON.
6. Select “A_OUT0 Pump” as a manipulated output.
7. Set the set point value into the controller.
8. Set the offset of a manipulated value to correspond the measured one in the Exercise 7.3.
9. Use values in the table for the PID controller and start the execution.

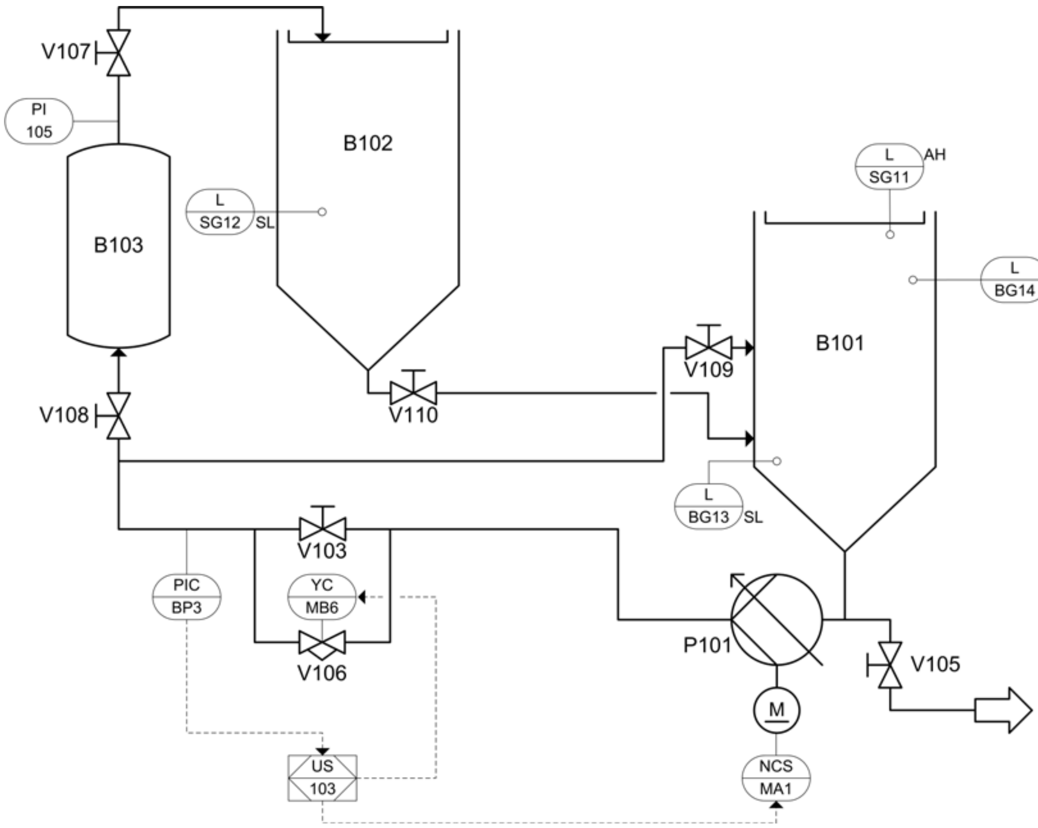
Parameter	Value
K_P	1
T_i	2
T_d	0.5

Questions

- How does the system respond when you change the set point in small steps or close valve V104 slightly?

Module 8 - Operating, identifying and analyzing a pressure control system

8.1 Introduction



PI diagram for a pressure control system

Information

The function of the pressure controlled system is to regulate the pressure of a fluid.

The pump P101 delivers a fluid from a storage tank B101 to the pressure tank B103 via a piping system. The pressure of the fluid is measured with a pressure sensor at PCE task 'PIC BP3'. The actual value should be kept within a certain range even in the event of disturbances or set point changes.
The pump P101 is the manipulated value which regulates the pressure in the pipe system. Disturbances can be simulated by slightly opening the manual valve V109.

All the exercises in the workbook and the preparation of solutions are done with the usage of EasyPort and FluidLab®-PA closed-loop software.

8.2 Exercise - Commissioning the pressure reservoir

Information

The pressure reservoir in the system damps the rise rate of pressure for smooth controlling. It can be thought as a spring and the amount of liquid in it affects the damping effect. More liquid in the reservoir, more stiff "the spring" is, which leads to slower rise of the pressure. During the exercises the pressure reservoir has to be filled approx. half way.

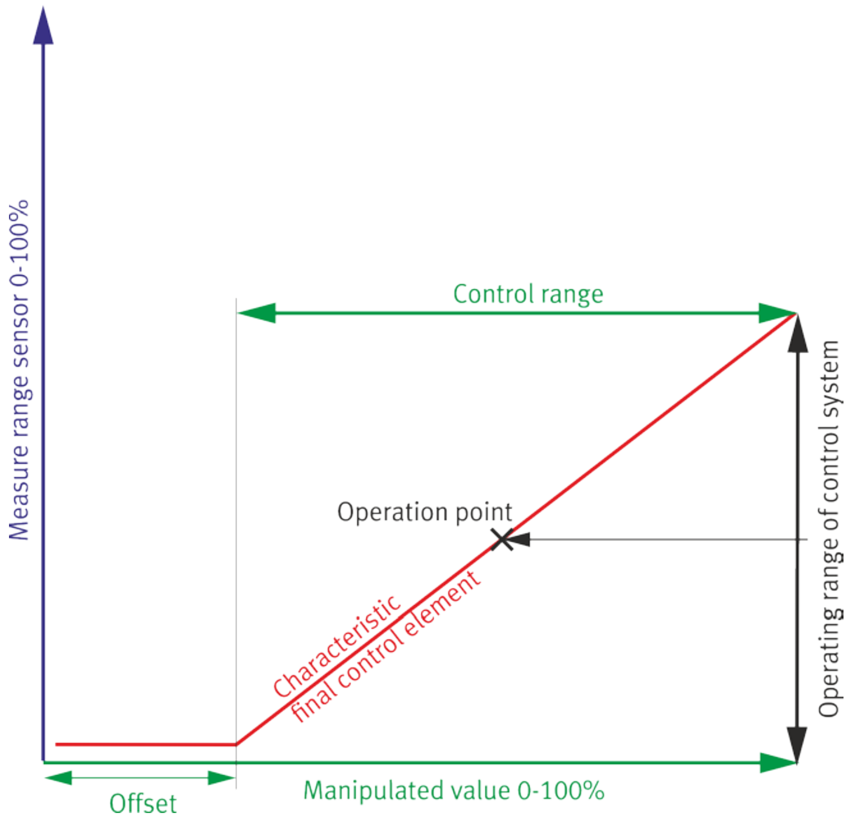
Preparation

1. Fill the lower tank with approx. 5l of water.
2. Open manual valves V103, V107 and V108.
3. Start FluidLab®-PA closed loop – choose menu "Setup".
4. Switch the pump motor binary ON (DQ3=1) so that the pressure reservoir gets filled with liquid.
5. Close the manual valve V107 when the transparent pipe is filled completely.
6. Switch the motor binary OFF (DQ3=0) and check the level of the liquid in the transparent pipe.
7. Repeat steps 4-6 until the water level in the pipe is approx. half way.
8. Leave V107 closed, V108 and V103 open for the rest of the exercises.

8.3 Exercise – Analysis working range of the controlled system

Information

The following diagram describes the main terms concerning the characteristics curve analysis of a final control element.



It is essential to identify the operating range of the controlled system. Operating range determines the minimum and maximum values possible in the process for the regulated quantity, i.e. pressure. With this information, the operating point can be determined.

In the pressure controlled system the operating point shall be in the middle of the operating range. Normally the operating point is chosen according to the requirements of the process.

Offset of the curve determines the voltage range of the final control element when there is no change in the regulated quantity. The offset can be adjusted for the final control element which results in more optimized control system.

Control range is the range of the final control element without offset. That also equals to the 0-100% output of the controller.

Task

Carry out the following series of measurements for determining the operating range of a pressure control system and the control range of pump.

Preparation

1. Fill the lower tank with approx. 5l of water.
2. Open manual valves V103 and V108. Close all others.
3. Start FluidLab®-PA closed loop – choose menu "Characteristics".
4. Select chart „p[bar] / U[V]".
5. Switch the relay K1 ON (DQ2).
6. Set measure time to 100s, choose "A_OUT0 Pump" as a manipulated output and start the execution.
7. Determine the offset in the beginning of the pressure characteristic.
8. Determine the control range of the final control element and the operating range of the regulated quantity.
9. Enter the measured values in the table.

Task

	Control range of pump **Manipulated variable [V]**	**Pressure sensor** **Pressure [bar]**	**Measure range** **Sensor [bar]**	**Reference scale** **Controller**
Maximum measured value				1,0
Minimum measured value	Offset:			0,0

8.4 Exercise – Determining the working point of the controlled system

Information

For the design of the working point of the rule stretch, knowledge of the measuring range of the sensor and the working area of the control line or actuator is required.
In practice, the selection of the working point of a control system is based on process specifications. The measuring and actuator elements are then defined and selected.
As a default, the working point of the pressure control system should be in the center of the working range of the actuator! The working point shall be in the middle of the working range.

Problem

Carry out the following series of measurements for determining the operating point of a flow rate control system.

Preparation

1. Determine the operating point of the pressure value in the middle of the operating range and enter the value in the table.
2. Fill/empty the lower tank to approx. 5l of water.
3. Open manual valves V103 and V108. Close all others.
4. Start FluidLab®-PA closed loop – choose menu “Measuring and Control”.
5. Select “Pressure”, “A_OUT0 Pump” and “OUT” as measured values.
6. Select “A_OUT0 Pump” as a manipulated value and set the voltage for the pump.
7. Switch the relay K1 ON.
8. Start the execution and turn the “Contr. val.” Switch ON.
9. Determine the pump voltage for the operating point by manipulating the control signal in the terms of control range. Fill the reading in the table.

Task

	Pressure sensor **Pressure [bar]**	**Control range of pump** **Manipulated variable [V]**
Operating point		

Questions

- State the system conditions which could influence the pressure control system.

8.5 Exercise – Identify a pressure control system

Information

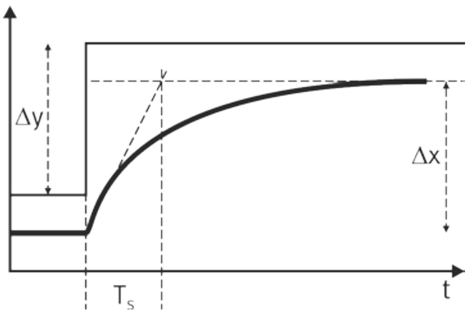
The time response of a controlled system must be known in order to make an optimal controller selection. Information can then be derived from this regarding the dynamics of the controlled system and the controller setting defined.
The time response of a controlled system is established by determining the step response of the system. In the case of controlled systems with time delay, e.g. energy storage, the time constant of a controlled system is determined by means of applying a tangent or inflectional tangent (with several time delays) to the step response curve.

Task

Carry out the following series of measurements for determining the step response and the order of the pressure controlled system.

Preparation

1. Fill the lower tank with approx. 5l of water.
2. Open manual valves V103 and V108. Close all others.
3. Start FluidLab®-PA closed loop – choose menu “Measuring and Control”.
4. Select “Pressure”, “A_OUT0 Pump” and “OUT” as measured values.
5. Select “A_OUT0 Pump” as a manipulated value.
6. Switch the relay K1 ON.
7. Adjust the pump control voltage to the operating point value.
8. Start the execution.
9. Turn the “Contr. val.” switch ON.
10. Identify the order of the controlled system by means of comparison with the following diagram.



Controlled systems with time delay

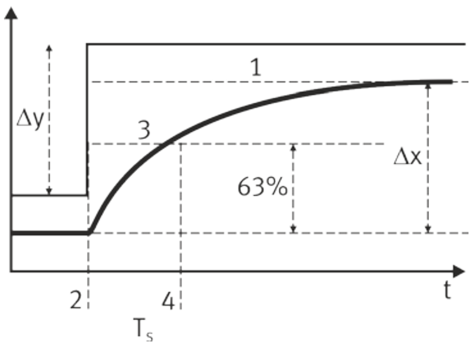
$$K_S = \frac{\Delta x}{\Delta y}$$

Measure value physical		Dimensionless 0…1
Δx =	$\left[\frac{l}{min}\right]$	Δx =
Δy =	$[V]$	Δy =

Value, physical		Dimensionless value
K_S =	$\left[\frac{l/min}{V}\right]$	K_S =
T_S =	$[s]$	

Use the dimensionless values for following exercises.

Procedure for graphically determining the time constant T_s of



1. Draw the ‘maximum value’ in the form of a horizontal line (1) at the maximum of curve.
2. Draw a vertical line (2) at the origin of the curve.
3. Draw a horizontal line (3) at 63% of the ‘maximal value’ of Δx.
4. Draw a vertical line (4) at the intersection of ‘63% value’ and the curve.
5. On the timescale, determine the time period the system requires reaching 63%. This is the time constant T_s.
6. Determine the system gain K_s in the stationary (steady) state after the input step.

8.6 ›Exercise - Operating a P-I controller for a pressure control system

Information

A continuous-action controller, in contrast to a two-position controller, has a continuous manipulated variable. This is calculated in relation to the system deviation.

Task

Familiarize yourself with the modes of operation of the various continuous-action controller types.

- Complete the table. The operating point determined in Exercise 8.4 is to be used as set point value.

Parameter	Value [bar]	Dimensionless value
Setpoint value (w) at operating point		

- Test the response of the controlled system using different continuous-action controllers.

Disturbance

Open manual valve V109 slightly.

8.6.1 P controller

- Control the system by means of a P controller
- Consecutively set the gain K_P specified in the table.
- Record the control response for each value.

Preparation

1. Fill the lower tank with approx. 5l of water.
2. Open manual valves V103 and V108. Close all others.
3. Start FluidLab®-PA closed loop – choose menu “Closed-loop Control - continuous”.
4. Select “Pressure” as a controlled system.
5. Switch the relay K1 ON.
6. Select “A_OUT0 Pump” as a manipulated output.
7. Set the set point value into the controller.
8. Set the offset of a manipulated value to correspond the measured one in the Exercise 8.3.
9. Use values in the table for the P controller and start the execution.

Parameter	Value
K_P	0,5
K_P	1
K_P	2
K_P	2,5

List of parameters

Questions

- How does the system respond with closed-loop control using a P controller?
- How does the system respond when you change the set point in small steps or open valve V109 slightly?

8.6.2 I controller

- Control the system by means of an I controller.
- Consecutively set the integral time T_I specified in the table.
- Record the control response for each value.

Preparation

1. Fill the lower tank with approx. 5l of water.
2. Open manual valves V103 and V108. Close all others.
3. Start FluidLab®-PA closed loop – choose menu “Closed-loop Control - continuous”.
4. Select “Pressure” as a controlled system.
5. Switch the relay K1 ON.
6. Select “A_OUT0 Pump” as a manipulated output.
7. Set the set point value into the controller.
8. Set the offset of a manipulated value to correspond the measured one in the Exercise 8.3.
9. Use values in the table for the I controller and start the execution.

Parameter	Value
T_I	5
T_I	2
T_I	1
T_I	0,5

List of parameters

Note

Because of the value of time for the I controller is not combined with any other control element we will call it “integral time” T_I .

Questions

- How does the system respond with closed-loop control using an I controller?
- How does the system respond when you change the set point in small steps or open valve V109 slightly?

8.6.3 PI controller

- Control the system by means of a PI standard controller.
- Consecutively set the gain K_P and the reset time T_i specified in the table.
- Record the control response for each value.

Preparation

1. Fill the lower tank with approx. 5l of water.
2. Open manual valves V103 and V108. Close all others.
3. Start FluidLab®-PA closed loop – choose menu “Closed-loop Control - continuous”.
4. Select “Pressure” as a controlled system.
5. Switch the relay K1 ON.
6. Select “A_OUT0 Pump” as a manipulated output.
7. Set the set point value into the controller.
8. Set the offset of a manipulated value to correspond the measured one in the Exercise 8.3.
9. Use values in the table for the PI controller and start the execution.

Parameter	Value	Parameter	Value
K_P	1	T_i	2
K_P	1	T_i	1
K_P	2	T_i	2
K_P	2	T_i	1

List of parameters

Note

Because the value of time for the I controller is combined with another control element we will call it “reset time” T_i .

Questions

- How does the system respond with closed-loop control using a PI controller?
- How does the system respond when you change the set point in small steps or open valve V109 slightly?
- Which PI parameter pair results in the smallest overshoot and/or shortest setting time?

8.7 Exercise – Setting a PID controller for a pressure control system

Task

- Commission the pressure control system with pump with set values for the control parameters.

Preparation

1. Fill the lower tank with approx. 5l of water.
2. Open manual valves V103 and V108. Close all others.
3. Start FluidLab®-PA closed loop – choose menu “Closed-loop Control - continuous”.
4. Select “Pressure” as a controlled system.
5. Switch the relay K1 ON.
6. Select “A_OUT0 Pump” as a manipulated output.
7. Set the set point value into the controller.
8. Set the offset of a manipulated value to correspond the measured one in the Exercise 8.3.
9. Use values in the table for the PID controller and start the execution.

Parameter	Value	Parameter	Value	Parameter	Value
K_P	1	T_i	1	T_d	1
K_P	1	T_i	2	T_d	1
K_P	1	T_i	2	T_d	5
K_P	1	T_i	5	T_d	1

Questions

- How does the system respond when you change the set point in small steps or open valve V109 slightly?

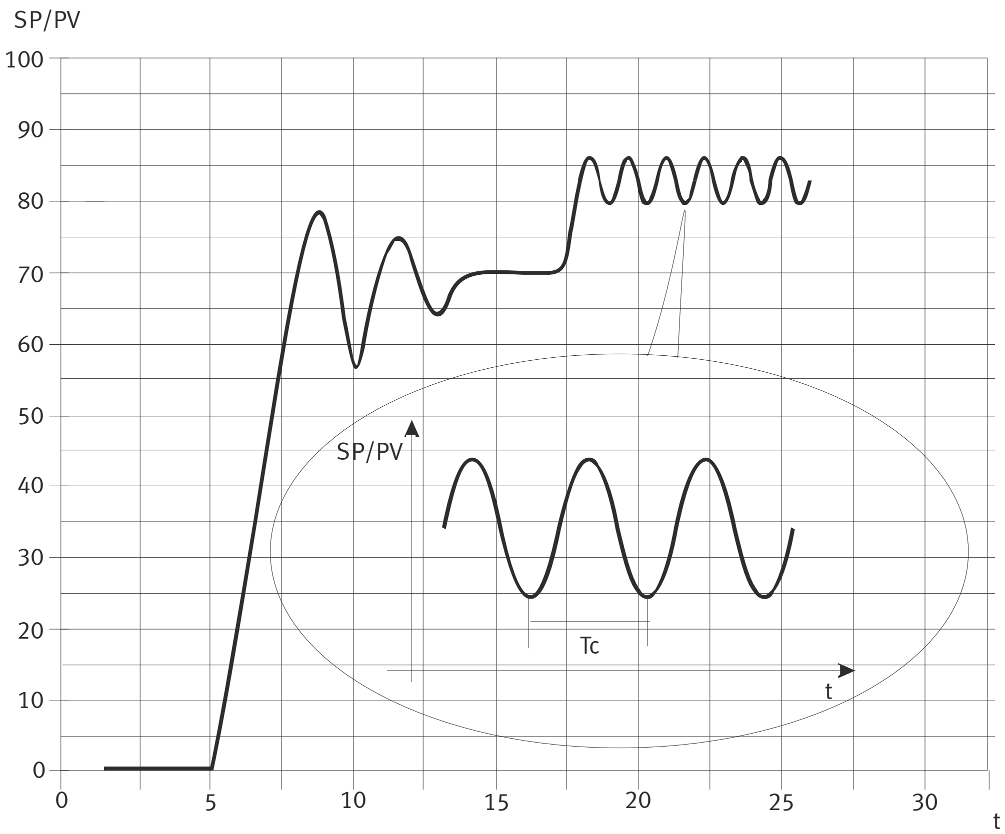
8.8 Exercise - Ziegler-Nichols tuning of a PID controller for a pressure control system

Information

Over the years, numerous methods have been developed to calculate controller parameters. However, it depends on the controlled system whether a particular method is suitable for the calculation of parameter values. A simple method of parameterization is the tuning method according to Ziegler-Nichols.

Preparation

1. Fill the lower tank with approx. 5l of water.
2. Open manual valves V103 and V108. Close all others.
3. Start FluidLab®-PA closed loop – choose menu “Closed-loop Control - continuous”.
4. Select “Pressure” as a controlled system. Switch the relay K1 ON.
5. Select “A_OUT0 Pump” as a manipulated output.
6. Set the offset of a manipulated value to correspond the measured one in the Exercise 8.3.
7. Tick the ”bumpless” operation ON.
8. Select the “Control values” window. Choose “Manual” operation and adjust the set point to correspond the operating point value. Set the “CO” to 0.
9. Select PI controller, set K_P =0,1 T_i =500s and start the execution.



Ziegler-Nichols oscillation method

> **Note**
>
> All the changes to the controller parameters have to be done in “Manual” mode. To check the result, switch the controller to “Automatic” mode. Always set the “CO” to 0 before switching to “Automatic”.

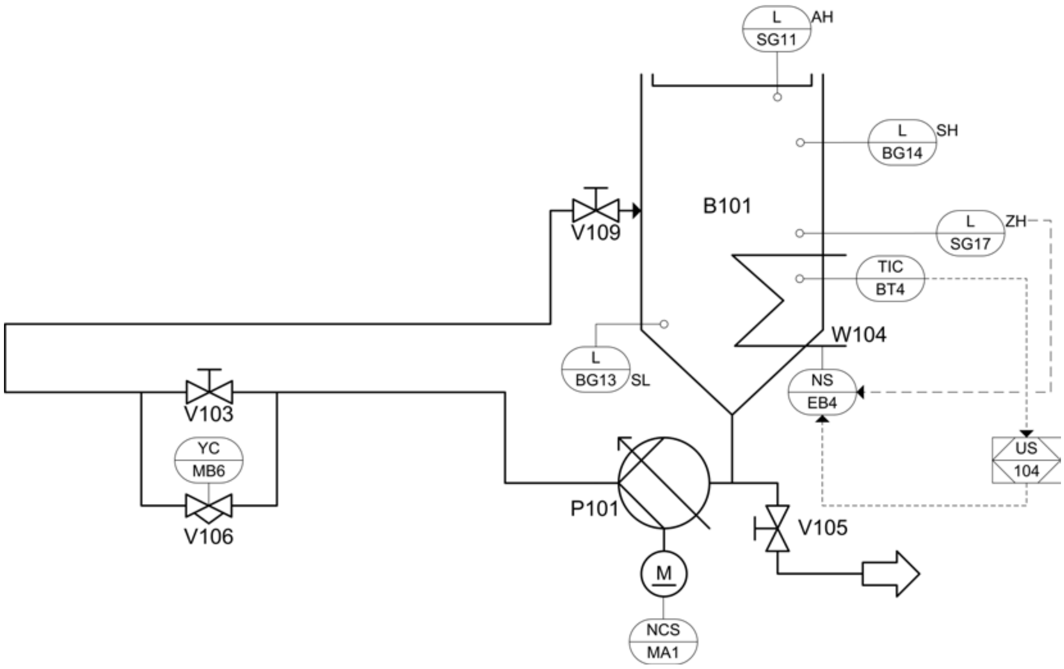
10. Slowly increase K_P until the critical proportional gain K_{pc} where the control loop periodically oscillates.
11. Determine K_{pc} and critical cycle duration T_c .
12. Set the desired controller by using the values for a PI-controller and record the control response.

Controller	K_P	T_i	T_d
PI	$0{,}45 \times K_{pc}$	$0{,}85 \times T_c$	-

Module 9 – Operating, identifying and analyzing a temperature control system

9.1 Introduction

The function of the temperature controlled system is to regulate the temperature of a fluid.



PI diagram for a temperature control system

The heating unit E104 stands as a manipulated value in the temperature control system. The temperature of the fluid is measured with a temperature sensor at PCE task TIC B104. The actual value should be kept within a certain range even in the event of set point changes. The pump P101 delivers a fluid from a storage tank B101 back to the storage tank B101 via a piping system so the fluid will be heated uniformly.

All the exercises in the workbook and the preparation of solutions are done with the usage of EasyPort and FluidLab®-PA closed-loop software.

9.2 Exercise – Analysis of temperature parameters

Information

The temperature of the process is measured with a temperature sensor. The resistance of the temperature sensor is converted with a measuring transducer PT100/U to a standard voltage signal. The voltage signal will be displayed in FluidLab®-PA closed-loop as a physical temperature value. Determine the parameter settings so that the displayed temperature value in the software matches with the process.

Note

Documentation:

- Datasheet: Temperature sensor
- Datasheet: Measuring transducer PT100/U

Procedure

1. Determine with the help of the datasheets the measure range of the temperature sensor and the transducer.
2. Research the resistance values of the sensor and transducer.

	Temperature sensor		Transducer		
	Temperature t [°C]	**Output resistance** R [Ω]	**Input resistance** R [Ω]	**Output signal** U [V]	**Temperature** t [°C]
MAX					
MIN					

3. Start FluidLab®-PA closed loop – choose menu “Setup”.
4. Determine the factor for the temperature voltage signal to display it as a physical value.

9.3 Exercise – Adjusting the cycle time

Information

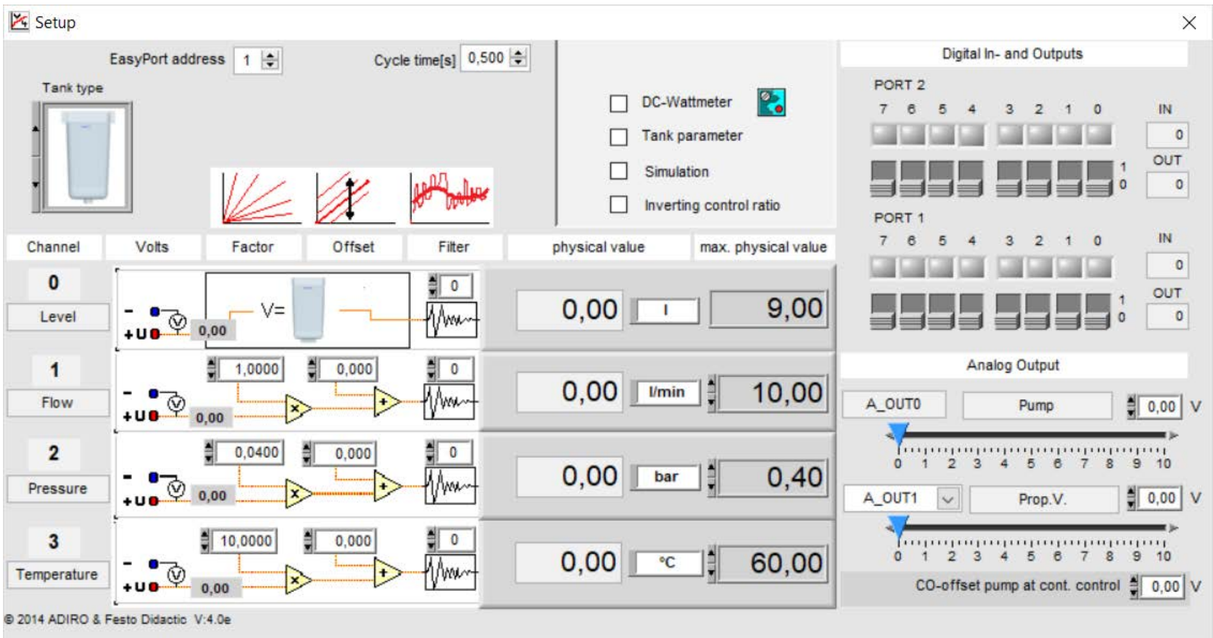
Because the temperature controlled system is a time consuming process, the cycle time of the program has to be adjusted so the diagrams printed are shown properly.

Task

Follow the instructions to setup the correct cycle time for FluidLab®-PA closed-loop software.

Preparation

1. Start FluidLab®-PA closed loop.
2. Choose menu "Setup".
3. Adjust the "Cycle time" of the program to 500 ms.



Adjusting the cycle time in FluidLab®-PA closed-loop.

9.4 Exercise – Determining the characteristics of a heating control system

Information

In order to determine the behavior of the heating system medium, you need to know the optimal measuring range of the temperature sensor and the operating range of the heater. This behavior changes depending on the medium that is heated.

Task

The power ON/Off time of the heating element EB4 is switches the heating power of the heater. Fill in the table.

Preparation

1. Fill the lower tank with approx. 4l of water. Empty the water into the upper tank.
2. Open manual valves V103 and V109.
3. Start FluidLab®-PA closed loop – choose menu “Measuring and Control”.
4. Select “Temperature” and “OUT” as measured values.
5. Switch the pump binary ON (DOUT3=1).
6. Select “DOUT1 Heating” as a manipulated value.
7. Start the execution and measure the temperature in the tank.
8. Terminate the execution and notice measure of the current temperature.
9. The current temperature is to be increased by 15K for the desired temperature.
10. Calculate the power P and pulse-width-modulation (in % of 1000W), if the desired temperature is to be reached in 600 seconds.

$$m \times c \times \Delta T = P \times t \times \eta$$

Symbol	Designation	Parameter	Value
EB4	Heater	Power P	.....................W
EB4	Heater	Pulse width %	.....................%
EB4	Heater	Efficiency factor η	0.8 (80%)
H_2O	Water	Specific heat capacity c	4182 J/(kg*K)
H_2O	Water	Minimum temperature(room temperature) T_{min}	.....................°C
H_2O	Water	Desired temperature T_{max}	.....................°C
H_2O	Water	Temperature difference ΔT	15 K
H_2O	Water	Measurement 1 mass m	4 l
-	-	Time t	600 s

11. Apply the calculated pulse width to the heater and set the time period to 10 s.
12. Clear the previous measurement and start the execution.
13. Turn the “Contr. val.” switch ON.
14. Record the characteristic curve until the desired temperature has been reached.
15. Compare the calculated values with the measured value.
16. Cool the water to room temperature.

Note: If necessary, replace the water with fresh cold water.

9.5 Exercise - Operating a 2-point controller

A two-point controller is also known as a Bang-Bang controller, hysteresis or On-off controller. A two-point controller in a closed loop system compares an operator specified set point parameter to the measured variable. It switches off the output when the set temperature is exceeded and switches it back on when the temperature falls below it.

Preparation

Use the reference value of preceding exercise and calculate the switching limits according to the given hysteresis.

Parameter	Value [°C]	Dimensionless value
Set point value (w) at operating point		

Parameter	Dimensionless value
Switching hysteresis	0.05
Upper switching limit	
Lower switching limit	

Task

1. Fill the lower tank with approx. 4l of water.
2. Open manual valves V103 and V109.
3. Start FluidLab®-PA closed loop – choose menu "Closed-Loop Control – 2-point".
4. Select "Temperature" as controlled system.
5. Select "DOUT1 Heating" as a manipulated value.
6. Turn the Pump binary ON (DOUT3=1) for circulation.
7. Set the set point value into the controller.
8. Use value in the table for the 2-point controller and start the execution.

Questions

- How does the system respond with a two-point controller?

9.6 Exercise - Operating a P-I controller for a temperature control system

Information

A continuous-action controller, in contrast to a two-position controller, has a continuous signal as manipulated variable which is generated according to the system deviation.

Task

Familiarize yourself with the mode of operation of different continuous-action controller types. Operate the heating with pulse-width-modulation:

- Complete the table. The operating point determined in Exercise 9.4 is to be used as the set point value.
- Cool the water down to room temperature and test the behavior of the controlled system using different continuous-action controllers.

Parameter	Value [°C]	Dimensionless value
Setpoint value (w) at operating point		

– Check the response of the controlled system using different continuous-action controllers.

Note

Instead of cooling down the water you can also replace it with cold water.
Before the next measure please check the temperature settling in tank B101.

Disturbance

Use cold water from the upper tank B102 or use the additionally available water-air-cooler or heat-exchanger with cooling unit.

9.6.1 P controller

- Control the system by means of a P controller.
- Set the gain K_P specified in the table.
- Record the control response for this value.

Task

1. Fill the lower tank with approx. 4l of water.
2. Open manual valves V103 and V109.
3. Start FluidLab®-PA closed loop – choose menu "Closed-Loop Control - continuous".
4. Select "Temperature" as controlled system.
5. Select "Heating PWM" as a manipulated value and set the time period to 10s.
6. Turn the Pump binary ON (DOUT3=1) for circulation.
7. Use value in the table for the P controller.
8. Set the set point value into the controller and start the execution.

Parameter	Value
K_p	10

Questions

- How does the system respond with closed-loop control using a P controller?

9.6.2 I controller

- Control the system by means of an I-controller.
- Consecutively set the integral time T_I specified in the table.
- Record the control response for each value.

Task

1. Fill the lower tank with approx. 4l of water.
2. Open manual valves V103 and V109.
3. Start FluidLab®-PA closed loop – choose menu "Closed-Loop Control - continuous".
4. Select "Temperature" as controlled system.
5. Select "Heating PWM" as a manipulated value and set the time period to 10s.
6. Turn the Pump binary ON (DOUT3=1) for circulation.
7. Complete the set point value table. The operating point will be 10K above the current temperature.
8. Set the set point value into the controller.
9. Use values in the table for the I-controller and start the execution.

Parameter	Value
T_I	100 s
T_I	20 s

List of parameters

Note

Because of the value of time for the I controller is not combined with any other control element we will call it "integral time" T_I .

Question

- How does the system respond with closed-loop control using an I controller?

9.6.3 PI controller

- Control the system by means of a PI standard controller.
- Consecutively set the gain K_P and the reset time T_i specified in the table.
- Record the control response for each value.

Preparation

1. Fill the lower tank with approx. 4l of water.
2. Open manual valves V103 and V109.
3. Start FluidLab®-PA closed loop – choose menu “Closed-Loop Control - continuous”.
4. Select “Temperature” as controlled system.
5. Select “Heating PWM” as a manipulated value and set the time period to 10s.
6. Turn the Pump binary ON (DOUT3=1) for circulation.
7. Complete the set point value table. The operating point will be 10K above the current temperature.
8. Set the set point value into the controller.
9. Use values in the table for the PI controller and start the execution.

Parameter	Value	Parameter	Value [s]
K_P	5	T_i	20 s
K_P	5	T_i	10 s

List of parameters

Note

Because the value of time for the I controller is combined with another control element we will call it “reset time” T_i .

Questions

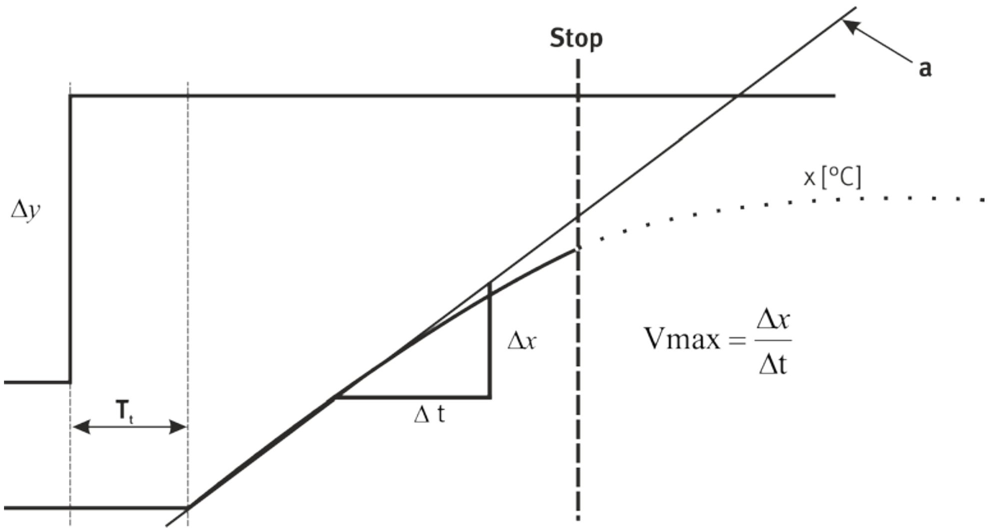
- How does the system respond react with closed-loop control using a PI controller?
- Which PI parameter pair results in the smallest overshoot and/or shortest setting time?

9.7 Exercise - Rate-of-rise tuning of a PID controller for a temperature control system

Information

The temperature control system of the station is a PT2 controlled system with mayor time delays. It is important find the optimal controller parameters in lowest test duration.

A simple and time-saving method of the parameterization is the rate-of-rise tuning method.
In the case of slow control systems with compensation, at least second order, a time-saving optimization method for the control parameters of a P-i-D controller can be applied by any step response of the manipulated value. The step with a certain size is switched on to the system until the change in the control variable has the maximum steepness.



Recording of the control variable with the state-of-rise method

Task

Carry out the following optimization procedure.

1. Fill the lower tank with approx. 4l of water.
2. Open manual valves V103 and V109.
3. Start FluidLab®-PA closed loop – choose menu “Closed-Loop Control - continuous”.
4. Select “Temperature” as controlled system.
5. Select “Heating PWM” as a manipulated value and set the time period to 10s.
6. Turn the Pump binary ON (DOUT3=1) for circulation.
7. Select the “Control values” window. Choose “Manual” operation and adjust the manipulated variable to Δy = 40 % controller and start the execution.
8. Determine the step response.
9. Stop execution if the maximum steepness of the curve is reached.
10. Print out curve and draw an inflectional tangent line (a).
11. Draw a slope triangle.
12. Determine the maximum state of rise V_{max} and the equivalent dead time T_e.
13. Insert the values for V_{max} and T_e into the formula for a PI-controller and calculate the controller parameters of the controller structure (see following table).

$$V_{\max} = \frac{\Delta x}{\Delta t}$$

Controller structure	Control parameters	Description
P	$K_P = \frac{\Delta y}{V_{MAX} \times T_U \times y_H}$	y_H = Maximum correcting range usually: 100%, no value limitation Δy = Specified step height. In this case equals to the PWM of the heating unit (40%).
PI	$K_P = \frac{\Delta y}{1.2 \times V_{MAX} \times T_U \times y_H}$ $T_i = 3.3 \times T_U$	
PID	$K_P = \frac{\Delta y}{0.83 \times V_{MAX} \times T_U \times y_H}$ $T_i = 2 \times T_U$ $T_d = 0.5 \times T_U$	

Formulas for the optimization of control parameters according to ramp response for compensated controlled systems (›PT2)

Questions

- What are the values determined for K_P and T_i?
- What criteria do you use to evaluate your results?

9.8 Exercise – Setting a PID controller for a temperature control system

Information

Acquaint yourself with the operation and parameterization of your controller.
Commission the temperature control system with heater and use given Parameters for the loop controller.

Task

1. Fill the lower tank with approx. 4l of water.
2. Open manual valves V103 and V109.
3. Start FluidLab®-PA closed loop – choose menu “Closed-Loop Control - continuous”.
4. Select “Temperature” as controlled system.
5. Select “Heating PWM” as a manipulated value and set the time period to 10s.
6. Turn the Pump binary ON (DOUT3=1) for circulation.
7. Complete the set point value table. The operating point will be 5K above the current temperature.
8. Set the set point value into the controller.
9. Use values in the table for the PID controller and start the execution.

Parameter	Value [°C]	Dimensionless value
Set point value (w) at operating point		

Parameter	Value
Kp	10.0
T_i	500.0 s
T_i	0.2 s

Question

- How does the system respond react with closed-loop control using a PI controller?

Module 10 – Loop tuning

10.1 Loop tuning methods for control loops with P-I-D controller

A PID controller can be adjusted to provide the desired behavior for a wide variety of process applications though change 1 to 3 parameters. That can be done with or without modest knowledge of the process. If it is done without knowledge of the process it should be at least done by using a common method to reduce adjustment error.

There are primary techniques to be discovered:

- Trail-and-error tuning
- Tuning based on open-loop test data
- Tuning based on closed-loop test data
- Improving “as found” tuning (intelligent “trial-and-error”)

Technical closed-loop control is part of automated systems, whose tasks is to stabilize processes. They are used:

• to establish certain process states (operating modes) and maintain them automatically,
• to eliminate the effect of disturbances on the process,
• as well as to prevent unwanted coupling of partial processes in the technical process.

The mentioned process states mainly concern certain process parameters such as pressure, flow, temperature and level.

A fundamental question is the optimization of controller settings:
"Which controller is suitable for which controlled system?"

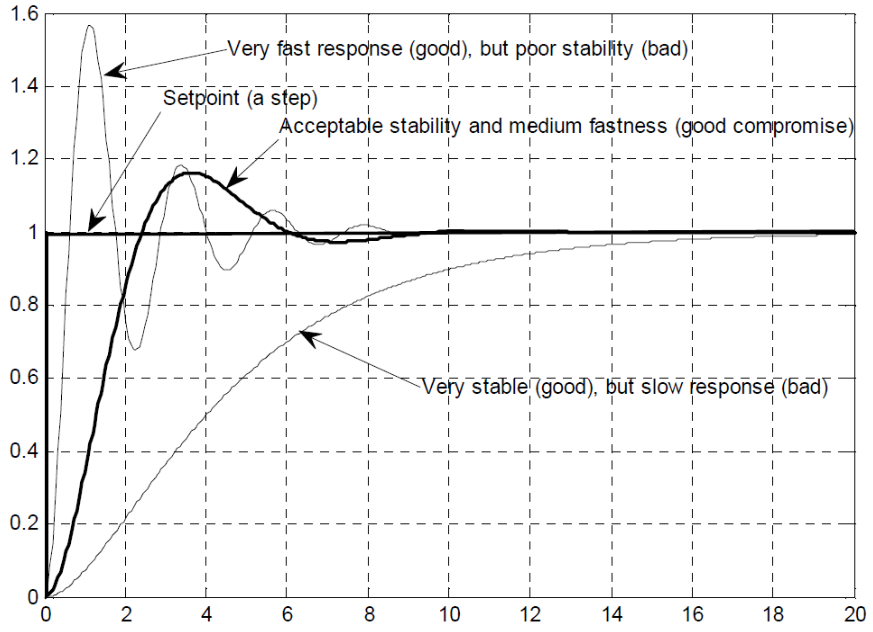
Therefore what is the aim of controller tuning? If it was possible to obtain, we would like to have both:

- fast responses of the process value and
- good system stability.

Unfortunately, for practical systems these two wishes cannot be achieved simultaneously:

- the faster response, the worse stability and
- the better the stability the slower response.

So we have to look for a compromise: Acceptable stability and medium fastness of response!



Example for control behaviour.

10.2 Manual tuning of control parameters (with knowledge of the system behaviour)

Information

In this case, the control parameters for optimal control of the system are not known. The following settings must be carried out in order to maintain control loop stability under all conditions:

P component	Proportional coefficient	Kp = 0.1
I component	Reset time	Tr = 500 s
D component	Derivative-action time	Td = 0

P controller

1. Set the desired setpoint value and manually reduce the system deviation to zero.
2. Switch to automatic mode.
3. Slowly increase Kp until the control loop is inclined to oscillate as a result of small setpoint value changes.
4. Slightly reduce Kp until the oscillations are eliminated.

PI controller

1. Set the desired setpoint value and manually reduce the system deviation to zero.
2. Switch to automatic mode.
3. Slowly increase Kp until the control loop is inclined to oscillate as a result of small setpoint value changes.
4. Slightly decrease Kp until the oscillations are eliminated.
5. Reduce Tr until the control loop is inclined to oscillate again.
6. Slightly increase Tr until the tendency to oscillate is eliminated.

PD controller

1. Set the desired setpoint value and manually reduce the system deviation to zero.
2. Switch to automatic mode.
3. Slowly increase Kp until the control loop is inclined to oscillate as a result of small setpoint value changes.
4. Switch Td from 0 to 1s.
5. Increase Td until the oscillations are eliminated.
6. Slowly increase Kp until the oscillations recur.
7. Repeat the setting in steps 5 and 6 until the oscillations can no longer be eliminated.
8. Slightly decrease Td and Kp until the oscillations are eliminated.

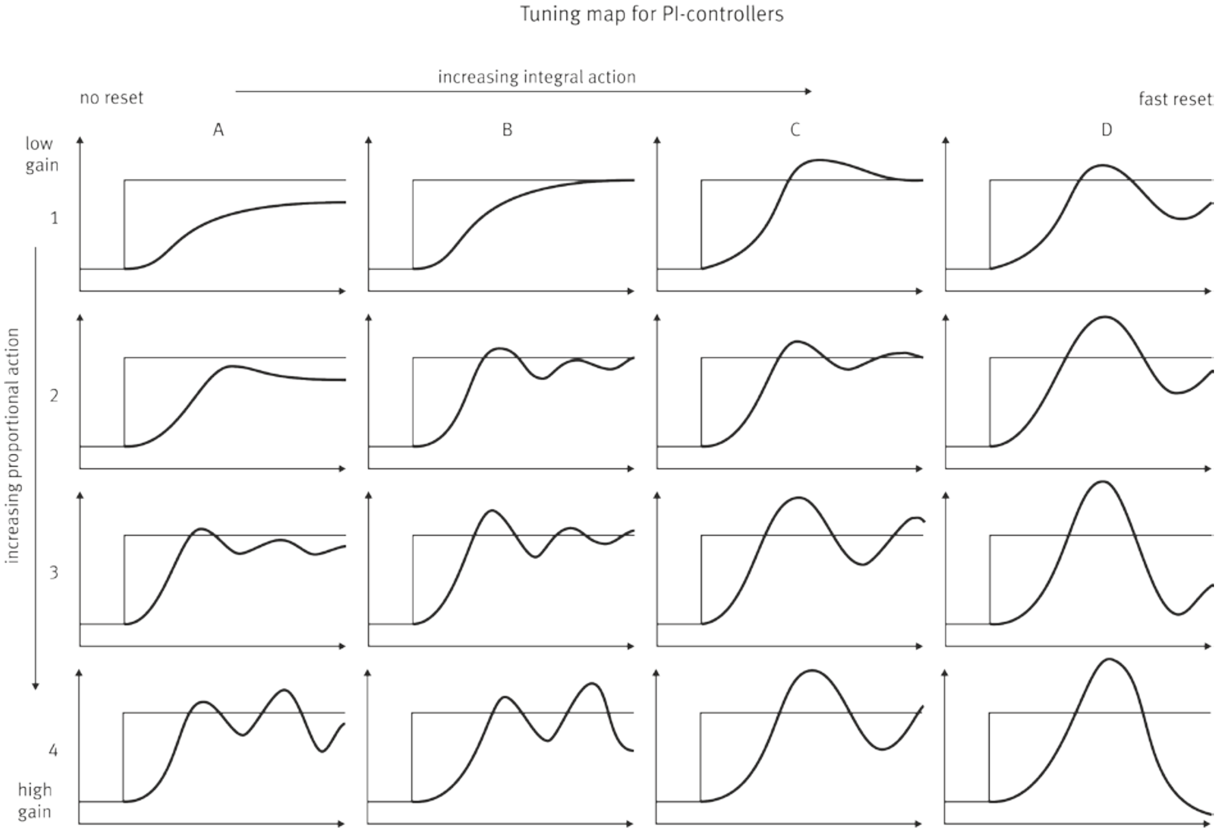
PID controller

1. Set the desired setpoint value and manually reduce the system deviation to zero.
2. Switch to automatic mode.
3. Slowly increase Kp until the control loop is inclined to oscillate as a result of small setpoint value changes.
4. Switch Td from 0 to 1s.
5. Increase Td until the oscillations are eliminated.
6. Slowly increase Kp again until the oscillations recur.
7. Repeat the setting according to steps 5 and 6 until the oscillations can no longer be eliminated.
8. Slightly decrease Td and Kp until the oscillations stop.
9. Reduce Tr until the control loop is inclined to oscillate again.
10. Slightly increase Tr until the tendency to oscillate is eliminated.

10.3 Tuning "for dummies"

PI-tuning map

For a self-regulating process controlled by a PI controller a tuning map "for dummies" shows the response of the control-loop to a setpoint change for various combinations of proportional and integral tuning.



Tuning map of a PI-controller "for dummies" (source: Basic and Advanced Regulatory Control, ISA)

The graph in the upper-left corner (A1) depicts the closed-loop response to a setpoint change when the controller is tuned with very low gain and no integral action. If integral action cannot be turned off, then the left-hand column represents minimum integral action, the largest possible value for seconds per repeat (cycle time of controller CPU) or the smallest possible value for repeats per second. Graph A1 shows an overdamping response – no oscillation – resulting in a significant steady-state deviation from setpoint.

As gain is increased, move down the left-hand side of the tuning map. First there is a slight tendency to overshoot, then a greater tendency to oscillate, with a corresponding reduction in steady-state offset. Finally if the gain is increased too much, the loop is driven into an unsteady state.

Note that as more you change from low to high gain, the less stable the loop.
To increase the speed of the integral action from very slow to fast you need to decrease the value of the reset time Ti (repeat per second).

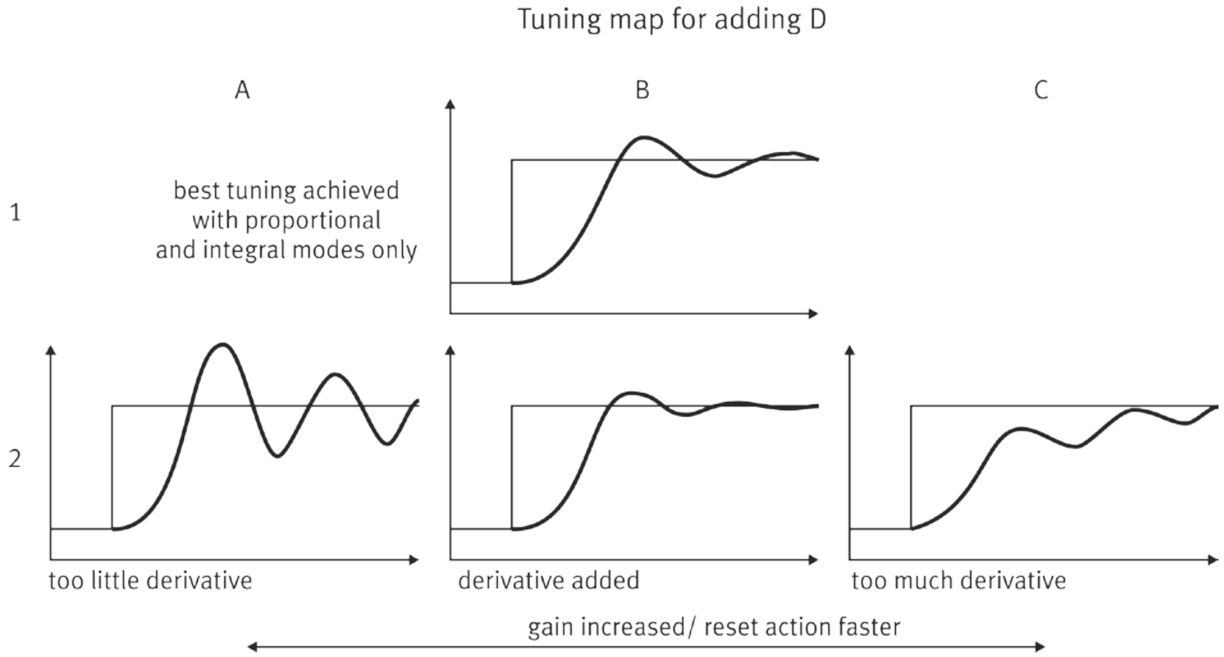
If the speed of the integral action is increased further from B1 to C1 the curve bends upwards and overshoots. An even further increase will create very undesirable oscillation of the loop (D1). An increase of speed in integral action is a move in a destabilizing loop.

In the end we want maximum stability for the closed-loop. Therefore both gain and integral time could be set to a minimum value. But then we cannot compensate the effect of any disturbances. For a reasonable stability both values should be kept away from one or the other direction which leads into unstable conditions of the loop.

If you look at the map, there can be more than one way of tuning both values Kp and Ti to have a reasonable stability (e.g. B1, B2, C2).

D-tuning map

At some states tuning with P & I alone doesn't get to an acceptable response as shown in B2. Add a small amount of derivative and the loop should produce an acceptable response for more stability. This allows us to increase the gain and integral action.



Tuning map of added derivative "for dummies" (source: Basic and Advanced Regulatory Control, ISA)

10.4 Ziegler-Nichols tuning rules

Information

In the initial phase of modern closed-loop control technology J. G. Ziegler and N.B. Nichols established tuning rules which are still frequently used today. They are intended for cases where

- A model of the controlled system does not exist (nor a inflectional tangent model) and
- The control loop can be operated safely within the stability limit range.

10.4.1 Oscillation method

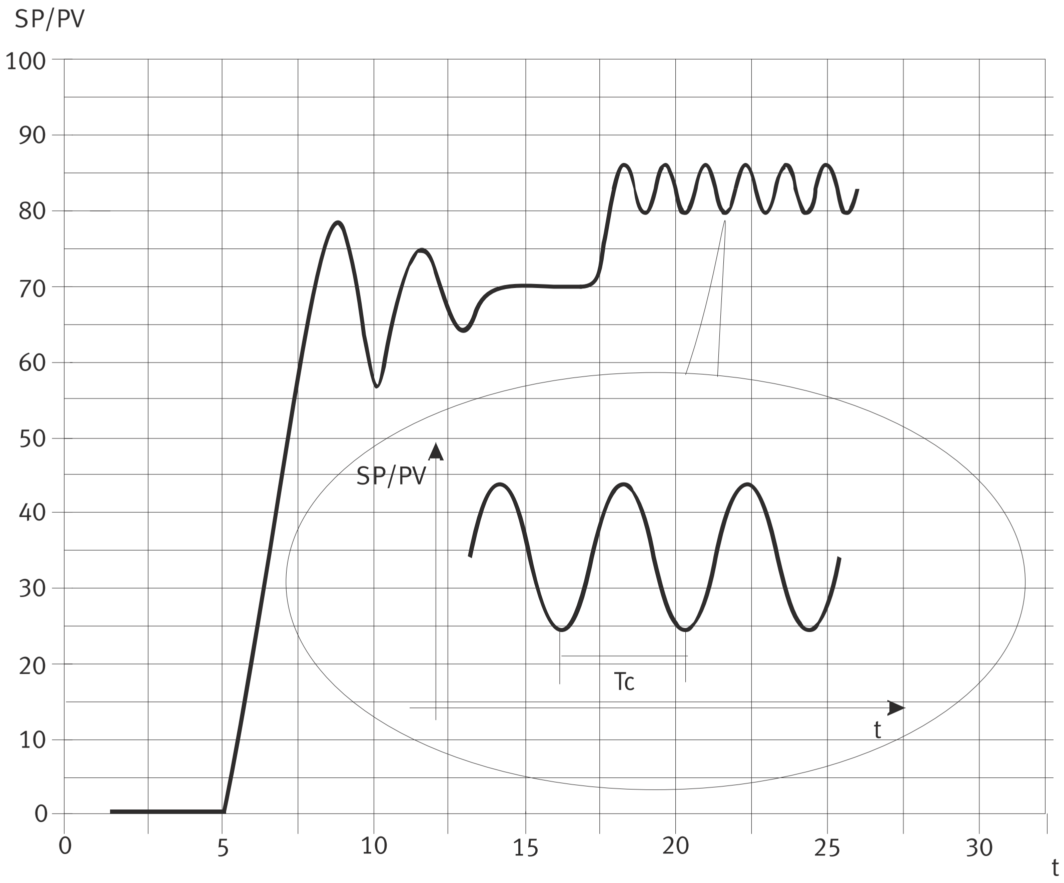
The first method according to Ziegler-Nichols defines for the control loop to be brought to the edge of stability in an experimental process, so that the control-loop (controller+system) oscillates "harmonically". In the case of a harmonic oscillation, the oscillation duration or period duration (T) is constant - in the case of a damped oscillation, the amplitude decreases over time.

These rules are as follows:
1. Setting the controller as a P controller (Td = 0, Ti = ∞).
2. Increase the amplification factor Kp of the controller until the control loop still just freely oscillates (stability limit). This determines the critical amplification factor Kc and the oscillation period Tc of this sustained oscillation.
3. On the basis of these two parameters (Kc, Tc), set the controller parameters Kp, Ti and Td according to controller type in line with the following rule.

	Kp	Ti	Td
P controller	0.5×Kc	-	-
PI controller	0.45×Kc	0.85×Tc	-
PID controller	0.6×Kc	0.5×Tc	0.12×Tc

Ziegler-Nichols tuning rules

However, applications in practice show that these tuning values only lead to practicable control loop behavior if the ratio of balancing time T_b to equivalent dead time T_e of the controlled system is not too great – that is the controlled system in the model exhibits a perceptible delay time.



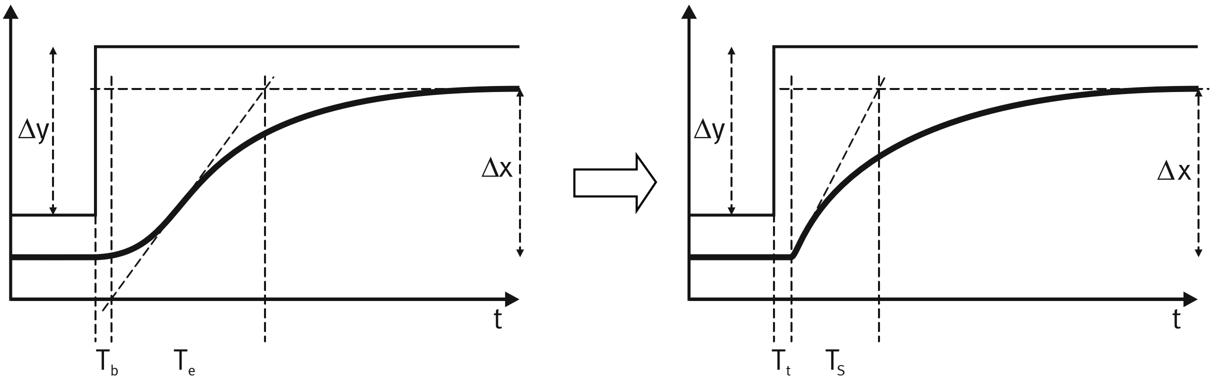
Ziegler-Nichols oscillation method

10.4.2 Step-response method

At the second Ziegler-Nichols method, the control loop is operated without a controller. The step response of the controlled-system is recorded at the operating point and the static and dynamic behaviour of the system therefore is assigned with the following parameters:

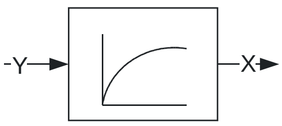
- system gain Ks - in static state
- system time constant Ts - in the dynamic range of the characteristic curve
- dead time Tt in the dynamic range of the characteristic curve

The prerequisite for this is a stable control system with compensation. The method provides for the conversion of a higher-order control system (inflectional tangent model) into a first-order path with dead-time.



Procedure

1. Record the step-response at the operating point.
2. Determine graphically the dead time and the time constant of the route.
3. Calculate the line gain Ks.
4. On the basis of the determined parameters, the controller parameters Kp, Ti and Td must then be calculated and set on the controller, depending on the controller type.



$$K_S = \frac{x}{y}$$

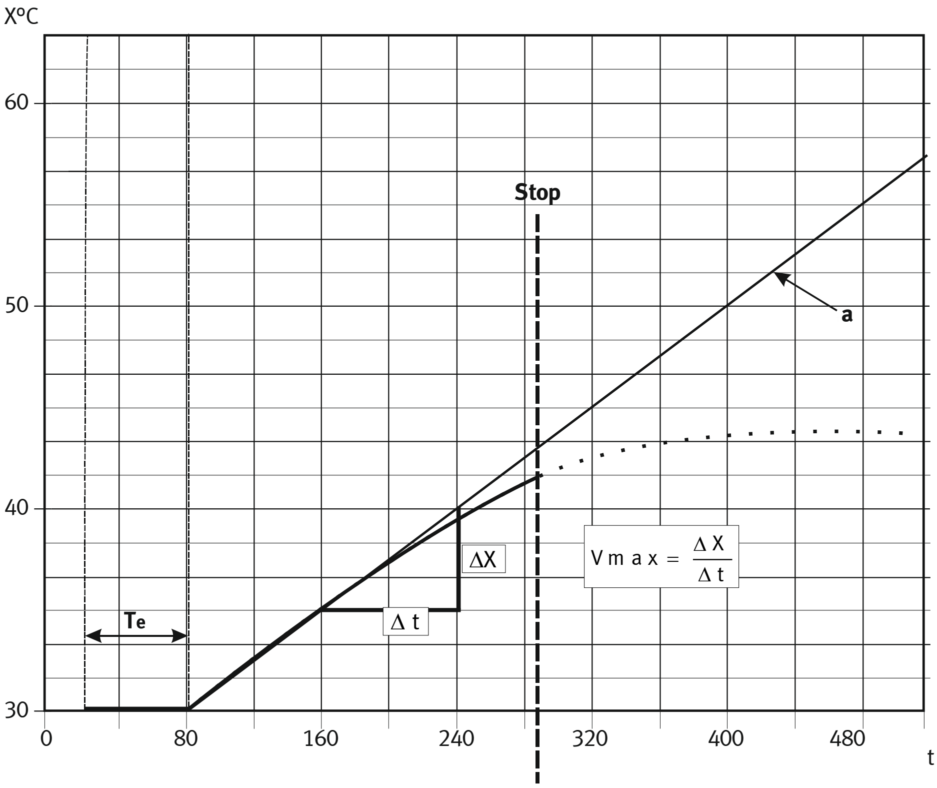
Control parameter	K_P	T_i	T_d
P-controller	$K_p = \frac{1}{K_s} \cdot \frac{T_S}{T_t}$	–	–
PI- controller	$K_p = \frac{0{,}9}{K_s} \cdot \frac{T_S}{T_t}$	$T_i = 3{,}3 \cdot T_t$	–
PID-Regler	$K_p = \frac{0{,}9}{K_s} \cdot \frac{T_S}{T_t}$	$T_i = 2 \cdot T_t$	$T_d = 0{,}5 \cdot T_t$

Reglerparameter nach Ziegler-Nichols Methode 2

10.5 Rate-of-rise method

Information

In the case of slow controlled systems with compensation (of second order as a minimum), a time-saving optimization method can be used for the control parameters of a PID controller by means of a step change to the controlled system. The step change with a specific manipulated variable is applied to the controlled system until the actual value change exhibits the maximum rate of rise.



Actual value curve using method according to rate of rise

Procedure

1. Introduce input step of the manipulated variable to the controlled system.
2. Enter actual value response.
3. Cancel step change when maximum rate of rise is reached.
4. Draw in inflectional tangent.
5. Draw in rise triangle.

$$V_{max} = \frac{\Delta x}{\Delta t}$$

6. Determine the rate of rise $V_{max.}$
7. Determine the time delay T_e (dead time).
8. Enter and calculate the values for V_{max} and T_e for the selected controller structure in the formula (see table below).

Controller structure	Control parameters	Description
P	$K_P = \frac{\Delta y}{V_{MAX} \times T_U \times y_H}$	y_H = Maximum correcting range usually: 100%, no value limitation Δy = Specified step height. In this case equals to the PWM of the heating unit (40%).
PI	$K_P = \frac{\Delta y}{1.2 \times V_{MAX} \times T_U \times y_H}$ $T_i = 3.3 \times T_U$	
PID	$K_P = \frac{\Delta y}{0.83 \times V_{MAX} \times T_U \times y_H}$ $T_i = 2 \times T_U$ $T_d = 0.5 \times T_U$	

Formulas for the optimization of control parameters according to ramp response for compensated controlled systems (>PT2)

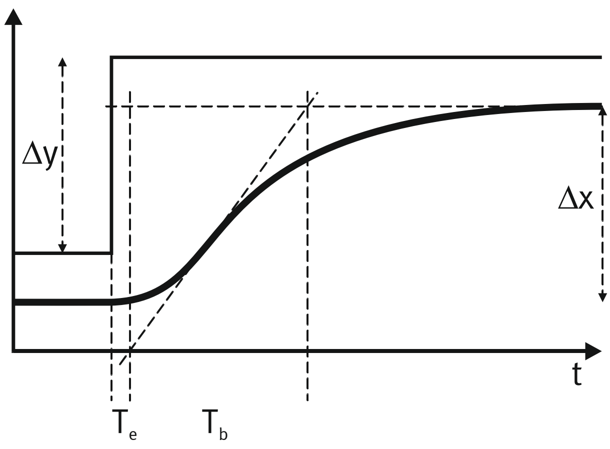
The inflectional tangent model

Information

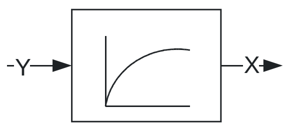
In numerous technical applications, primarily in the areas of process technology or power engineering, the step responses of systems occur without oscillation sections and only exhibit proportional or integral behavior in relation to dead time. The transient function is therefore often used in the form of a linear dynamic model.

The behavior of systems of a higher order is therefore characterized in a much simplified way by means of three properties:

- Proportional or integral-action coefficient
- Dead time
- Adjustment time



Frequently used transient function model (inflectional tangent model)



$$K_S = \frac{\Delta x}{\Delta y}$$

K_s – Proportional coefficient of the system
T_e – equivalent dead time (EN 60027-6)
T_b – balancing time
Δy – Height of the input step to the control loop
Δx – Height of the step response of the control loop

$K_{IS} = \frac{\Delta h}{\Delta t} = \frac{K}{T_g}$ - Integral action coefficient

The inflectional tangent used to obtain the characteristic values Tu and Tg is for example drawn by eye in the experimentally determined step response. If this is superimposed by high-frequency interference, this is to be smoothed by eye (or computer-aided). With low-frequency interference, the process cannot be evaluated. In this case, a repetition of the experiment and smoothing by means of mean value calculation are sometimes helpful.

The table below lists the model characteristic values of typical controlled systems.

Variable to be controlled	Type of controlled system	Dead time T_u	Adjustment time T_g
Temperature	Annealing furnace laboratory	0.5 – 1 min	5 – 15 min
	Industry	1 – 3 min	10 – 30 min
	Distillation column	1 – 5 min	40 – 60 min
	Superheater	1 – 2 min	20 – 100 min
	Room heating	1 – 5 min	10 – 60 min
Flow rate	Piping – gas	0 – 5 s	0.2 – 10 s
Flow rate	Piping - liquid	0	0

Model characteristic values of typical controlled systems

The degree of difficulty to be expected can already be assessed from the ratio $\frac{T_e}{T_b}$ for a closed-loop controlled system:

Ratio $\frac{T_e}{T_b}$	Degree of difficulty
> 10	Easily controllable
≈ 6	Still controllable
< 3	Difficult to control

Assessment of the degree of difficulty of closed-loop control

10.6 Chien-Hrones-Reswick Tuning Rules

If an inflectional tangent model of the controlled system exists, then the tuning rules of Chien, Hrones and Reswick can be used. These are listed in the table below.

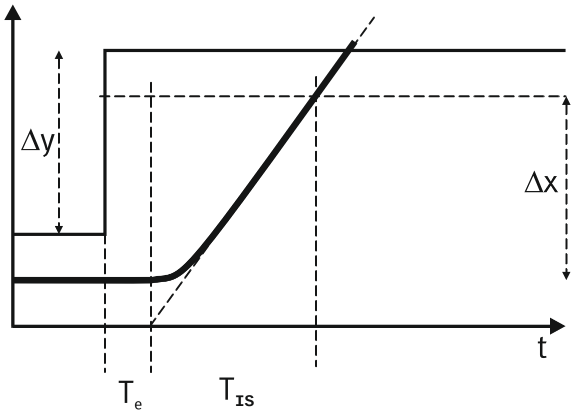
Controller type	Overshoot 20% after step change		No overshoot (0%) after step change	
	of disturbance variable z	of setpoint values w	of disturbance variable z	of setpoint value w
P	$Kp \approx \frac{0.7}{K_s} \times \frac{T_g}{T_u}$	$Kp \approx \frac{0.7}{K_s} \times \frac{T_g}{T_u}$	$Kp \approx \frac{0.3}{K_s} \times \frac{T_g}{T_u}$	$Kp \approx \frac{0.3}{K_s} \times \frac{T_g}{T_u}$
PI	$Kp \approx \frac{0.7}{K_s} \times \frac{T_g}{T_u}$ $Tr \approx 2.3 \times T_u$	$Kp \approx \frac{0.6}{K_s} \times \frac{T_g}{T_u}$ $Tr \approx Tg$	$Kp \approx \frac{0.6}{K_s} \times \frac{T_g}{T_u}$ $Tr \approx 4 \times Tu$	$Kp \approx \frac{0.35}{K_s} \times \frac{T_g}{T_u}$ $Tr \approx 1.2 \times T_g$
PID	$Kp \approx \frac{1.2}{K_s} \times \frac{T_g}{T_u}$ $Tr \approx 2 \times Tu$ $Td \approx 0.42 \times Tu$	$Kp \approx \frac{0.95}{K_s} \times \frac{T_g}{T_u}$ $Tr \approx 1.35 \times Tg$ $Td \approx 0.47 \times Tu$	$Kp \approx \frac{0.95}{K_s} \times \frac{T_g}{T_u}$ $Tr \approx 2.4 \times Tu$ $Td \approx 0.42 \times Tu$	$Kp \approx \frac{0.6}{K_s} \times \frac{T_g}{T_u}$ $Tr \approx Tg$ $Td \approx 0.5 \times Tu$

Chien-Hrones-Reswick Tuning Rules

Instead of using $\frac{T_b}{K_s \cdot T_e}$ for I controlled systems, the expression $\frac{1}{K_{IS} \cdot T_e}$ and $T_b = T_{IS}$ is to be used.

Application for I-system with dead time

Instead of using $\frac{T_b}{K_s \cdot T_e}$ for I controlled systems, the expression $\frac{1}{K_{IS} \cdot T_e}$ and $T_b = T_{IS}$ is to be used.



This results in the following setting formulas:

Controller type	Overshoot 20% after step change		No overshoot (0%) after step change	
	of disturbance variable z	of setpoint values w	of disturbance variable z	of setpoint value w
P	$K_p = \frac{0{,}7}{K_{IS} \cdot T_e}$	$K_p = \frac{0{,}7}{K_{IS} \cdot T_e}$	$K_p = \frac{0{,}3}{K_{IS} \cdot T_e}$	$K_p = \frac{0{,}3}{K_{IS} \cdot T_e}$
PI	$K_p = \frac{0{,}7}{K_{IS} \cdot T_e}$ $T_i = 2{,}3 \cdot T_e$	$K_p = \frac{0{,}6}{K_{IS} \cdot T_e}$ $T_i = T_{IS}$	$K_p = \frac{0{,}6}{K_{IS} \cdot T_e}$ $T_i = 4 \cdot T_e$	$K_p = \frac{0{,}35}{K_{IS} \cdot T_e}$ $T_i = 1{,}2 \cdot T_{IS}$
PID	$K_p = \frac{1{,}2}{K_{IS} \cdot T_e}$ $T_i = 2 \cdot T_e$ $T_d = 0{,}42 \cdot T_e$	$K_p = \frac{0{,}95}{K_{IS} \cdot T_e}$ $T_i = 1{,}35 \cdot T_{IS}$ $T_d = 0{,}47 \cdot T_e$	$K_p = \frac{0{,}95}{K_{IS} \cdot T_e}$ $T_i = 2{,}4 \cdot T_e$ $T_d = 0{,}42 \cdot T_e$	$K_p = \frac{0{,}6}{K_{IS} \cdot T_e}$ $T_i = T_{IS}$ $T_d = 0{,}5 \cdot T_e$

Chien-Hrones-Reswick Tuning Rules for controlled systems without compensation

10.7 Optimization method for controller settings

Information

Technical controls are a component part of automation systems whose primary function is to stabilise processes. They are used with the aim of:

- Automatically bringing about and maintaining certain process states (operating modes)
- Eliminating the effects of disturbances in a process sequence
- Eliminating unwanted coupling of sub processes within a technical process

The process states primarily addressed concern certain process parameters such pressure, flow, temperature and filling level.

A basic question regarding the optimisation of controller settings is: "Which controller is suitable for which controlled system?"

The following lists the controllers used traditionally for the most important controlled system.

	Residual system deviation		No residual system deviation	
	P	**PD**	**PI**	**PID**
Temperature	Simple controlled systems for minimal requirements	Simple controlled systems for minimal requirements	Suitable	Ideally suited
Pressure	Generally impracticable	Generally impracticable	Highly suitable, for controlled systems with large delay time also I controller	Suitable if controlled variable does not oscillate excessively
Flow	Unsuitable	Unsuitable	Practicable, although I controller on its own often better	Suitable
Filling level	For short dead time	Suitable	Suitable	Ideally suited
Materials handling	Unsuitable due to dead time	Unsuitable	Practicable, although I controller alone is often better	No advantages over PI

Choice of controller types for the control of the most important control variable

Particular controllers can be classified on the basis of controlled systems identified by means of the step response. For example, an I controlled system can be adjusted using a P controller or conversely a P controlled system can be controlled using an I controller.

Controlled system	Controller structure			
	P	PD	PI	PID
Pure dead time	Unsuitable due to dead time	Unsuitable	Practicable, although I controller generally adequate	Offers hardly any advantages compared to PI
1st order with short dead time	Suitable if system deviation is acceptable	Suitable if system deviation is acceptable	Highly suitable	Suitable
2nd order with short dead time	System deviation is generally too large for required Kp	System deviation generally too large for required Kp	Inferior to PID	Highly suitable
Higher order	Unsuitable	Unsuitable	Inferior to PID	Highly suitable
Non-compensating with delay time	Suitable	Suitable	Suitable	Ideally suited

Tuning methods

The controller parameters of the controller selected can be theoretically calculated by means of mathematical algorithms or practically determined by means of tuning methods.

Practical tuning methods for control parameters are:
- "Trial and-error" or the empirical method
- Oscillation methods according to Ziegler-Nichols for fast controlled systems
- Step response using the inflectional tangent model according to Chien-Hrones-Reswick for higher-order controlled systems.
- Rate-of-rise method for slow controlled systems

10.8 Summary

Information

Here is a summary of all the necessary points to be taken into account when solving closed-loop control problems.

Assignment of closed-loop control variables

- Which machine or system 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 this.

Breakdown 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?

Controlled system

- Where is the controlled variable to be adjusted to the setpoint value?
- What is the time response of the controlled system (slow or fast)?
- The controller response to be set is based on these factors.

Controller

- What type of controller response is required?
- What time response must the controller have, particularly with regard to disturbances?
- What values must be controller parameters have?

Controller type

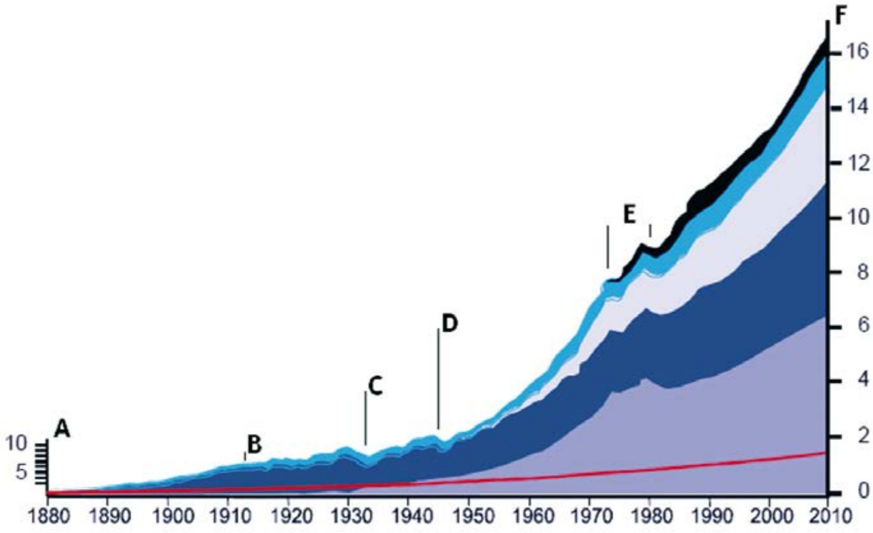
- What type of control is required?
- Does the time response and the controlled system require a P, I, PI or PID controller?

Module 30 – Energy monitoring, analysing and optimizing of a pump

1 Energy consumption and power generation – Fundamentals

1.1 Primary energy consumption

Today, energy affects all aspects of life and represents a prerequisite for performing most types of work. If energy was available in unlimited amounts, there would be no need to worry about power generation and its associated problems. Worldwide energy consumption is closely related to the growing world population and the increasing per capita consumption produced by industrialisation, rising levels of mobility and growing numbers of electrical appliances.



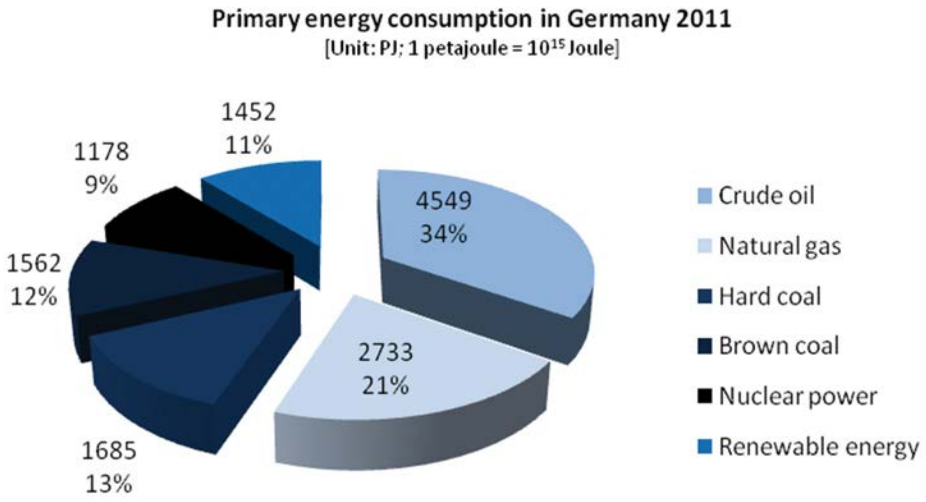
Worldwide energy consumption

Letter	Explanation		Colour	Explanation
A	Population growth in billions			Nuclear power
B	World War I			Water, biomass, etc.
C	World economic crisis			Natural gas
D	World War II			Hard coal and brown coal
E	Oil crisis			Crude Oil
F	Unit: billions of tons of coal equivalent			World population

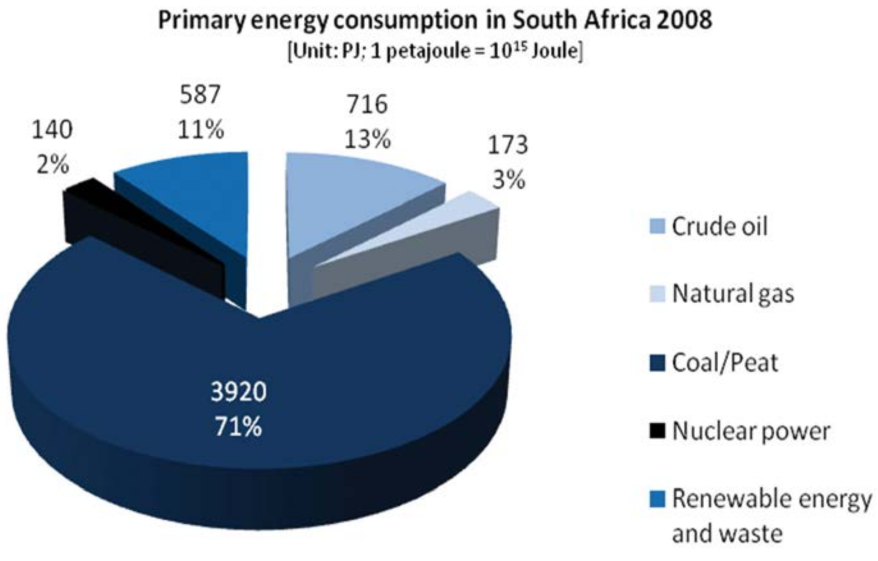
The graph above shows that crises and wars have had only little effect on the overall trend of rising energy consumption. Since the 1880s worldwide energy consumption increases and accelerates.

Due to the fact that primary energy sources such as oil, gas and coal are limited, conflicts between individual countries regarding these resources are likely to happen. Shortages will also result in rising energy costs.

There are great regional differences in what types of energy are used. The following figures show the consumption of primary energy of Germany and South Africa.



Source: AG Energiebilanzen Nr. 02/2012



Source: www.eia.doe.gov and International Energy Agency (IEA)

1.2 Problems of energy generation

In any case, energy consumption leads to costs and environmental pollution. The technology used for energy generation strongly affects the environmental impact.

- **Fossil fuel based technologies**

Energy generation with fossil fuels results in the production of harmful exhaust fumes and gases, like particulate matter, sulphur dioxide, nitrogen oxides and carbon dioxide. The quantities of these fumes and gases are subject to the composition of the fuels. The harmful fumes and gases result from the burning of gas, oil or coal either directly by the consumer or by the power plant that generates electricity. Even if flue gas treatment is applied, which removes most of the harmful matter, carbon dioxide is set free during the burning process. CO2 emission is considered to be one of the main causes for climate change.
In industrial production, the consumption of electricity plays an important role.

- **Nuclear power**

Although nuclear power is CO2-neutral, nuclear fuel emits dangerous levels of radioactivity which pose a threat to living organisms. The final disposal and conditioning of nuclear waste is still an unsolved problem. Thus, the ecological assessment of atomic energy remains highly disputed.

- **Renewable energy**

Renewable energy originates from sources which are naturally regenerated. The energy is produced from wind, sun (photovoltaic and solar heat), water, biomass or ground heat.

Some renewables do not emit CO2 during their operation. Others emit CO2 but compensate the emission by gathering CO2 from the atmosphere while growing (biomass, wood). Fossil fuels like oil, coal or gas; need millions of years to “regenerate” and can therefore not be counted as renewable energy.

Renewable energy sources serve about 16% of the energy needs worldwide.
(Source: Renewables 2011 Global status report)

Water

Wind

Photovoltaics (source: Festo)

1.3 Consumption of primary energy

Problem description

The rapidly increasing world energy consumption has raised concerns about supply difficulties, exhaustion of energy resources and serious environmental impacts (climate change, ozone layer depletion, global warming, etc.). Different approaches how to treat these challenges are discussed in politics on national and international levels. As a responsible citizen who actively takes part in the shaping of the future of your country it is important that you inform yourself about the facts.

Exercise

a) Name the most important sources of primary energy in your country/region

Fossil fuels

- ☐ Hard coal
- ☐ Brown coal
- ☐ Peat
- ☐ Natural gas
- ☐ Crude oil

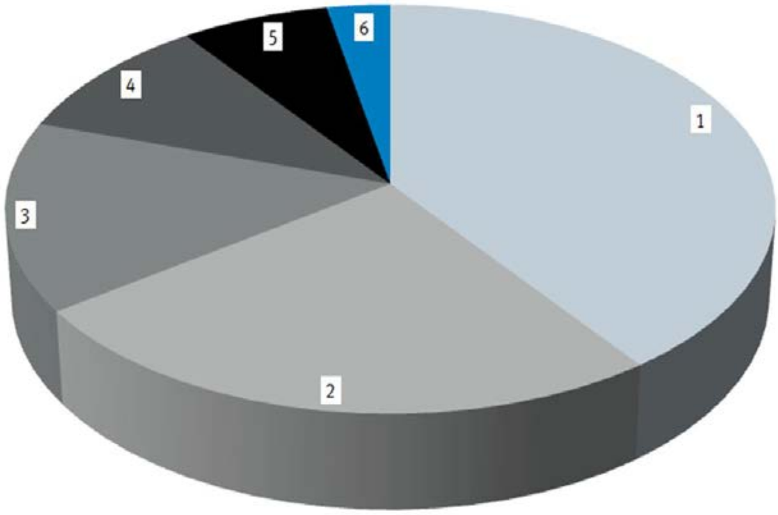
Renewable energy

- ☐ Solar energy (solar radiation for the generation of light and heat)
- ☐ Electricity from solar energy (photovoltaic and thermal power plants)
- ☐ Biomass
- ☐ Wind energy
- ☐ Hydropower (including wave power, tidal power)
- ☐ Geothermal energy

Nuclear energy

- ☐ Nuclear fission
- ☐ Nuclear fusion

b) Allocate the most important sources of primary energy in your country / region according to their percentage of consumption. Fill in the percentages and the energy sources.



1. .... %	4. .... %
2. .... %	5. .... %
3. .... %	6. .... %

c) Name at least two sources and one advantage of the use of renewable energy:

1.4 Energy saving in daily life

Problem description

The use of fossil fuels like coal, oil and natural gas produces greenhouse gases and contributes to global warming. Saving energy and improving energy efficiency is one of the main energy sources, and the only one that saves money. For example, an average German four-person household consumes about 4500 kWh of electricity per year. This amount of energy could be reduced by 2000 kWh, which corresponds to saving 600 kilograms of carbon dioxide (CO_2). By saving energy, anyone can cut energy expenses and help nature at the same time.
Before analysing industrial energy demand, we approach the topic in an easy way and investigate energy consumption in our daily life.

Exercise

Describe three actions that can contribute to the saving of energy in your daily life:

a) ______________________________

____

b) ______________________________

____

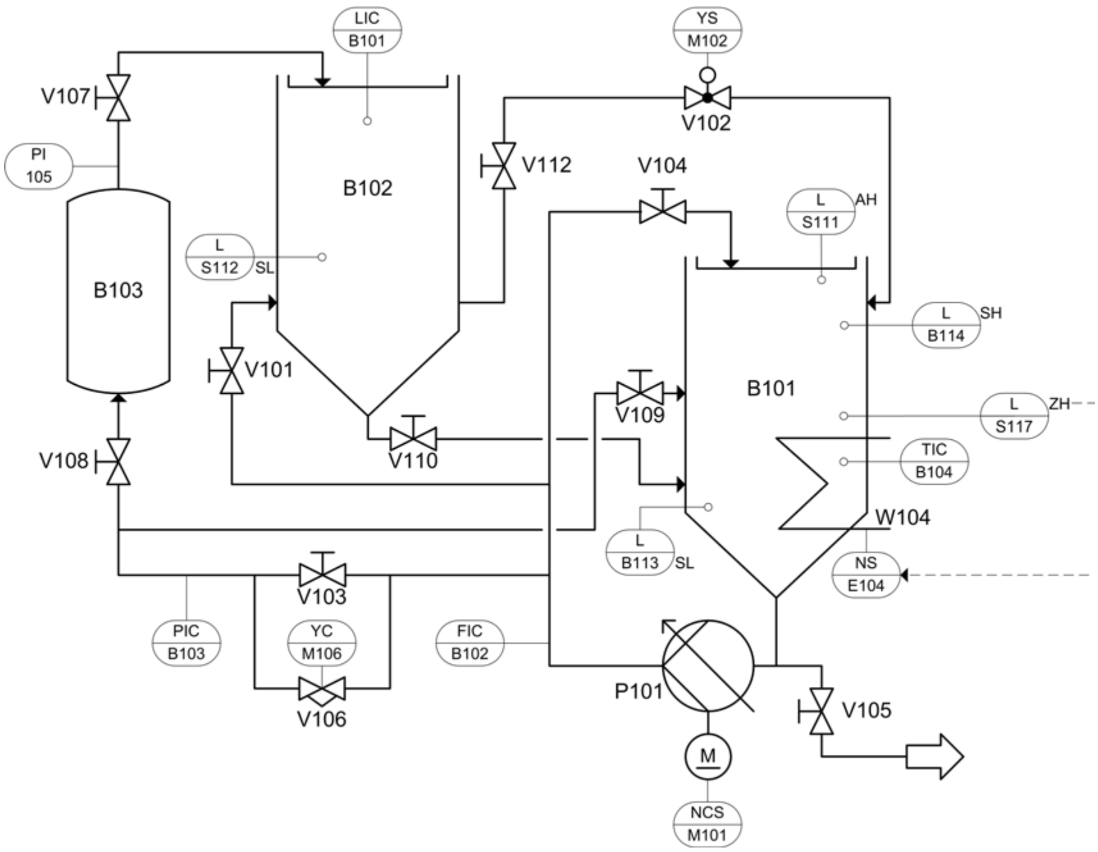
c) ______________________________

____

2 System layout and function analysis

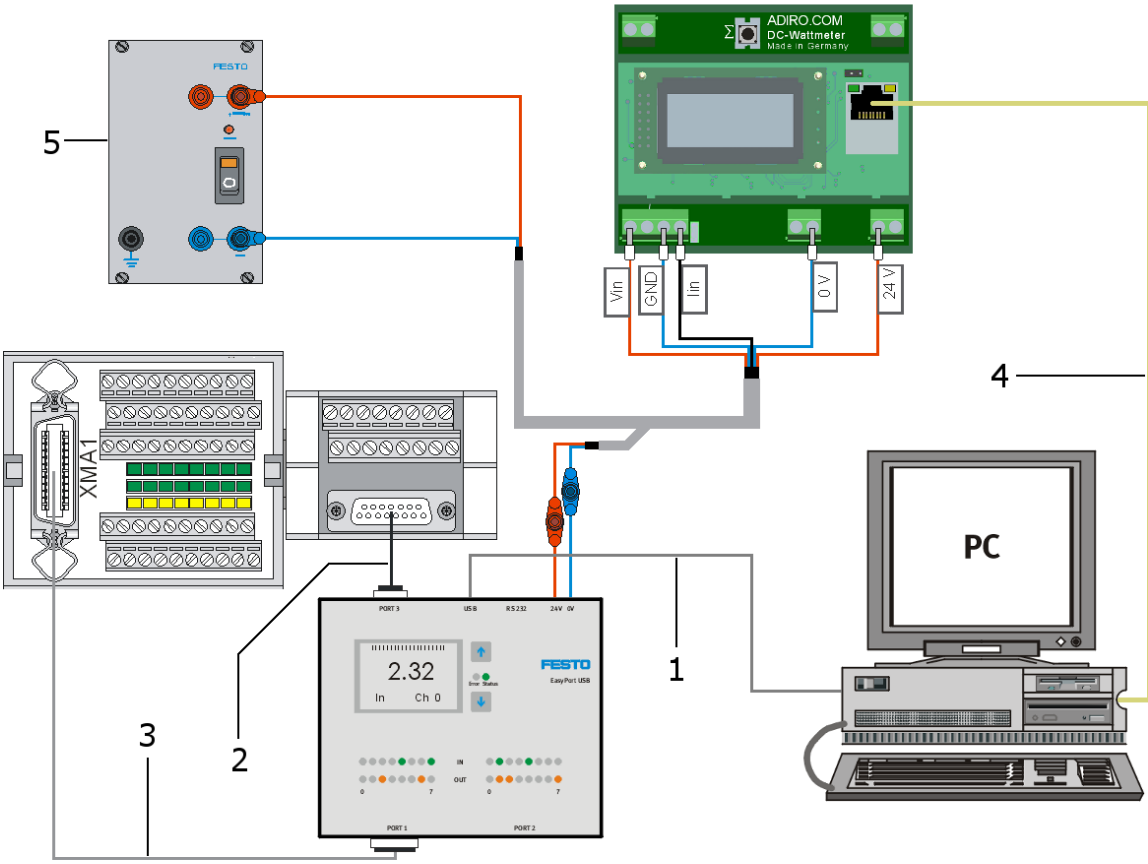
2.1 Layout and connection of the Installation

The MPS PA Compact Workstation consists of a lower tank (B101) and an upper tank (B102). Depending on the position of the manual valves the pump pumps water in a circular flow, builds up pressure in the pressure accumulator or fills the upper tank. From there, the water can flow back to the lower tank through a piping system or directly through a ball valve (V102). Furthermore there's a proportional valve integrated and in the lower tank a heater as well as several sensors to measure the state of the system like flow rate, pressure, filling level or temperature.



PI flow diagram

a) Connect the plant



Connection diagram

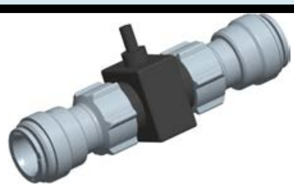
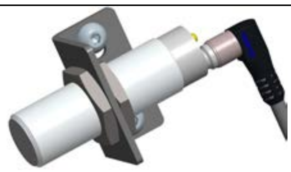
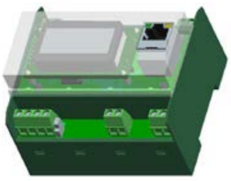
Item	Designation	Instructions
1	USB/serial cable	Connect the USB/serial cable to the PC and to EasyPort
2	D-Sub 15-pin cable	Connect the EasyPort to the I/O board via the D-Sub 15-pin cable.
3	SysLink cable	Connect the EasyPort to the I/O board via the SysLink cable.
4	Ethernet cable	Connect the DC-Wattmeter to the PC via the Ethernet cable.
5	24 V power pack	Connect the power pack. Don't switch it on before the DC-Wattmeter is connected.

b) Connect the DC wattmeter. Make use of the descriptions included in the accompanying user's manual to this end.

c) Overall commissioning
Conduct a visual inspection each time before starting or restarting the system.
Check the following before starting the system:
- Electrical connections
- Correct seating, possible leaks and the condition of piping and pipe connectors
- Mechanical components for visible defects (cracks, loose connections etc.)
- Fill Level in tank B101 (max. 10 litres of water in the entire system)

2.2 Function analysis of the components

– Fill in the following worksheet with the help of the data sheets.

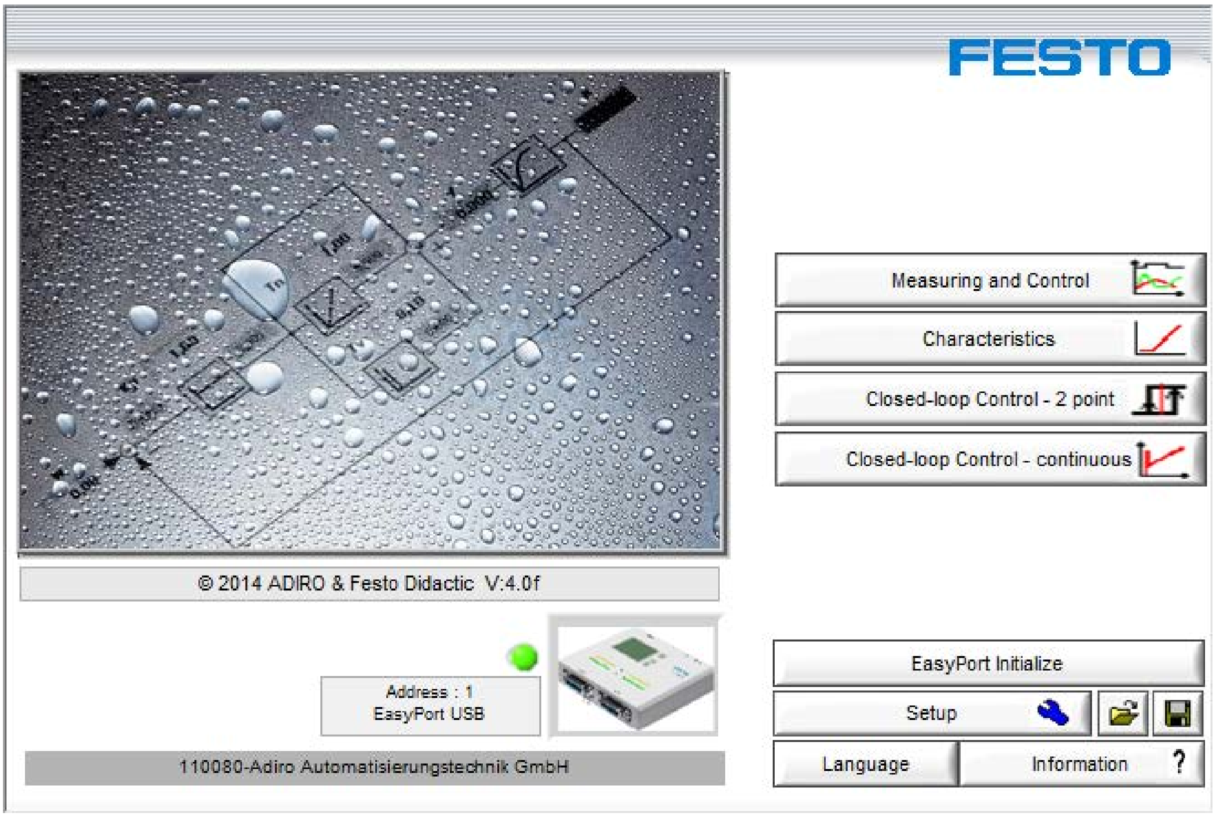
Individual system components			
	Designation:		Designation:
	Function:		Function:
	Working range:		Measuring range:
	Designation:		Designation:
	Function:		Function:
	Measuring range:		
	Designation:		Designation:
	Operating voltage:		Function:
	Max. flow rate:		Sampling rate:
	Power:		Indicating range:

2.3 Function analysis of the software

- **Resources**

– Instructions for starting and using the software are included below.

1. FluidLab®-PA closed-loop: used to control the process
   Start → Programs → Festo Didactic → FluidLab®-PA closed-loop → open FluidLab-PA closed-loop V4.0

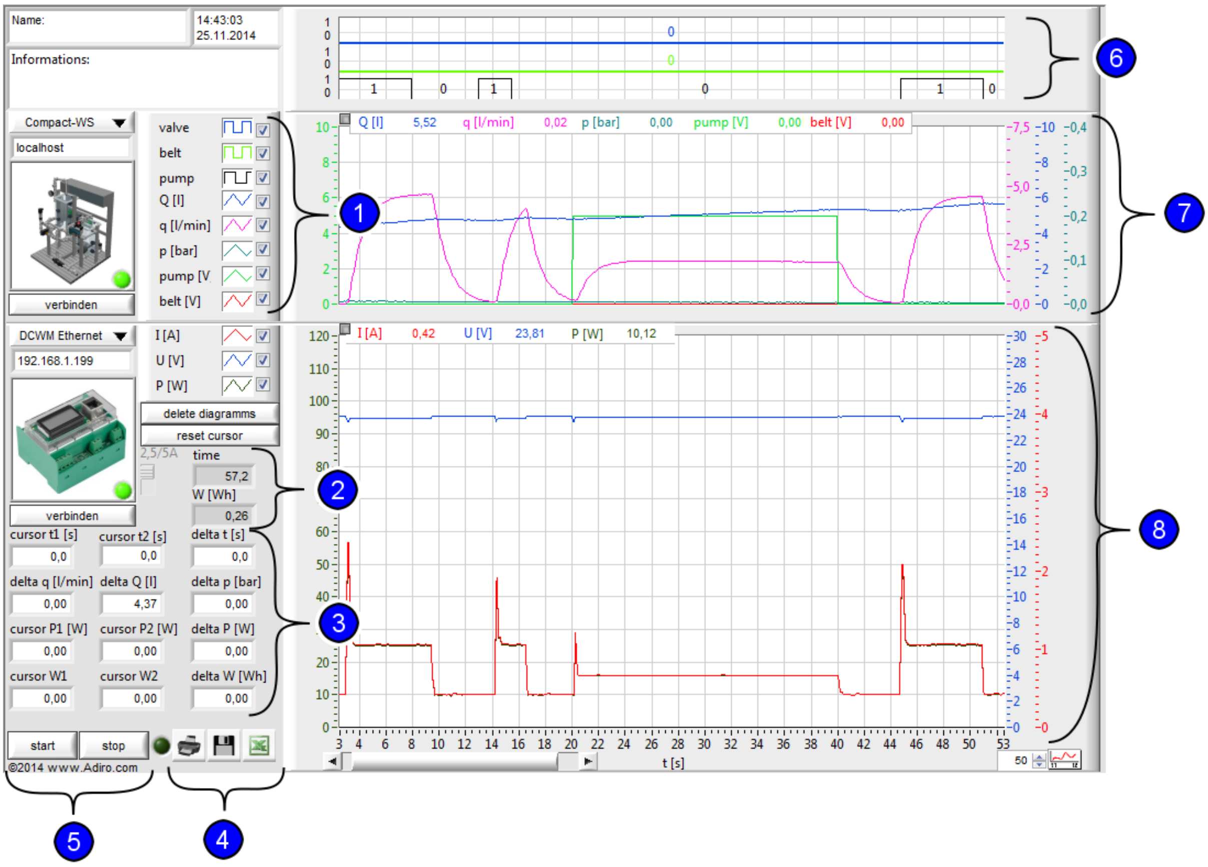


FluidLab®-PA closed-loop software

2. Switch the power pack on, plug the USB cable into the USB port at the PC.
3. Initialise EasyPort (start EasyPort).
4. DataSocket Server: used for data exchange
   Sart → Programs → National Instruments → DataSocket → Open and minimize DataSocket Server
5. FluidLab®-PA energy: used to measure and evaluate required power and energy
   Start → Programs → Festo Didactic → FluidLab®-PA energy → Open FluidLab®-PA energy
6. Select menu *EnergyMonitoring* in FluidLab®-PA energy.
7. Select *Compact-WS* and *DCWM Ethernet*, insert IP-address and connect.
8. Open submenu *Setup* in FluidLab®-PA closed-loop, set the *DC wattmeter* checkmark, select tanktyp.

Resources

– Read the following explanation based on an example of energy monitoring software (FluidLab® PA energy).



FluidLab® PA energy software

No.	Meaning
1	Enter a checkmark in order to record the components’ switching signals (e.g. pump) or characteristic curves.
2	Required electrical energy as a numerical value in watt hours [Wh] and measuring time in seconds [s].
3	Display of values at the cursor from characteristic energy and power curves.
4	Print, save or export data to Excel for evaluation.
5	Start and stop buttons to start and stop measurement.
6	Representation of switching signals
7	Representation of sensor signals and analogue outputs
8	Characteristic curves for the systems current, voltage and power

3 Forms of Energy, efficiency and power

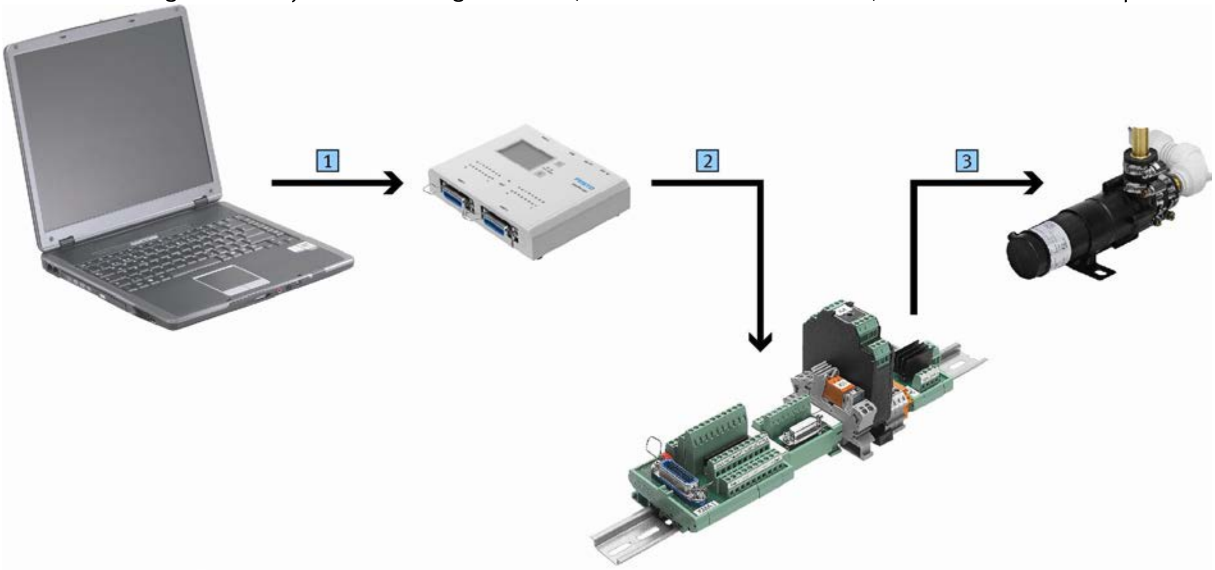
3.1 Energy

Information

Electrical energy is required for many industrial processes, equipment and machines. The specification of electrical energy is used as an indication of consumption. It is calculated as the product of power and the amount of time required. Electrical energy E_{el} corresponds to electrical work W.

Electrical energy:	$E_{el}\,[Ws] = U\,[V] \cdot I\,[A] \cdot t\,[s]$

The unit of measure for electrical energy is based on the consumption of 1 watt for a duration of 1 second. Consumption of electrical energy is usually specified in kilowatt-hours [kWh].
The centrifugal pump can be controlled in two different ways: either in the binary mode (0 to 24 V), or by means of changeover relays in the analogue mode (controllable from 0 to 10 V) with downstream amplifier.



Item	1	2	3
Digital pump control, on/off	PC transmits bit 3 to EasyPort.	EasyPort generates a voltage signal (relay) of 0 V or 24 V.	Motor runs at rated power in case of 24 V.
Analogue control	PC transmits decimal value (e.g. double word), which corresponds to a voltage within a range of 0 to 10 V.	EasyPort generates a control signal within a range of 0 to 10 V.	Motor controller boosts the signal up to 0 to 24 V. The motor is operated with infinitely adjustable speed.

Exercise

Complete the following table with typical examples.

Order of magnitude	Practical example
W [Ws]	
W [kWh]	
W [MWh]	

3.2 Power

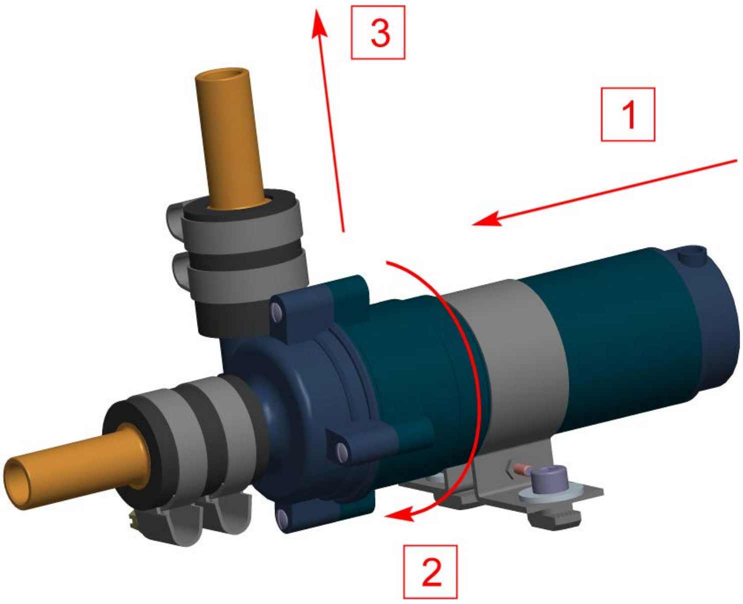
Information

Generally speaking, power is defined as energy per unit of time. In the case of our system, the pump converts mechanical power from the drive motor (e.g. an electric motor operated with electrical power) into hydraulic power, which is the product of volumetric flow rate [l/min] and pressure to be transferred [bar].

Exercise

a) Name the various types of power at the centrifugal pump.

b) Label the arrows at the pump in the following figure with the different types of power for the centrifugal pump.



c) Complete the computation formulas of the different power types:

Type of power at the pump	Formula
Mechanical power	
Hydraulic power	
Electric power	

3.3 Forms of energy

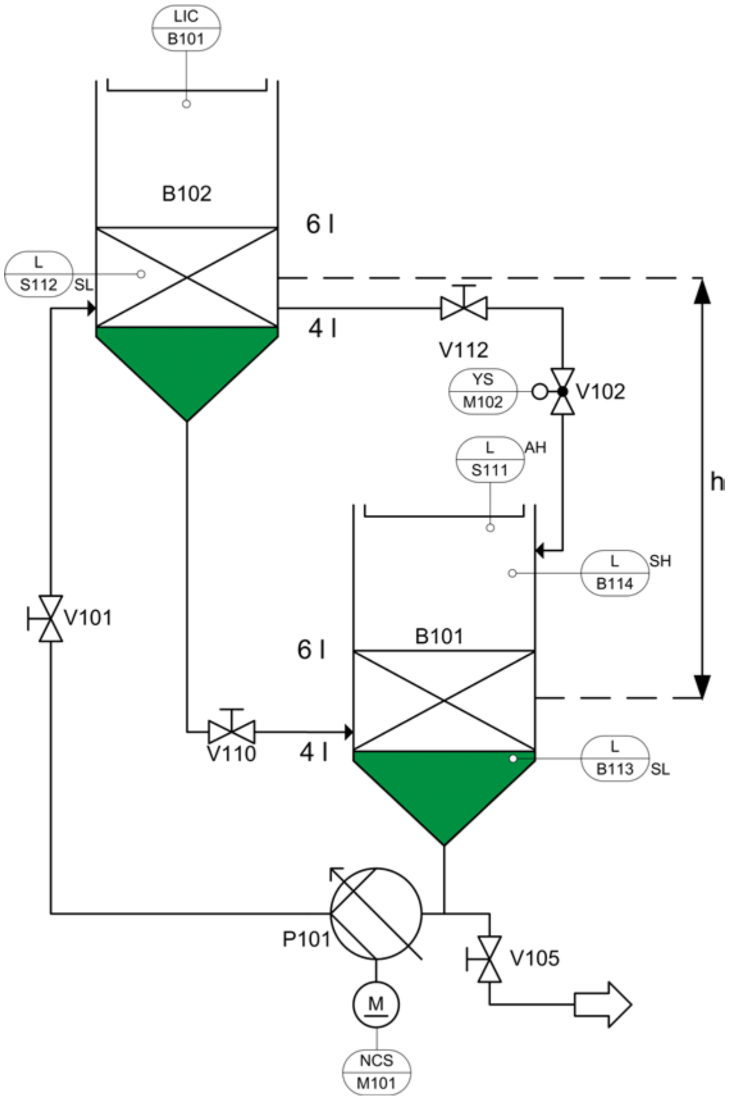
Information

Various forms of energy are required in modern technology, and these are put into action by means of machines. The preceding exercises have demonstrated that we need electrical energy in order to operate thy system. Other forms of energy are known in the field of classical mechanics:

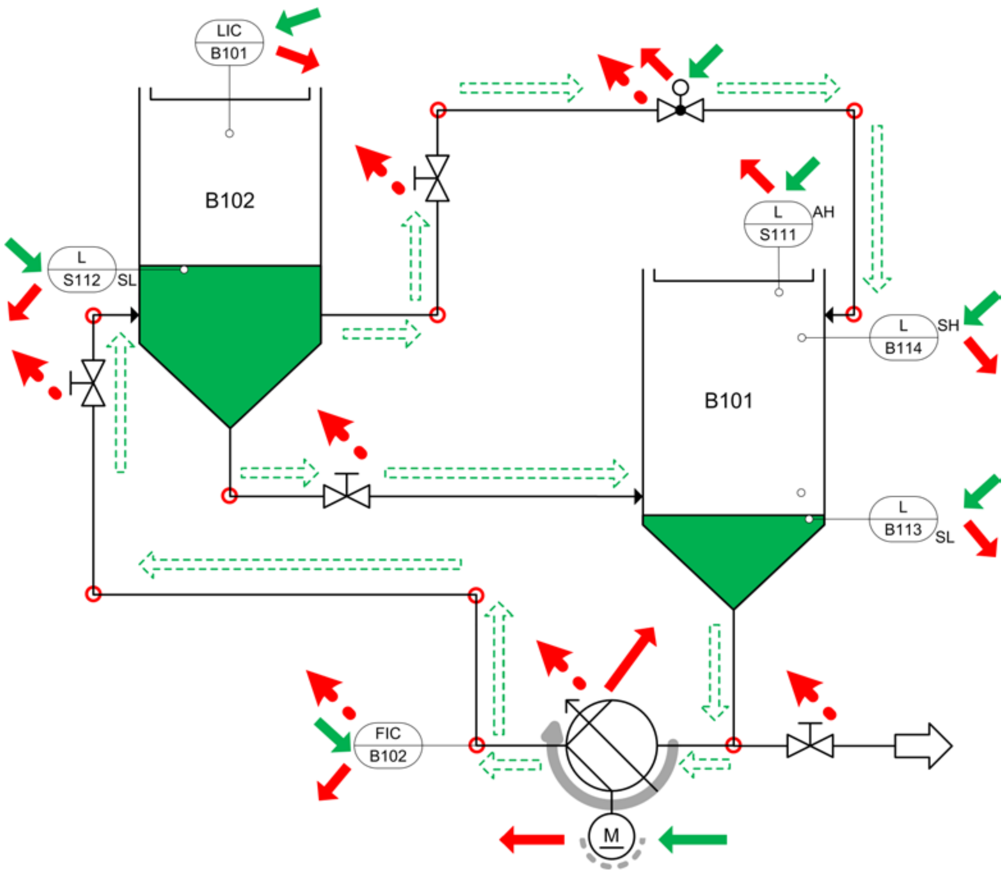
- Potential energy – stored energy
  The energy of a body (with a mass *m*) is the result of the position (height *h*) of the body within a force field (gravitational constant *g*). The energy is released when the body falls.
  Potential energy is calculated as follows: $E_{pot} = m \cdot g \cdot h$
- Elastic energy
  When a spring (with spring constant *D*) is elastically expanded over a given distance *s* (i.e. also within a force field), energy is introduced which is released when the spring contracts.
  Elastic energy is calculated as follows: $E_{elast} = 0.5 \cdot D \cdot s^2$
- Kinetic energy – energy of motion
  This energy is stored in a body's state of motion, and is proportional to moving load *m* and velocity *v* squared.
  Kinetic energy is calculated as follows: $E_{kin} = 0.5\ m\ v^2$

Exercise

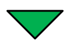
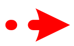
a) Calculate potential energy in the feed tank with 2 litre of water. Measure the difference in height to this end (you will need a folding rule).



b) Together with your team, think about the meanings the different colours and symbols have with regard to forms of energy and energy conversion.



c) Draw lines from the symbols to the appropriate designation which appear in random order.

Symbol	Connecting line	Designation
		Kinetic energy (liquid)
		Electrical (input) power
		Potential energy
		(Released) thermal energy
		Flow resistance
		Hydraulic power
		Mechanical power
		Flow energy dissipation (due to branch)

3.4 Efficiency

Information

In every conversion process, released power is less than input power.
The resulting relationship is called efficiency.

Exercise

Complete the following formula.

Efficiency $\eta =$

Complete the table with typical degrees of efficiency.

Component	Consume energy – usable energy	Achieved degree of efficiency [%]
Single stage helical gear box	Mechanical energy – mechanical energy	
Electric motor (10 – 200 W)	Electrical energy – mechanical energy	
Diesel engine	Chemical energy – mechanical energy	
Petrol engine	Chemical energy – mechanical energy	
Centrifugal pump	Mechanical energy – fluidic energy	

If more than one energy conversion takes place, efficiency-degrees for each step are multiplied to get the efficiency for the overall process.

4 Energy analysis and monitoring

4.1 Energetic analysis

Information

In order to be able to conduct an energetic analysis, the system's actual status must first be examined. This analysis is conducted by means of energy monitoring software, which indicates or measures the amount of energy required. This is comparable to the electric meter in a private home.

The pump is running 120 min per day, 5 days per week, 38 weeks a year in training operations.

Exercise

a) How many operating hours is the pump running each year?

b) Which operating mode has the system?

4.2 Determining standby energy consumption

Exercise

a) Record the characteristic curve in standby mode. Work through the steps in the following table to this end.

No.	Work step
1	Open FluidLab® - PA closed loop (→ menu *Setup*)
2	Open FluidLab® - PA energy (→ menu *EnergyMonitoring*)
3	Close manual valves V103, V104, V105, V110 and V112.
4	Open manual valve V101.
5	Switch the pump on until the lower tank is empty. Then stop the pump and close V101. **Make sure that the pump does not run dry!!!**
6	Start the measurement in FluidLab® - PA energy. Then open manual valve V110
7	When the water has run back, stop the measurement.
8	Save the recorded graph.

b) Explain the standby consumption dependent on water level and identify the according devices.

4.3 Determining operating energy consumption

Exercise

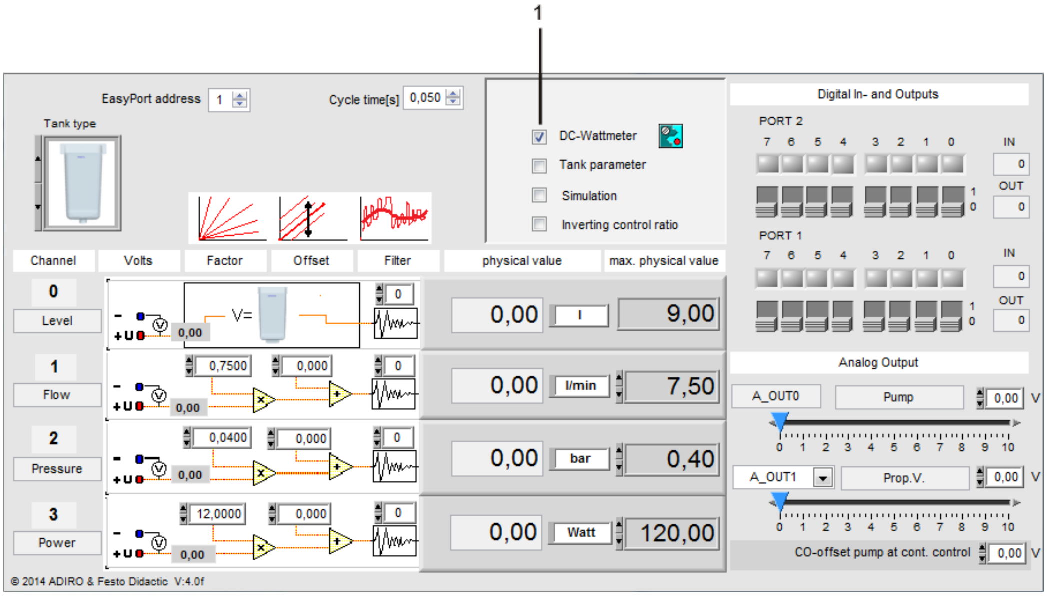
Determine how many time and electrical energy is required to fill the upper tank from 4 litres to 6 litres filling level. The pump should run in binary mode to this end. Follow the instructions below.

No.	Work step
1	Open FluidLab® - PA closed loop (→ menu *Setup*)
2	Open FluidLab® - PA energy (→ menu *EnergyMonitoring*)
3	Close manual valves V103, V104, V105, V110 and V112.
4	Open manual valve V101.
5	Switch the pump on until the upper tank contains about 3.5 litres of water.
6	Start the measurement in FluidLab® - PA energy.
7	After reaching 6 litres in the upper tank stop the measurement and switch off the pump.
8	Save the recorded graph as csv-file and use a spreadsheet software to evaluate how much energy was needed to fill the upper tank from 4 litres to 6 litres.

Note
If the filling level prompt in FluidLab® - PA energy differs from the one in FluidLab® - PA closed loop, compare the tank parameter.

General conditions

- Piping complies with the standard layout.
- The lower tank is to be filled with a constant volume of 10 litres.



1: set checkmark at DC Wattmeter to write data to DataSocket Server.

Required time [s]	Required electrical power(whole system) [Ws]	Required electrical power (pump) [Ws]
27 s	~682 Ws	~416 Ws

5 Reducing energy consumption for increased energy efficiency

5.1 Examination of the main consuming process devices – efficiency of the installed pump

Information

It has already become apparent in advance that the pump has a considerable influence on energy requirements. It is frequently the case that devices within the process are not operated with the best possible settings and working points, and do not achieve the best possible degree of efficiency.

Exercise

a) How do low levels of system efficiency effect energy costs?

b) How can system efficiency for pumping liquid up to the feed tank be ascertained?

c) Complete the following table.
Open menu Setup in FluidLab® - PA closed loop and start FluidLab® - PA energy to this end.

Note

To get a value for efficiency of the pump that is as realistic as possible, the pressure has to be measured immediately after the pump. This is because the flow resistance of the flow sensor causes a pressure loss which falsifies the measurement.

For modifications please follow the instructions of the modification instructions.
Restore the standard layout after finishing the exercises.

Control Voltage [V]	Pump pressure [bar]	Flow rate [l/min]	Hydraulic power [W]	Electrical power [W]	Efficiency [%]
6					
7					
8					
9					
10					

Note
When converting the units of measure bar into Pascal and l/min into cubic m/s, look up the units if necessary and use your results for calculation. Observe factors of magnitude!

Space for your calculations

d) Evaluate your results with regard to the selected settings.

5.2 Examination of the filling variant

Information

Interference caused by, for example, contaminated filters or leaks in the piping system are very costly for the production process, and they impair the system's economic efficiency. But also other constrictions and flow resistances in the pipe can affect energy consumption.
These resistances are to be examined here.

Exercise

a) How does a flow resistance in the pipe affect filling of the upper tank and, consequently, energy required by the pump? Make an initial assumption.

b) Determine time and electrical energy required to fill the upper tank from 4 litres to 6 litres with following filling variants (FV). The pump should run in binary mode to this end.
Fill variant 1 corresponds to the standard layout. (see Exercise 4.3)

> **Note**
> For modifications, needed in the following exercises, please follow the instructions in the Power Point presentation.

1. Replace manual valve V101 by a pipe. (FV 2)
2. Insert a non-return valve in the feed line. (FV 3)
3. Install a rising pipe to fill the tank from above. (FV 4)

Filling variant	Time [s]	Energy [Ws]
1 standard layout		
2 without manual valve		
3 non-return valve instead of manual valve		
4 from above (with manual valve)		

c) Which conclusions do you draw?

5.3 Examination of the controller setting

Information

Energy can be saved by means of control technology as well. For example, the current fill-level of the feed tank (actual value) can be better adapted to the targeted fill-level (target value) by means of reasonable pump control (manipulated value).

Exercise

a) Do the exercise with filling variants FV 4 and FV 1!
Follow the instructions below.

No.	Work step
1	Open FluidLab® - PA closed loop → menu *Closed-loop Control - continuous* (in menu *Setup* the check mark at DC-Wattmeter has to be checked)
2	Select Level control and switch on Out2 (analogue manipulation of pump)
3	Select PI controller (k_p = 10; T_i = 10) and adjust set point to 0.44
4	Start execution
5	Wait until level is at 4 litres for at least 10 seconds
6	Open FluidLab® - PA energy and start measuring
7	Change set point in FluidLab® - PA closed loop to 0.67
8	Stop measurement when filling level is levelled out to 6 litres
9	Save the measurement in FluidLab® - PA energy.

b) Compare the both filling variants. What do you notice?

6 Evaluation of learning objectives

- **Knowledge transfer exercise**

Peter watches television 2 hours a day. He has an old television in his room with a satellite receiver (together they require 25 W in standby mode). Peter also enjoys listening to music – for 2 hours a day, he says. His stereo system consumes 15 W in standby mode.

1. What is Peter's annual standby consumption? Calculate the electrical power costs assuming a price of €0.20 per kWh for private housholds.

2. How can these costs be avoided?

3. Evaluate your own energy habits. How could you save energy or electrical power in your daily routine?

Refresher exercises

1. Why does it make good sense to save energy?

2. Explain why energy consumption is specified for the system in terms of watt hours instead of watts per hour. Justify your explanation with a formula.

3. Explain the term efficiency.

4. How can efficiency of the system be determined for pumping water up?

5. Make a note of some energy optimising options within the production process.

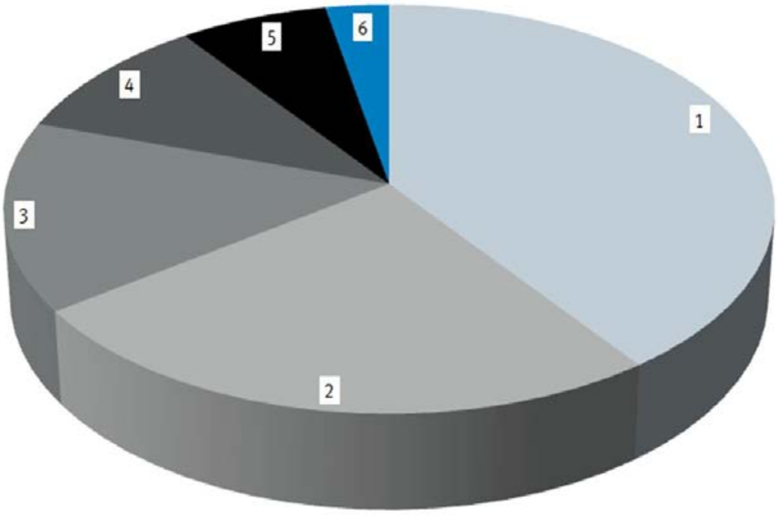
Solutions Module 30 – Energy monitoring, analysing and optimizing of a pump

1 Energy consumption and power generation – Fundamentals

1.3 Consumption of primary energy

Exercise

a) Allocate the most important sources of primary energy in your country / region according to their percentage of consumption. Fill in the percentages and the energy sources.



1.	.... %	4.	.... %
2.	.... %	5.	.... %
3.	.... %	6.	.... %

b) Name at least two sources and one advantage of the use of renewable energy:

- Solar energy (electricity from photovoltaics)
- Directly usable solar radiation: light, heat
- Biomass
- Wind energy
- Hydropower (including wave power, tidal power)
- Geothermal energy.

Renewable energy offers great potential for reducing CO2 emissions significantly.
This protects our climate and the future of people around the world.

1.4 Energy saving in daily life

Exercise

Describe three actions that can contribute to the saving of energy in your daily life:

a) Don't leave your mobile phone charger plugged in when you have finished charging your phone.

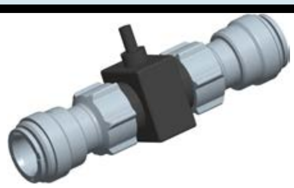
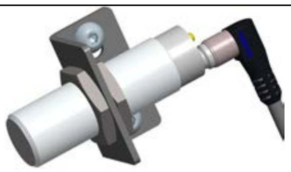
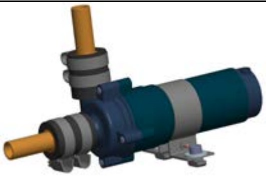
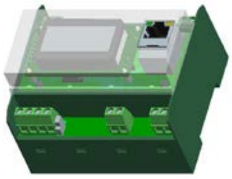
b) Replace light bulbs by LED lamps.

c) Replace your WC cistern by a modern one with water saving economy flush.

2 System layout and function analysis

2.2 Function analysis of the components

– Fill in the following worksheet with the help of the data sheets.

Individual system components			
	Designation: Tank Function: Storage of the fluid Working range: 10.0 litres		Designation: Flow sensor Function: Ascertainment of volumetric flow rate Measuring range: 0.3 to 0.9 l/min
	Designation: Ultrasonic sensor Function: Analogue fill-level indicator in the upper tank Measuring range: 0 – 9 litres		Designation: Capacitive sensor Function: Digital fill-level indicator e.g. for switching the pump off when the upper/lower limit value is reached in the lower tank
	Designation: Centrifugal pump Operating voltage: 24 V DC Max. flow rate: 10 l/min Power: 26 W		Designation: DC wattmeter Function: Measures voltage and current, computes power Sampling rate: 5 measurements per second Indicating range: 0.0 to 120.0 W 0.0001 to 5000.0 Wh

3 Forms of Energy, efficiency and power

3.1 Energy

Exercise

Complete the following table with typical examples.

Order of magnitude	Practical example
W [Ws]	Small electrical devices
W [kWh]	Billing for private households, lower power range
W [MWh]	Power plants

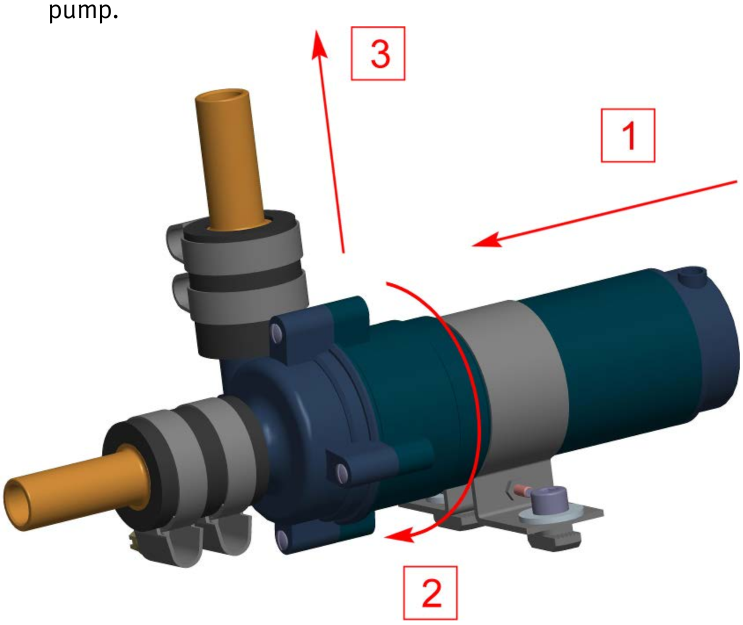
3.2 Power

Exercise

a) Name the various types of power at the centrifugal pump.

Electrical power, mechanical power, hydraulic power (also applies to the order in which the types of power occur for the exercise below with arrows)

b) Label the arrows at the pump in the following figure with the different types of power for the centrifugal pump.



1: electrical power, 2: mechanical power, 3: hydraulic power

c) Complete the computation formulas of the different power types:

Type of power at the pump	Formula
Mechanical power	$P = M \cdot \omega = 2 \cdot \pi\ n\ M$ (numeric value equation: P[kW] = M[Nm] · n[min-1] / 9550)
Hydraulic power	$P = Q \cdot p$ (numeric value equation: P[kW] = Q[l/min] · p[bar] / 600)
Electric power	$P = U \cdot I$ (numeric value equation: P[kW] = U[V] · I[A] / 1000)

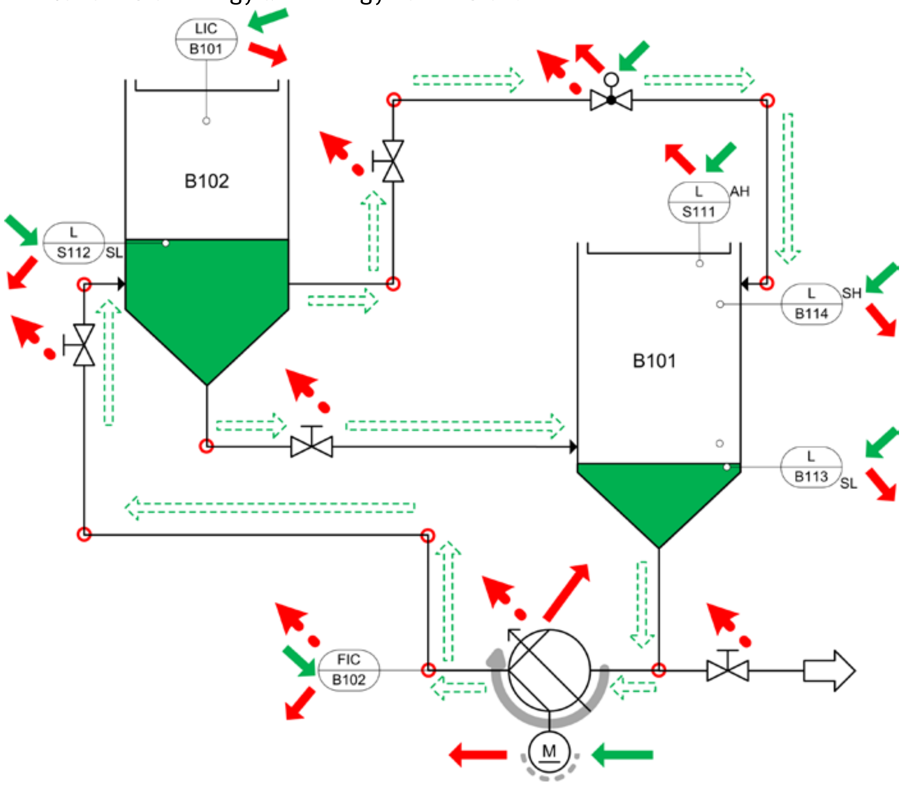
3.3 Forms of energy

Exercise

a) Calculate potential energy in the feed tank with 2 litre of water. Measure the difference in height to this end (you will need a folding rule).

$E = m \cdot g \cdot h = 2\ kg \cdot 9.81\ m/s^2 \cdot 0.3\ m = 5.886\ J$

b) Together with your team, think about the meanings the different colours and symbols have with regard to forms of energy and energy conversion.



c) Draw lines from the symbols to the appropriate designation which appear in random order.

Symbol	Connecting line	Designation
		Kinetic energy (liquid)
		Electrical (input) power
		Potential energy
		(Released) thermal energy
		Flow resistance
		Hydraulic power
		Mechanical power
		Flow energy dissipation (due to branch)

3.4 Efficiency

Exercise

Complete the following formula.

Efficiency $\eta = P_{out} / P_{in}$

Complete the table with typical degrees of efficiency.

Component	Consume energy – usable energy	Achieved degree of efficiency [%]
Single stage helical gear box	Mechanical energy – mechanical energy	~98
Electric motor (10 – 200 W)	Electrical energy – mechanical energy	50 – 90
Diesel engine	Chemical energy – mechanical energy	Up to 50
Petrol engine	Chemical energy – mechanical energy	35 – 40
Centrifugal pump	Mechanical energy – fluidic energy	60 – 90

4 Energy analysis and monitoring

4.1 Energetic analysis

Exercise

a) How many operating hours is the pump running each year?

38 weeks · 5 d/week · 120 min/d ·1/60 h/min = 380 h

b) Which operating modes has the system?

System on
System off
Stand by

4.2 Determining standby energy consumption

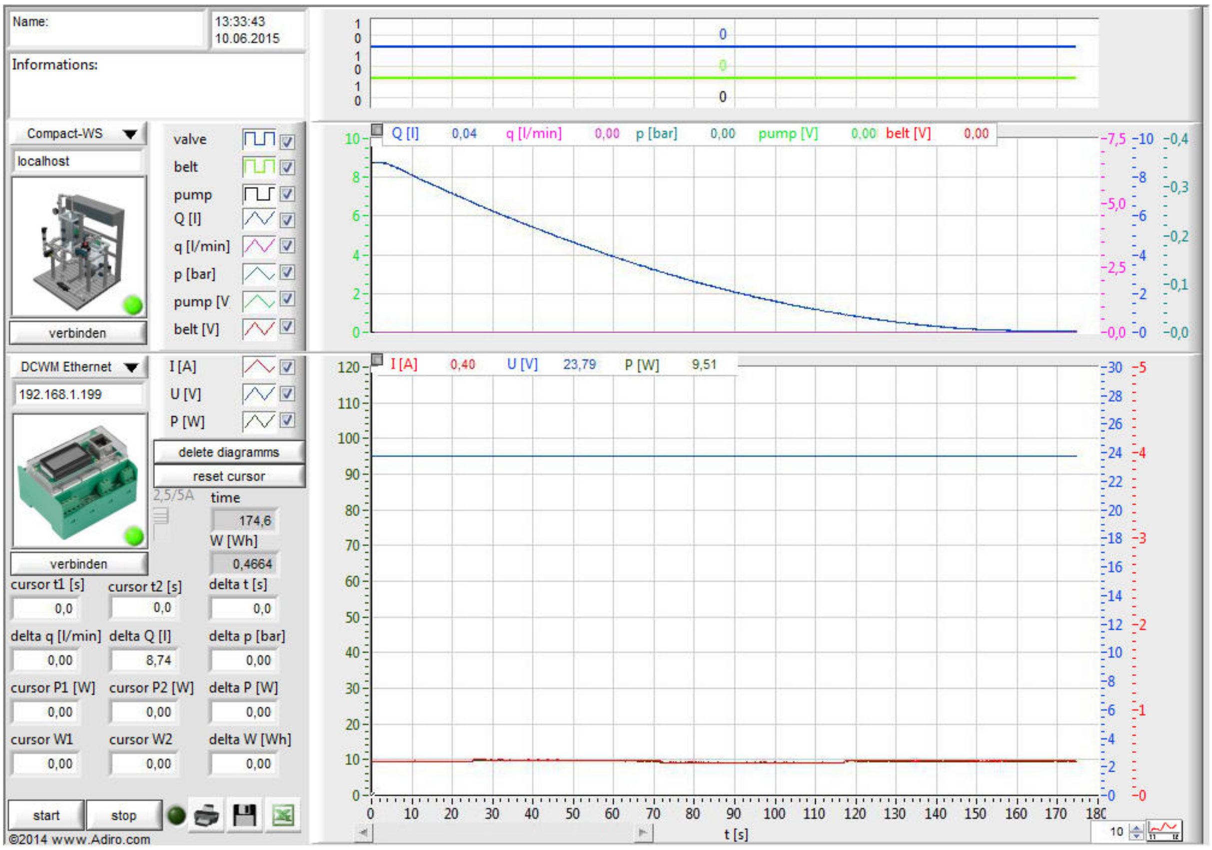
Exercise

a) Record the characteristic curve in standby mode. Work through the steps in the following table to this end.

b) Explain the standby consumption dependent on water level and identify the according devices.

By plotting the consumed power over the filling level, one gets a diagram which shows a linear function with several discontinuities. Depend on how much water is in the system, the edges can shift relative to each other. This is because the electrical consumers are in different tanks.
Starting with a filled upper tank, the first edge is generated by switching of the lower capacitive sensor (B113), the second by the floating switch in the upper tank (S112) and the last one by the upper capacitive sensor (B114).
The linear component is caused by the analogue signal of the ultrasonic sensor (B101), which shows the measured value in form of a current (4 ... 20 mA).
The switching of the floating switch in the lower tank is not visible because it is connected directly to the heater and switches no input of the EasyPort.

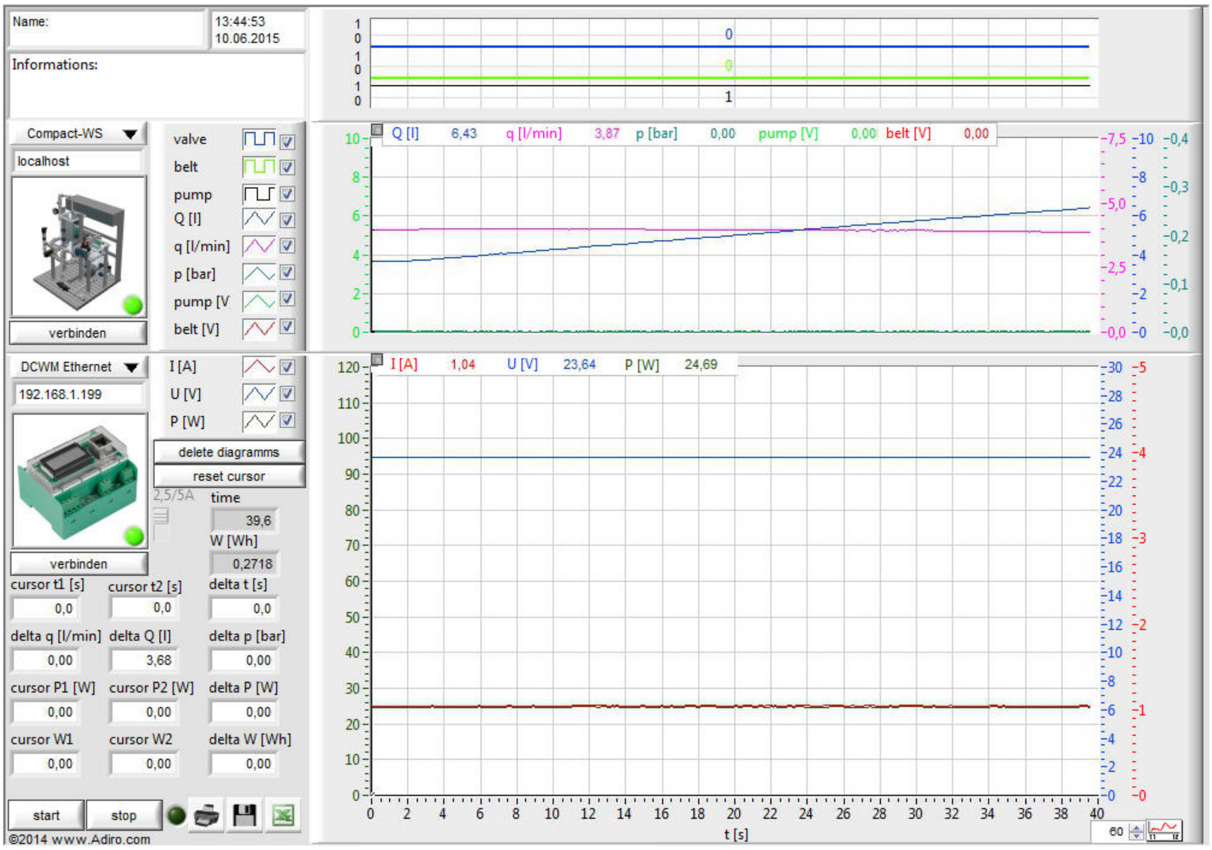
One can see the consumption of a capacitive sensor plus an EasyPort-input (~500 mW) and, by switching the floating switch, the consumption of a single EasyPort-input (~350 mW).


Name:
13:33:43
10.06.2015
Informations:
Compact-WS
localhost
verbinden
valve
belt
pump
Q [l]
q [l/min]
p [bar]
pump [V
belt [V]
DCWM Ethernet
192.168.1.199
verbinden
I [A]
U [V]
P [W]
delete diagramms
reset cursor
time
174,6
W [Wh]
0,4664
cursor t1 [s]
cursor t2 [s]
delta t [s]
delta q [l/min]
delta Q [l]
delta p [bar]
cursor P1 [W]
cursor P2 [W]
delta P [W]
cursor W1
cursor W2
delta W [Wh]
start
stop
©2014 www.Adiro.com
Q [l] 0,04 q [l/min] 0,00 p [bar] 0,00 pump [V] 0,00 belt [V] 0,00
I [A] 0,40 U [V] 23,79 P [W] 9,51
t [s]

4.3 Determining operating energy consumption

Exercise

Required time [s]	Required electrical power(whole system) [Ws]	Required electrical power (pump) [Ws]
27 s	~682 Ws	~416 Ws



5 Reducing energy consumption for increased energy efficiency

5.1.1 Examination of the main consuming process devices – efficiency of the installed pump

Exercise

a) How do low levels of system efficiency effect energy costs?

I need more energy in order to run the desired filling process, and my costs are higher as a result.

b) How can system efficiency for pumping liquid up to the feed tank be ascertained?

I fill the top tank with the help of the pump and measure pressure and flow rate while doing so. Hydraulic power can be calculated with the resulting values ($P_{hyd} = Q \cdot p$ measured), and electrical power can be measured with the help of energy monitoring software. Efficiency can then be calculated as follows: $\eta = P_{out} / P_{in} = P_{hyd} / P_{el}$

c) Complete the following table.
Open menu Setup in FluidLab® - PA closed loop and start FluidLab® - PA energy to this end.

Control Voltage [V]	Pump pressure [bar]	Flow rate [l/min]	Hydraulic power [W]	Electrical power [W]	Efficiency [%]
6	0.121	2.473	0.498	7.892	6.3
7	0.156	2.939	0.765	9.937	7.7
8	0.197	3.396	1.116	12.299	9.1
9	0.246	3.841	1.575	14.271	11.0
10	0.263	4.003	1.756	14.947	11.7

Units of measure:
1 bar = 10^5 Pa = 10^5 N / m^2
l / min = dm^3 / 60 s = $10^{-3} \cdot$ m^3 / 60 s

Formula:
P[W] = Q[l / min] $\cdot$ p[bar]
$\eta = P_{out} / P_{in} = P_{hyd} / P_{el}$

Example – calculation of efficiency with 10 V control voltage:

→ Calculation of hydraulic power

$P = 4.003 \cdot 10^{-3} / 60\,[m^3 / s] \cdot 10^5 \cdot 0.263\,[N / m^2]$
$= 4.003 \cdot 0.263 \cdot 100 / 60\,[m / s] \cdot [kg \cdot m / s^2]$
$= 1.756\,[kg\,m^2 / s^3] = 1.756\,[W]$

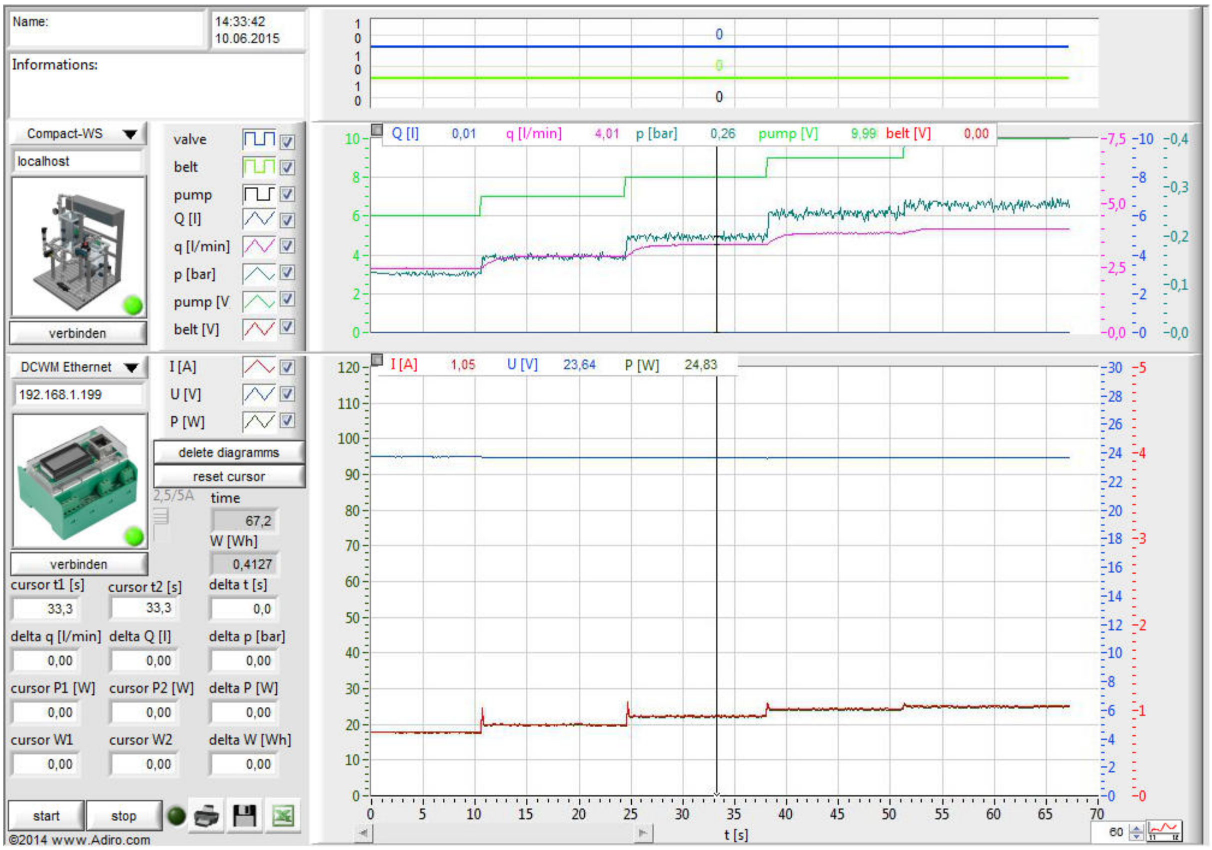
Or by means of formula from book of tables: P[kW] = Q[l / min] $\cdot$ p[bar] / 600

→ Calculation of efficiency

$\eta[\%] = P_{in} / P_{out} \cdot 100 = P_{hyd} / P_{el} \cdot 100 = 1.756\,[W] / 14.974\,[W] \cdot 100 = 11.7$

d) Evaluate your results with regard to the selected settings.

The greatest degree of efficiency is achieved for pumping water up with a control voltage of 10 V.



5.2 Examination of the filling variant

Exercise

a) How does a flow resistance in the pipe affect filling of the upper tank and, consequently, energy required by the pump? Make an initial assumption.

The flow resistance leads to a rise of pressure, which must be overcome by the pump. Therefor the pump needs more energy.

b) Determine time and electrical energy required to fill the upper tank from 4 litres to 6 litres with following filling variants (FV). The pump should run in binary mode to this end.
Fill variant 1 corresponds to the standard layout. (see Exercise 4.3)

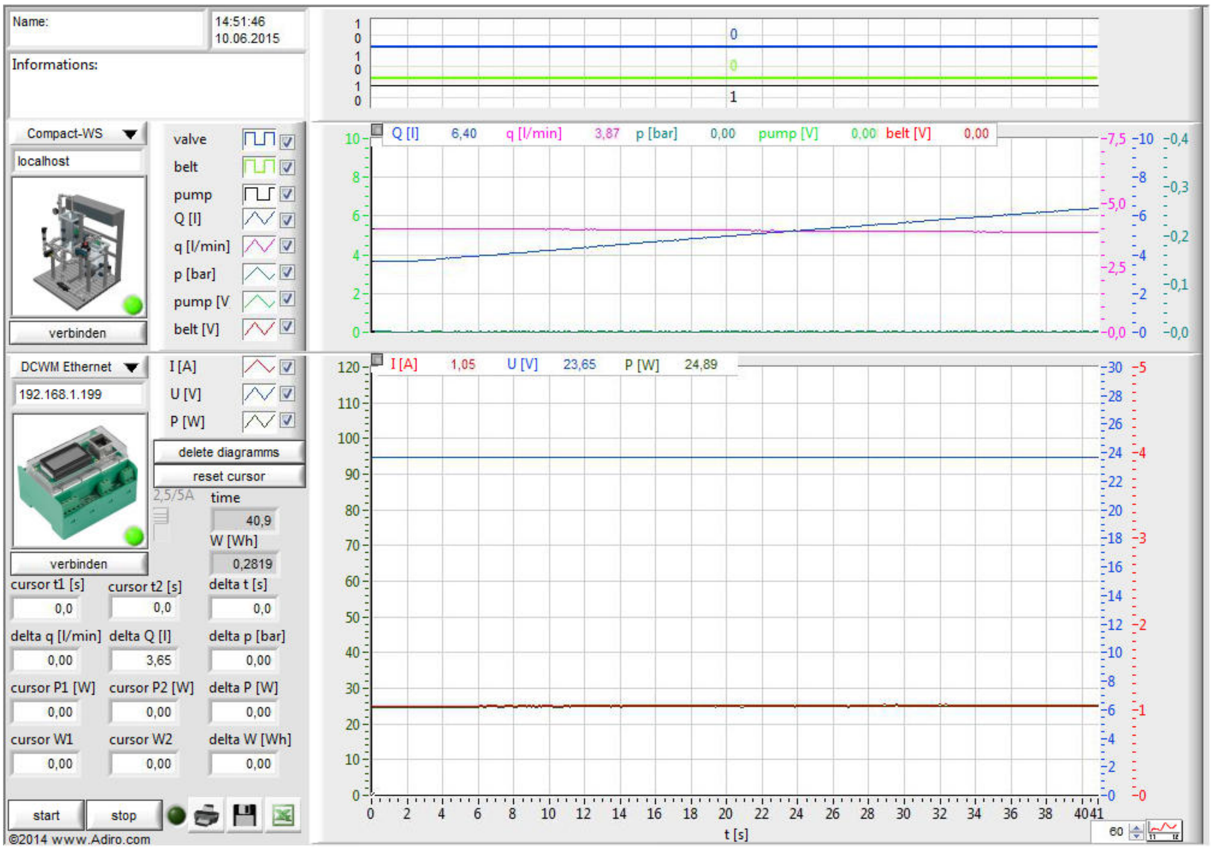
Filling variant	Time [s]	Energy [Ws]
1 standard layout	28.0	432.4
2 without manual valve	28.0	432.4
3 non-return valve instead of manual valve	37.5	568.7
4 from above (with manual valve)	29.8	457.2

c) Which conclusions do you draw?

Filling variant FV 1 and FV 2 show no difference, so the manual valve represents no significant flow resistance. Regarded to energy efficiency these variants are favourable, but with the utilized centrifugal pump the water flows back to the lower tank after switching off the pump.

Filling variant FV 3 with non-return valve produces the worst result.

Filling variant FV 4 requires a little more energy than FV 1 and FV 2, but the water stays in the upper tank without any manual intervention.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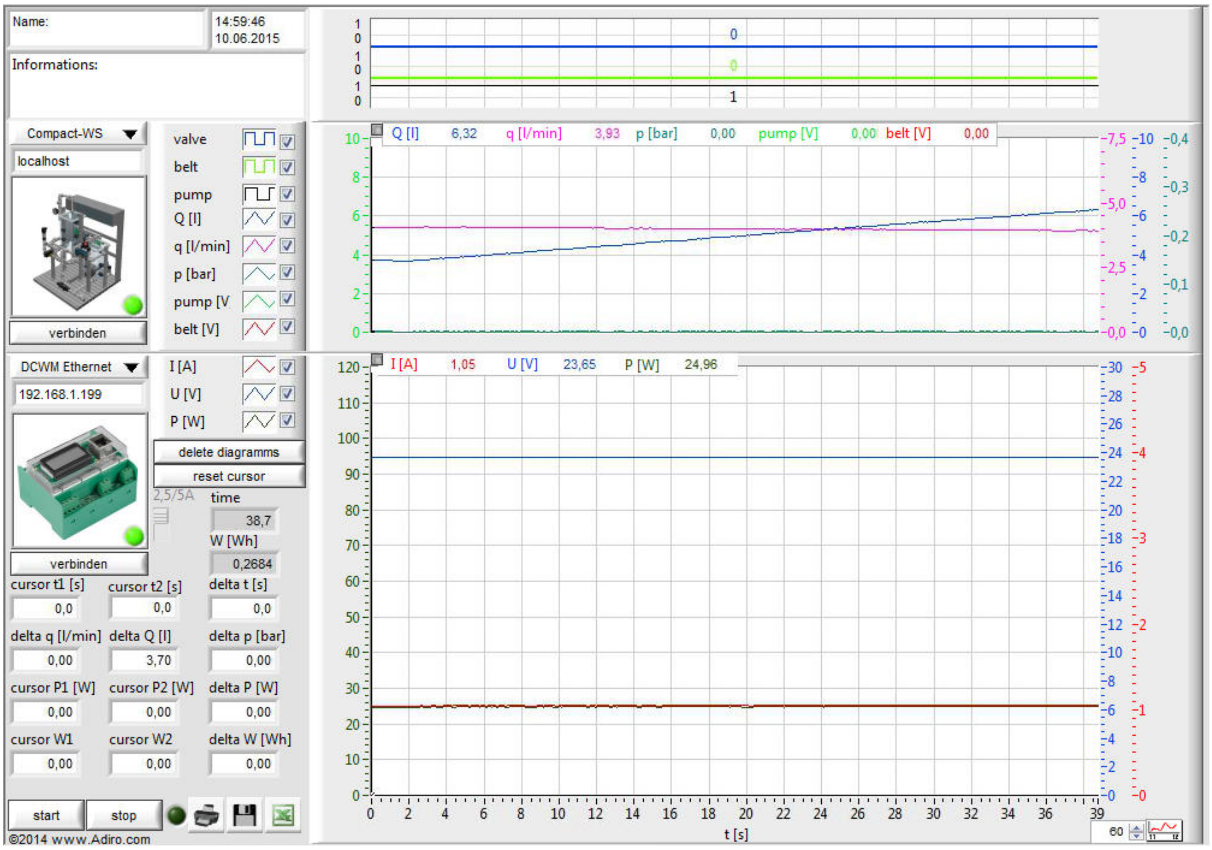
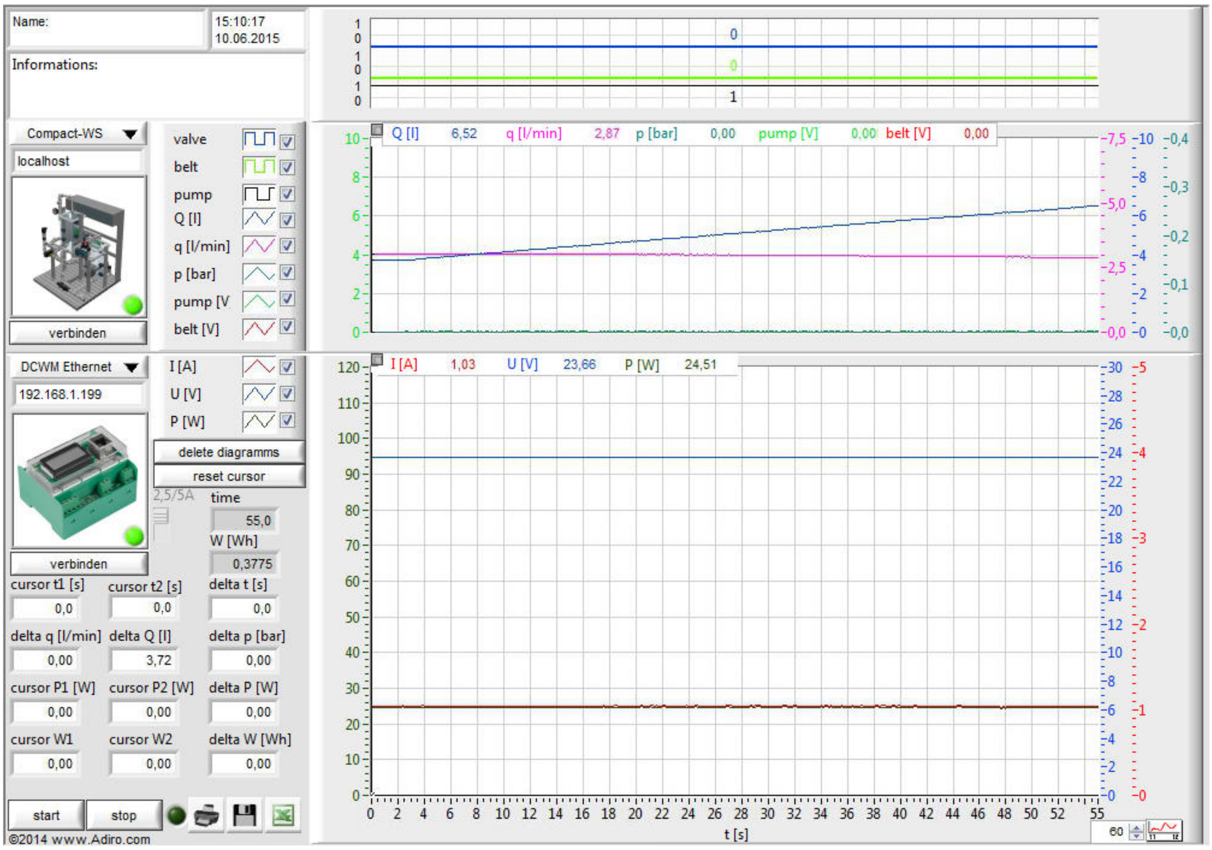
10.06.2015
Informations:
Compact-WS
localhost
verbinden
valve
belt
pump
Q [l]
q [l/min]
p [bar]
pump [V
belt [V]
Q [l] 6,40 q [l/min] 3,87 p [bar] 0,00 pump [V] 0,00 belt [V] 0,00
DCWM Ethernet
192.168.1.199
verbinden
I [A]
U [V]
P [W]
delete diagramms
reset cursor
2,5/5A
time
40,9
W [Wh]
0,2819
I [A] 1,05 U [V] 23,65 P [W] 24,89
cursor t1 [s] 0,0
cursor t2 [s] 0,0
delta t [s] 0,0
delta q [l/min] 0,00
delta Q [l] 3,65
delta p [bar] 0,00
cursor P1 [W] 0,00
cursor P2 [W] 0,00
delta P [W] 0,00
cursor W1 0,00
cursor W2 0,00
delta W [Wh] 0,00
start
stop
©2014 www.Adiro.com
t [s]
60

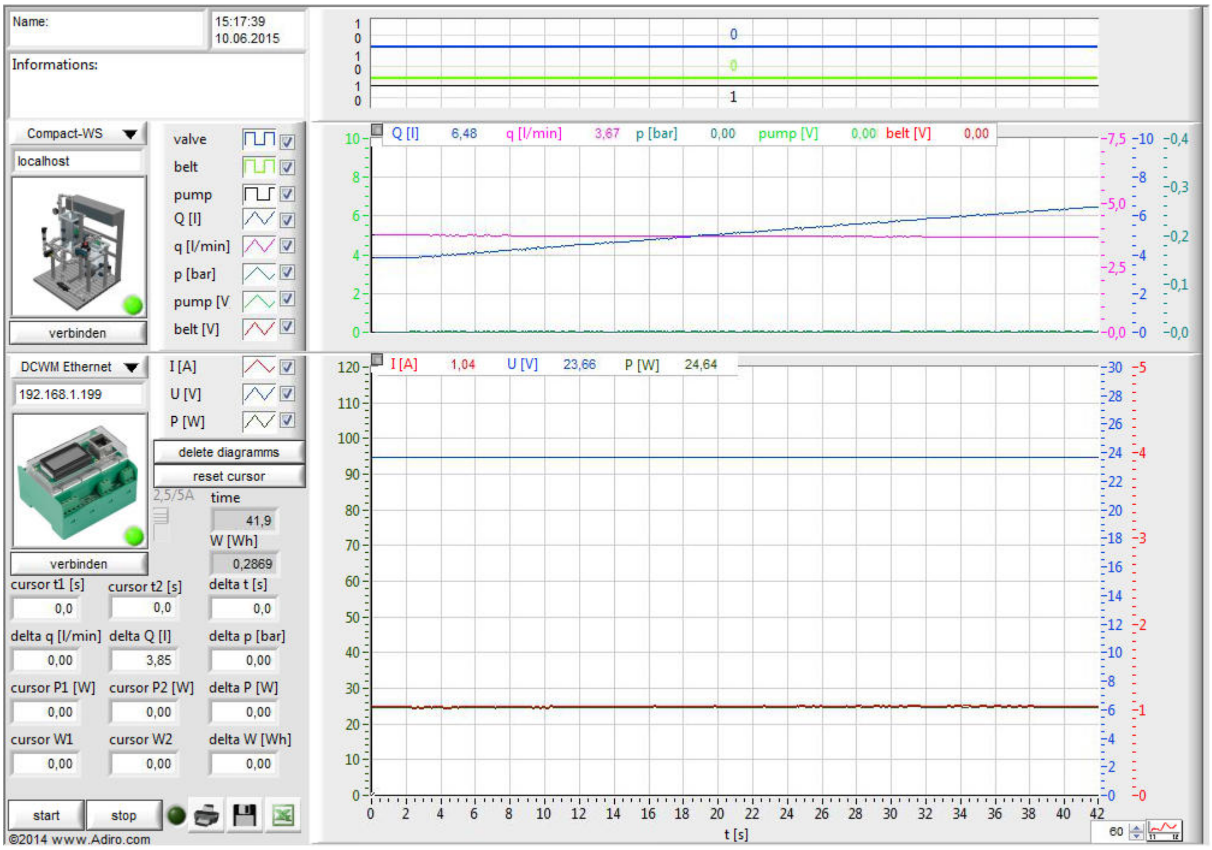
FV1


Name:
14:59:46
10.06.2015
Informations:
Compact-WS
localhost
verbinden
valve
belt
pump
Q [l]
q [l/min]
p [bar]
pump [V
belt [V]
Q [l] 6,32 q [l/min] 3,93 p [bar] 0,00 pump [V] 0,00 belt [V] 0,00
DCWM Ethernet
192.168.1.199
verbinden
I [A]
U [V]
P [W]
delete diagramms
reset cursor
2,5/5A
time
38,7
W [Wh]
0,2684
I [A] 1,05 U [V] 23,65 P [W] 24,96
cursor t1 [s] 0,0
cursor t2 [s] 0,0
delta t [s] 0,0
delta q [l/min] 0,00
delta Q [l] 3,70
delta p [bar] 0,00
cursor P1 [W] 0,00
cursor P2 [W] 0,00
delta P [W] 0,00
cursor W1 0,00
cursor W2 0,00
delta W [Wh] 0,00
start
stop
©2014 www.Adiro.com
t [s]
60

FV2



FV3



FV4

5.3 Examination of the controller setting

Information

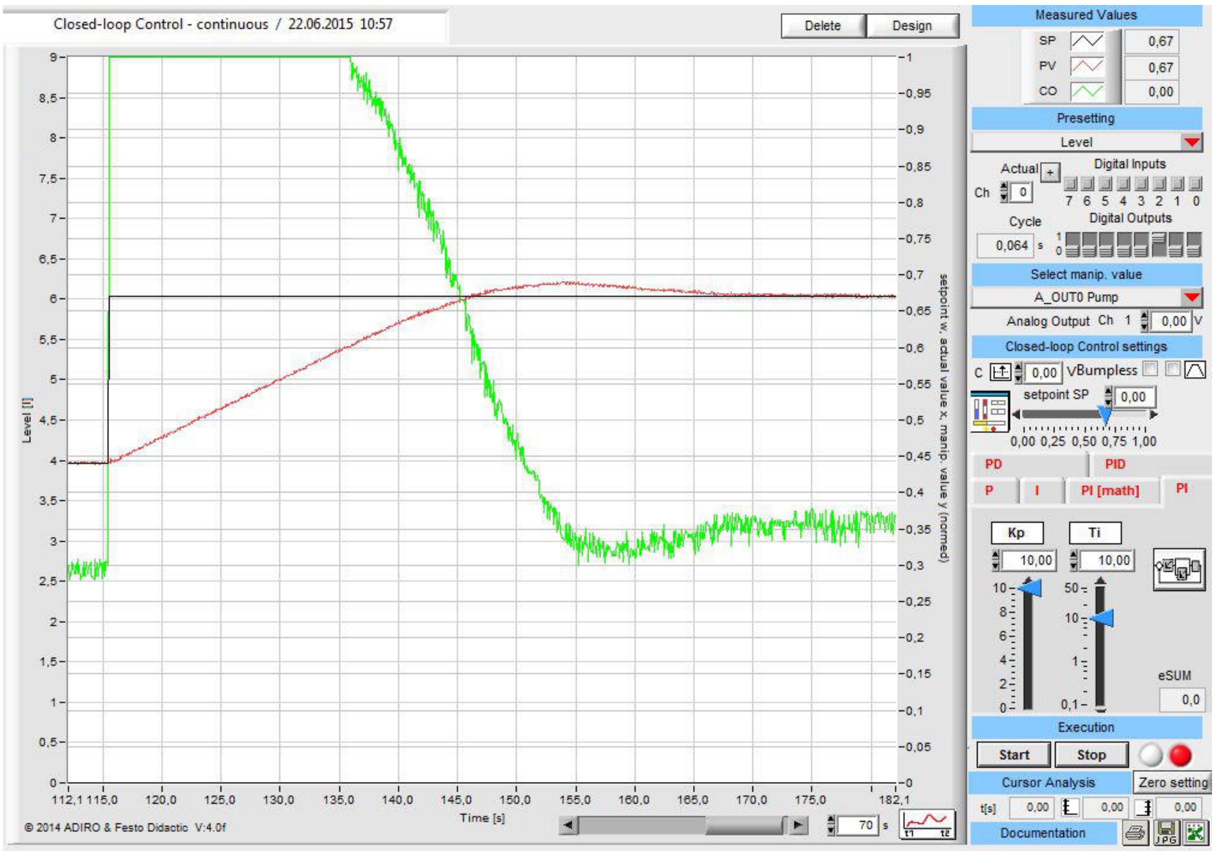
Energy can be saved by means of control technology as well. For example, the current fill-level of the feed tank (actual value) can be better adapted to the targeted fill-level (target value) by means of reasonable pump control (manipulated value).

Exercise

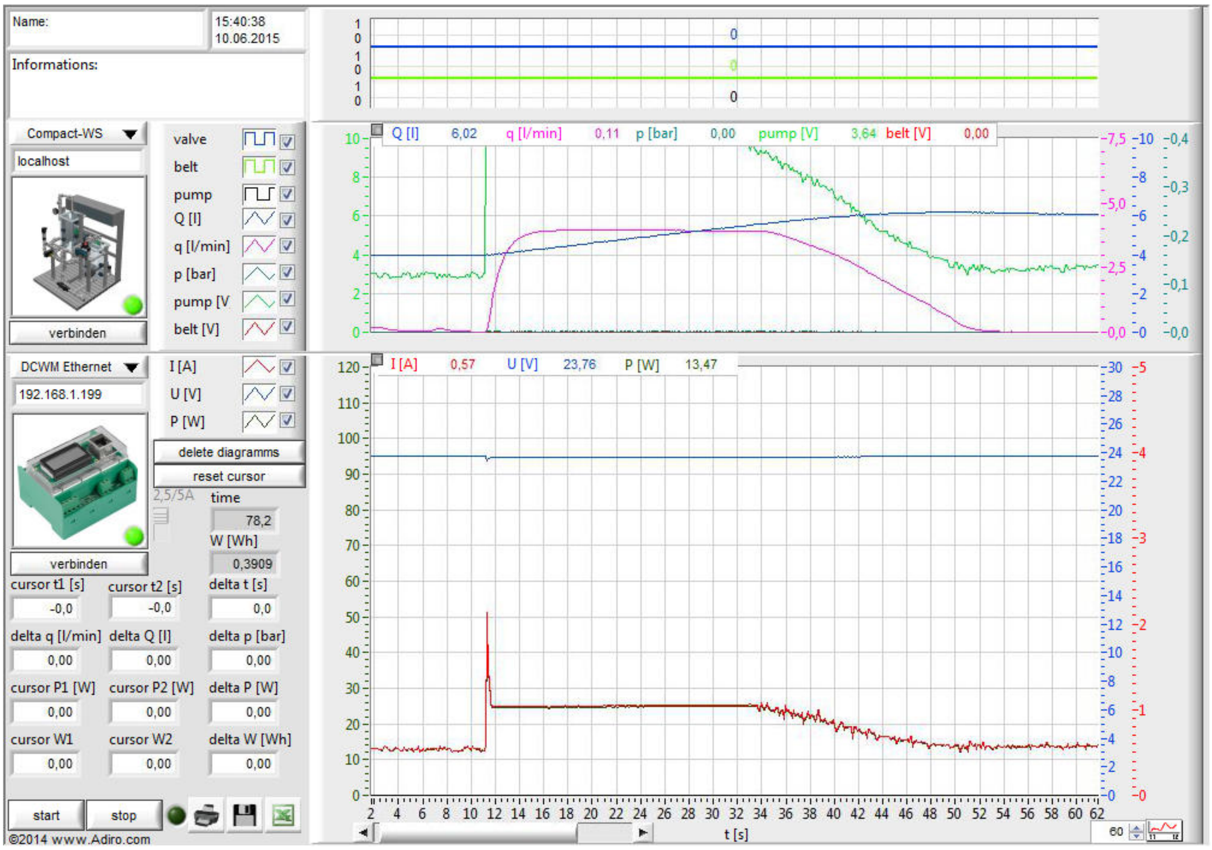
a) Do the exercise with filling variants FV 4 and FV 1!
Follow the instructions below.

b) Compare the both filling variants. What do you notice?

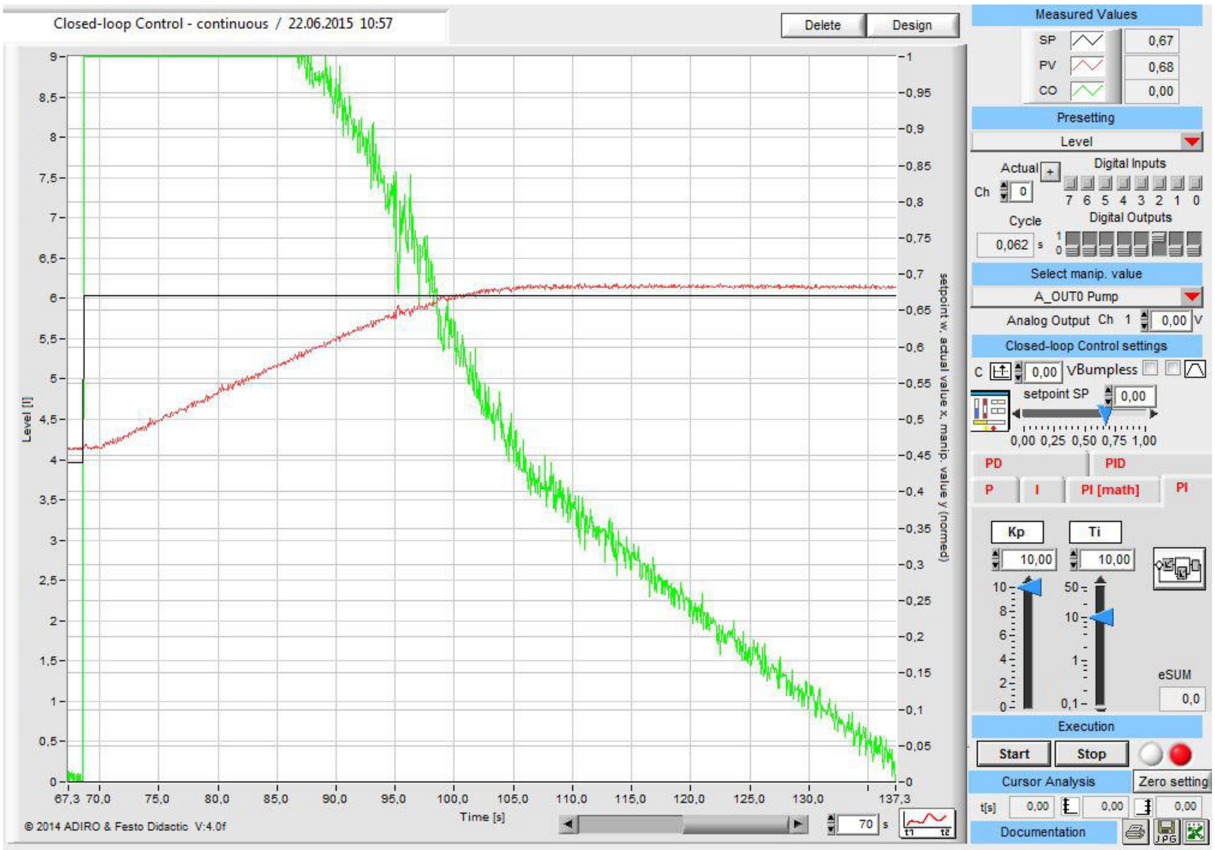
With filling from below the desired level is reached more accurate. This is due to the possibility of the water to run backwards through the pump in the lower tank, while with filling from above and closed outlet valves no water can flow back.
Filling from above needs little more time, due to the fact that flow rate is a bit lower because of the hydrostatic pressure, which has to be overcome.
After reaching the set point the pump is regulated slowly down until it stops. With filling from below the pump is forced to keep running to maintain the filling level.



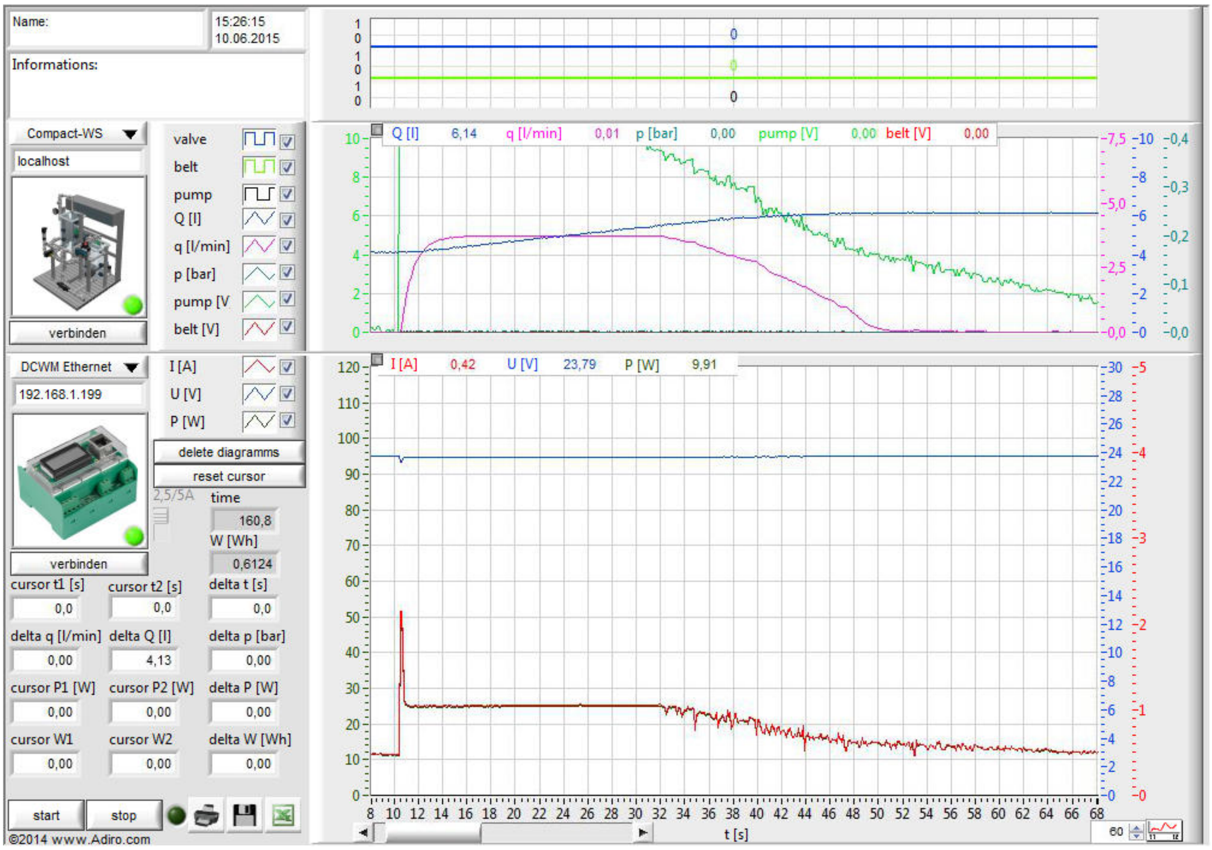
FluidLab® - PA closed loop FV1



FluidLab® - PA energy FV1



FluidLab® - PA closed loop FV4



FluidLab® - PA energy FV4

6 Evaluation of learning objectives

Knowledge transfer exercise

Peter watches television 2 hours a day. He has an old television in his room with a satellite receiver (together they require 25 W in standby mode). Peter also enjoys listening to music – for 2 hours a day, he says. His stereo system consumes 15 W in standby mode.

1. What is Peter's annual standby consumption? Calculate the electrical power costs assuming a price of €0.20 per kWh for private housholds.

   25 W + 15 W = 40 W
   40 W · 22 h = 880 Wh = 0.88 kWh per day
   0.88 kWh per day · 365 days = 321.2 kWh per year

   321.2 kWh · €0.20 per kWh = annual costs of €64.24!

2. How can these costs be avoided?

   Switch off the electronic devices completely with the help of a multiple outlet strip.

3. Evaluate your own energy habits. How could you save energy or electrical power in your daily routine?

   I could ...

Refresher exercises

1. Why does it make good sense to save energy?

   The actual problem surrounding the "energy" issue is power generation, because this results in high levels of emission to the environment. On the one hand, CO_2 is emitted through the use of coal and crude oil, and people may be exposed to dangerous levels of radioactivity through the use of nuclear power, which also involves the problems of final disposal and conditioning of nuclear waste.

2. Explain why energy consumption is specified for the system in terms of watt hours instead of watts per hour. Justify your explanation with a formula.

   Energy is defined as power times time.
   The following applies to the calculation of electrical power:
   $P[\mathrm{W}] = U[\mathrm{V}] \cdot I[\mathrm{A}]$, and for electrical energy: $W[\mathrm{Wh}] = P[\mathrm{W}] \cdot t[\mathrm{h}]$

3. Explain the term efficiency.

   Regardless of the energy conversion process, input energy can never be fully converted to useful energy. The relationship of useful energy to input energy is efficiency.

4. How can efficiency of the system be determined for pumping water up?

   Pressure and flow rate can be measured while pumping water to the upper tank. Hydraulic power during pumping can be obtained by multiplying these two quantities. Required electrical power is ascertained with the help of energy monitoring software. Efficiency is arrived at by means of calculation (P_{hyd}/P_{el}).

5. Make a note of some energy optimising options within the production process.

   - Use more efficient components.
   - Adjust consuming devices more carefully in order to improve their efficiency.
   - A more favourable piping layout reduces filling time.
   - Standby consumption can be reduced for the system.
   - The filling strategy can be changed.