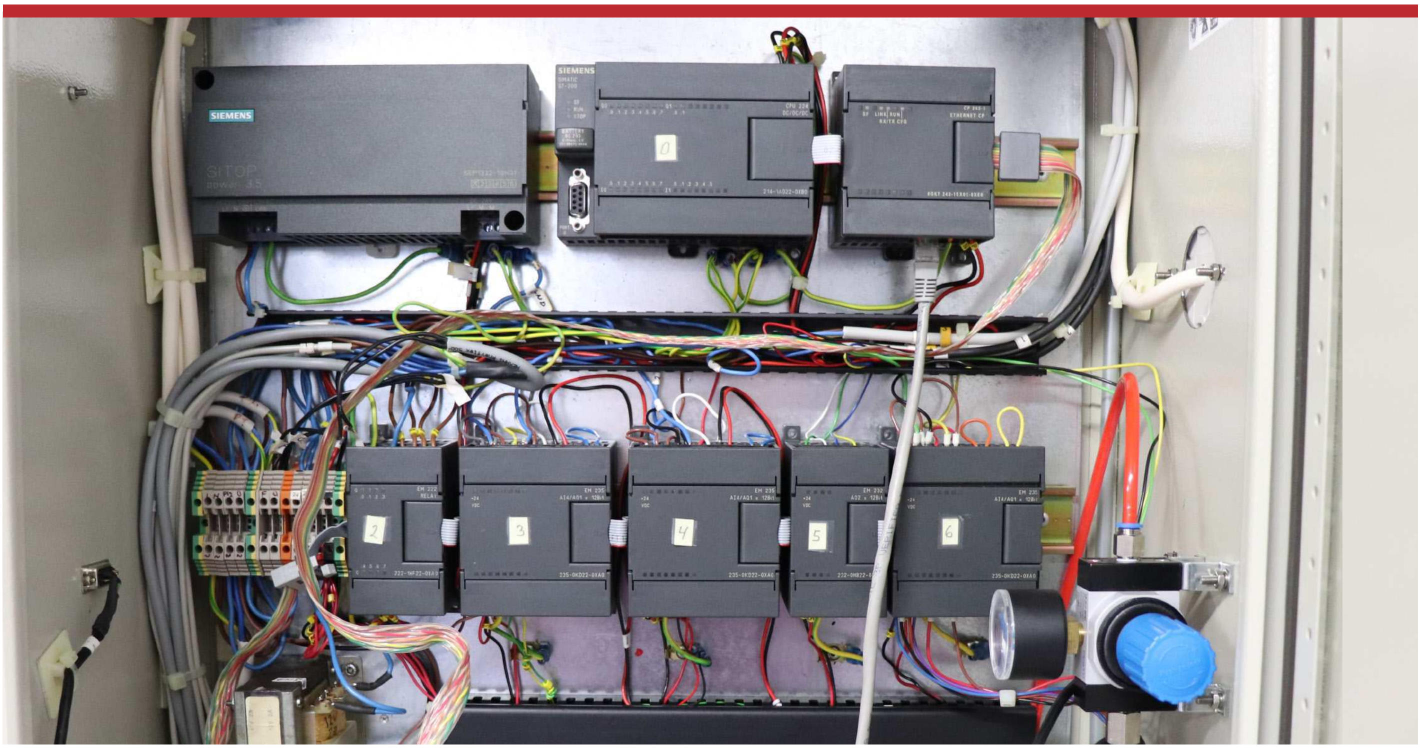
Implementation of Advanced Process Control on the Four Tank Pilot Plant

DTU Compute Technical Report 2017-02



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August 2017

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Abstract

The four tank process laboratory experiment is used as a relevant case to unfold problems that arise when implementing advanced process control such as model predictive control.

The controller, which is executed on a computer, and the process equipment communicate using OPC to exchange process measurements and actuator set points. The process equipment is described along with the setup of the PLC and the OPC server in order to be able to access process variables on a dimensional scale.

A process emulator in which a process simulator is embedded in an OPC interface has been developed in Python. Using the detailed information of sensor and actuator calibration as well as PLC functionality, the emulator appears identical to the actual process and may be used to perform virtual tests of controllers prior to commissioning. Examples of how to interact with OPC servers are presented for both Matlab and Python.

An MPC has been designed based on a linearized model of the process and tested using the emulator. This controller was then implemented on a realization of the process at the Technical University of Denmark, demonstrating MPC experimentally.

Acknowledgments

We acknowledge Innovation Fund Denmark in the project "CITIES: Centre for IT-Intelligent Energy Systems in Cities" (1305-00027B) for the partial funding of this work.

Contents

1 Introduction

This report introduces a range of issues that arise when implementing process control on a physical system using the four tank process as a representative case. For a description of the process the reader is referred to Henrik Johansson [1].

A model predictive controller (MPC) may be designed by performing simulations of a system as shown in Figure 1. The controller is designed and tuned to obtain the desired response with regards to process output, subject to a given reference trajectory $\mathbf{r}$ and a series of disturbances $\mathbf{d}$ some of which, $\mathbf{d_m}$, are measured. At this stage of control design one not only has access to the true system states $\mathbf{x}$ but one may also make use of dimensional values of the disturbances, measurements $\mathbf{y}$ and the manipulated variables $\mathbf{u}$. Hence the MPC will also require dimensional values when implemented in practice.

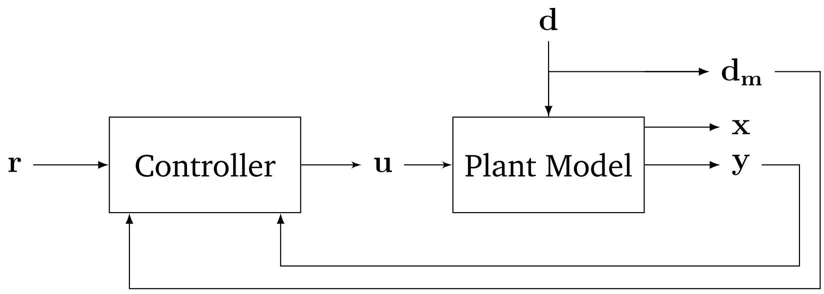


Figure 1: System considered in the design phase.

The MPC may communicate with the plant through an Open Platform Communications (OPC) interface as illustrated in Figure 2. OPC is a standard for the exchange of data between industrial equipment using a client-server model[2]. The OPC layer facilitates data exchange between the programmable logic controller (PLC) level and the control algorithm running on a computer. The OPC server may offer values of $\mathbf{d_m}$ and $\mathbf{y}$, and require values of $\mathbf{u}$, on an arbitrary scale thus necessitating calibration of sensors and actuators in order to be compatible with the MPC designed using dimensional values. Furthermore, data exchange may fail at any time due to a number of reasons and an industrial MPC should be designed to handle this gracefully. Fault detection and safety precautions are not covered in the present report.

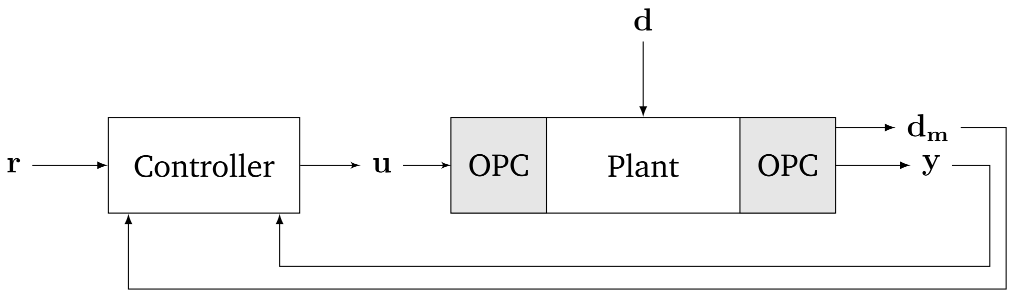


Figure 2: System considered in the implementation phase.

There may also be other applications which exchange data using OPC e.g. ERP (Enterprise Resource Planning), database, HMI (Human Machine Interface), SCADA (Supervisory Control And Data Acquisition), PLC (Programmable Logic Controller), alarm, cloud and GUI (General User Interface) applications among others as illustrated in Figure 3.

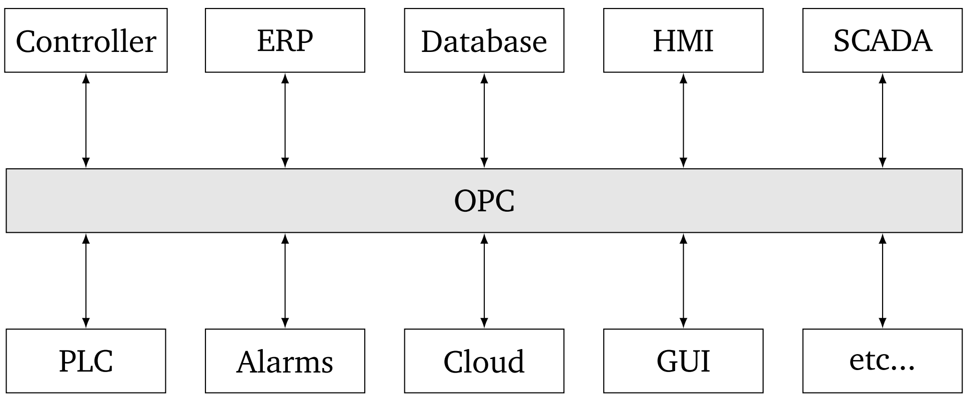


Figure 3: OPC as a common communication channel.

The present report is concerned with the implementation phase and does not cover the design phase. Initially the four tank process is described in terms of equipment and software. Sensor and actuator calibration procedures are also discussed. This description is followed by a few minimal and elaborate code examples which show how to connect and communicate with an OPC server using Matlab or Python. Then a process emulator which may be used for testing a regulator which communicates through an OPC interface is presented. This emulator may be used as a substitute for the actual plant during development since its OPC interface is identical to that of the actual plant. Finally, an MPC which regulates the four tank process is demonstrated.

2 Process Description

A PI&D of the four tank process is presented in Figure 4. The process offers measurements and actuators as listed:

1. Hydrostatic pressure measurements: LT1, LT2, LT3, LT4
2. Flow rate measurements: FT1, FT2
3. On/off magnetic valve actuators: MV1, MV2, MV3, MV4
4. 3-way control valve actuators: V1, V2
5. Pump actuators: P1, P2

These measurements and actuators may be accessed on a computer through an OPC Data Access (OPC-DA) or OPC Unified Access (OPC-UA) interface.

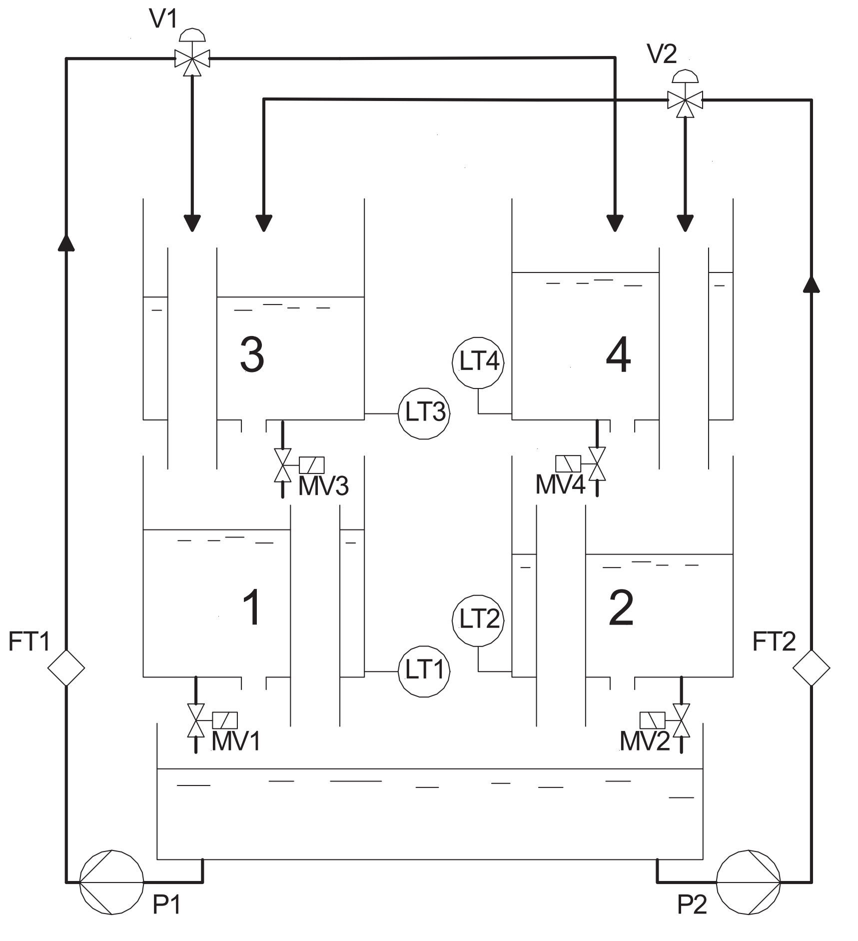


Figure 4: Process instrumentation diagram of the four tank process.

The equipment is described in Section 2.1 while the software is described in Section 2.2.

2.1 Equipment

The equipment comprises the process equipment listed in Table 1, PLC equipment listed in Table 2 and a desktop computer which operates OPC-DA and OPC-UA servers. Datasheets for the equipment are listed in Appendix C.

Table 1: Process equipment.

PID Id.	Brand	Model	Interfaces
V1, V2	Samson	3226, I/P positioner 3760	$4-20\,\mathrm{mA}$
MV1–MV4	Bürkert	6213	0 or $10\,\mathrm{V}$
LT1–LT4	Siemens SITRANS	7MF1563-3AA-00	$4-20\,\mathrm{mA}$
FT1, FT2	Danfoss MAG	1100/5000	$4-20\,\mathrm{mA}$
P1, P2	Grundfos MAGNA	25-60 N 180 1x230-240V PN6/10	$0-10\,\mathrm{V}$
Tanks	–	$22\,\mathrm{cm}$ diameter, $1.2\,\mathrm{cm}$ diameter piping	

Table 2: PLC equipment. All PLC components are Siemens S7-200 brand.

Model	Interfaces
CPU 224	14 digital inputs, 10 digital outputs
EM 235	8 analog inputs, 2 analog outputs
EM 232	2 analog outputs
CP 243-1	Industrial ethernet
PROFIBUS DP SLAVE	PROFIBUS DP/MPI

2.2 Software

The four tank process may be interacted with through three software levels which are structured in a hierarchy:

1. PLC level
2. OPC-DA level
3. OPC-UA level

A graphical user interface which communicates with the process through the OPC-DA level is also available, see Figure 5.

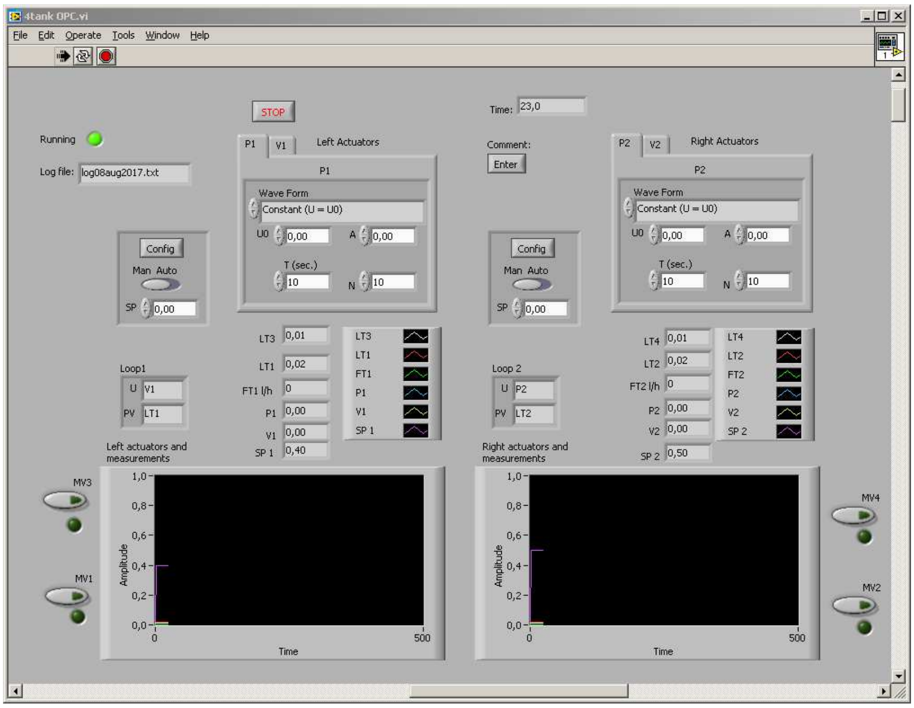


Figure 5: Labview graphical user interface which can be used to operate the four tank process.

PLC Level

The PLC interfaces electrically with sensors and actuators. It runs a sequence of operations in a loop in which sensors are read, actuators are written and control loops and safety interlocks are executed. Variables are stored as 16 bit integers and typically in the range from 0 to $32\,000$. A comprehensive list of variables is presented in Table 6. The PLC offers four configurable PID-FF control loops. It also has safety interlocks in place to power off the pumps P1 and P2 should a measurement by LT1, LT2, LT3 or LT4 exceed $47.5\,\mathrm{cm}$ such that flooding of the tanks is prohibited.

The PLC may be programmed using STEP7/MicroWin software. The CP 243-1 networking unit which connetcs the PLC to the desktop computer has the MAC address `00-1B-1B-3D-9B-73` and is connected to the wired network at DTU Chemical Engineering. Its IP address, which is required in order to program the unit, may be discovered by issuing `ping 130.225.65.255` followed by `arp -a` in the command prompt and then finding the IP address which corresponds with the known MAC address of the unit.

Each control loop is configured by six variables: A set-point y_{ref}, feed-forward proportional gain K_{ff}, feedback proportional gain K_{fb}, integral time τ_{i} $[\mathrm{min}]$ and derivative time τ_{d} $[\mathrm{min}]$ and a loop configuration parameter which should be set according to Table 3.

Table 3: Loop configuration parameter bits.

Bit	Description
0	Not used.
1	Loop active = 1, Loop inactive = 0.
2	Inverse action = 1, Direct action = 0.
3	Feed-forward action = 1, No feed-forward action = 0. Feed-forward is not documented presently.
4–7	Feed-forward variable y_{ff} designated by integer according to column A in Table 4.
8–11	Manipulated variable u designated by integer according to column B in Table 4.
12–15	Feedback variable y_{fb} designated by integer according to column A in Table 4.

Example

Activate loop 1 and use it to manipulate P1 in response to LT2 with inverse action. The binary representation of the designator for P1 is $(1)_{10} = (0001)_2$ and for LT2 it is $(5)_{10} = (0101)_2$.
It follows that `QW24` should be set to $(0101000100000110)_2$ or in decimal $(20742)_{10}$.

Table 4: PID-FF control loop variable designations.

No.	Binary representation	A	B
0	0000	Not connected	Not connected
1	0001	`IW00` (LT1)	`QW04` (P1)
2	0010	`IW02` (LT3)	`QW06` (P2)
3	0011	`IW04` (FT1)	`QW08` (V1)
4	0100	–	`QW10` (V2)
5	0101	`IW08` (LT2)	–
6	0110	`IW10` (LT4)	`QW14` (L1 y_{ref})
7	0111	`IW12` (FT2)	`QW26` (L2 y_{ref})
8	1000	–	`QW38` (L3 y_{ref})
9	1001	–	`QW50` (L4 y_{ref})
10	1010	–	–
11	1011	–	–
12	1100	–	–
13	1101	–	–
14	1110	–	–
15	1111	–	–

The control law has the following form in the direct action configuration:

$$u_k = u_{k-1} + K_{\mathrm{fb}} \left(e_k + \frac{I_k}{\tau_{\mathrm{i}}} + d\,\tau_{\mathrm{d}} \right), \tag{1}$$
$$I_k = I_{k-1} + e_k\,\Delta T, \quad d = \frac{e_k - e_{k-1}}{\Delta T}, \quad e_k = y_{\mathrm{fb},\,k} - y_{\mathrm{ref}},$$
$$I_0 = 0, \quad e_0 = 0, \quad u_0 = u_{\mathrm{ss}}, \quad k \in \mathbb{N}$$

In the inverse action configuration $e_k = y_{\mathrm{ref}} - y_{\mathrm{fb},\,k}$. Beware that the behavior is undefined if a single manipulated variable is assigned to multiple loops.

Like the loop configuration tags, tag `IW62` also contains multiple pieces of information stored in specific bits. The `IW62` tag holds information on the state of the magnetic valves MV1 through MV4 and should be interpreted according to Table 5.

Table 5: `IW62` bits.

Bit	Description
8	MV1 open = 1, MV1 closed = 0
9	MV2 open = 1, MV2 closed = 0
10	MV3 open = 1, MV3 closed = 0
11	MV4 open = 1, MV4 closed = 0

OPC-DA Level

An OPC-DA server is in place (Siemens SIMAITIC NET PB SOFTNET-DP V6.0 SW, 6GK1704-5DW61-3AA0) which makes PLC endpoints (measurements and actuators) available to higher-level software at a frequency of approximately $1\,\mathrm{Hz}$ (1 data exchange per second). Process variables and their OPC names are listed in Table 6. A connection to the OPC-DA server may be established only on the wired network at DTU Chemical Engineering at `opc://kt-pr-4tank/S7200.OPCServer/` using an OPC-DA V2 client.

The OPC-DA server is configured using S7 PC Access in which OPC items may be connected with PLC addresses.

OPC-UA Level

An OPC-UA server implemented in Python offers access to the PLC level through the OPC-DA level. Process variables and their OPC names are listed in Table 6.

A connection to the OPC-UA server may only be established on the wired network at DTU Chemical Engineering at
`opc.tcp://kt-pr-4tank:4840/four_tank_process/` using an OPC-UA client.

Table 6: List of variables and their OPC and PLC designations. See Section 2.2 regarding †.

OPC Name	PLC Address	Process Variable	Scale	Type
QX30	4992	MV1	0 or any value	Write
QX31	4992	MV2	0 or any value	Write
QX32	4992	MV3	0 or any value	Write
QX33	4992	MV4	0 or any value	Write
QW04	4994	P1	$0 - 32\,000$	Write
QW06	4996	P2	$0 - 32\,000$	Write
QW08	4998	V1	$0 - 32\,000$	Write
QW10	5000	V2	$0 - 32\,000$	Write
QW14	5004	L1 y_{ref}	$0 - 32\,000$	Write
QW16	5006	L1 K_{fb}	$0 - 320$	Write
QW18	5008	L1 τ_{i}	$0 - 320$	Write
QW20	5010	L1 τ_{d}	$0 - 320$	Write
QW22	5012	L1 K_{ff}	$0 - 320$	Write
QW24	5014	L1 configuration	†	Write
QW26	5016	L2 y_{ref}	$0 - 32\,000$	Write
QW28	5018	L2 K_{fb}	$0 - 320$	Write
QW30	5020	L2 τ_{i}	$0 - 320$	Write
QW32	5022	L2 τ_{d}	$0 - 320$	Write
QW34	5024	L2 K_{ff}	$0 - 320$	Write
QW36	5026	L2 configuration	†	Write
QW38	5028	L3 y_{ref}	$0 - 32\,000$	Write
QW40	5030	L3 K_{fb}	$0 - 320$	Write
QW42	5032	L3 τ_{i}	$0 - 320$	Write
QW44	5034	L3 τ_{d}	$0 - 320$	Write
QW46	5036	L3 K_{ff}	$0 - 320$	Write
QW48	5038	L3 configuration	†	Write
QW50	5040	L4 y_{ref}	$0 - 32\,000$	Write
QW52	5042	L4 K_{fb}	$0 - 320$	Write
QW54	5044	L4 τ_{i}	$0 - 320$	Write
QW56	5046	L4 τ_{d}	$0 - 320$	Write
QW58	5048	L4 K_{ff}	$0 - 320$	Write
QW60	5050	L4 configuration	†	Write
IW00	5054	LT1	$0 - 32\,000$	Read
IW02	5056	LT3	$0 - 32\,000$	Read
IW04	5058	FT1	$0 - 32\,000$	Read
IW08	5062	LT2	$0 - 32\,000$	Read
IW10	5064	LT4	$0 - 32\,000$	Read
IW12	5066	FT2	$0 - 32\,000$	Read
IW24	5078	P1	$0 - 32\,000$	Read
IW26	5080	P2	$0 - 32\,000$	Read
IW28	5082	V1	$0 - 32\,000$	Read
IW30	5084	V2	$0 - 32\,000$	Read
IW34	5088	L1 y_{ref}	$0 - 32\,000$	Read
IW36	5090	L1 y_{fb}	$0 - 32\,000$	Read
IW38	5092	L1 u	$0 - 32\,000$	Read
IW40	5094	L2 y_{ref}	$0 - 32\,000$	Read
IW42	5096	L2 y_{fb}	$0 - 32\,000$	Read
IW44	5098	L2 u	$0 - 32\,000$	Read
IW46	5100	L3 y_{ref}	$0 - 32\,000$	Read
IW48	5102	L3 y_{fb}	$0 - 32\,000$	Read
IW50	5104	L3 u	$0 - 32\,000$	Read
IW52	5106	L4 y_{ref}	$0 - 32\,000$	Read
IW54	5108	L4 y_{fb}	$0 - 32\,000$	Read
IW56	5110	L4 u	$0 - 32\,000$	Read
IW62	5116	MV1-4, active loops	†	Read

2.3 Calibration

At the PLC level all variables are stored as 16 bit unsigned integers. These values may be calibrated to known physical scales to enable a dimensional interpretation which is practical for model based control development.

Level Indicators LT1, LT2, LT3 and LT4

The level indicator tags at the PLC level output a signal of 0 corresponding to a hydrostatic pressure of 0 and a signal of $32\,000$ corresponding to a hydrostatic pressure of $100\,\mathrm{mbar}$. It follows that the hydrostatic pressure is related to the measurement reading by Equation (2)

$$\Delta p = \frac{S}{32\,000}\,100\,\mathrm{mbar}. \tag{2}$$

The hydrostatic pressure is related to the liquid level by Equation (3)

$$\Delta p = \rho\, g\, \Delta h \Longrightarrow \Delta h = \frac{\Delta p}{\rho\, g}, \tag{3}$$

where ρ is the density of water and g is the gravitational acceleration. Equations (2) and (3) may be combined to yield Equation (4)

$$\Delta h = S\,\frac{100\,\mathrm{mbar}}{32\,000 \cdot 998.2\,\frac{\mathrm{kg}}{\mathrm{m}^3} \cdot 9.81\,\frac{\mathrm{m}}{\mathrm{s}^2}} = S\,3.19 \cdot 10^{-3}\,\mathrm{cm}. \tag{4}$$

This relation may be validated by comparison with rulers placed on each of the four tanks which indicate the liquid level.

Flow Indicators FT1 and FT2

The PLC reading of the flow transmitters is proportional to a maximum flow rate specified on the individual flow transmitters. Additionally a first-order filter time constant in the range $0.1\,\mathrm{s}$ to $5\,\mathrm{s}$ may be specified. Presently the maximum flow rate is specified to be $2\,\frac{\mathrm{m}^3}{\mathrm{h}}$ and the time constant as $5\,\mathrm{s}$ on both flow transmitters. It follows that the PLC signal is related to the volumetric flow rate by Equation (5)

$$Q = S\,\frac{5}{288}\,\frac{\mathrm{cm}^3}{\mathrm{s}}. \tag{5}$$

Pumps P1 and P2

The volumetric flow rate through a pump at a given set-point may be calibrated towards the flow rate measurements by FT1 and FT2 for a given setting of V1 and V2. The setting of V1 and V2 influences the calibration because the pumps are operated in constant pressure mode, hence downstream pressure variations influence the throughput. Sample calibration data is listed in Table 7. A linear fit to the data is presented in Figure 6.

Table 7: Calibration data, 25$^{\text{th}}$ of July 2017. V1 and V2 both fully opened towards tank 1 and 2 respectively.

QW04	FT1 $[\mathrm{L\,h^{-1}}]$	QW06	FT2 $[\mathrm{L\,h^{-1}}]$
		6 000	532
7 000	520	7 000	620
8 000	666	8 000	728
9 000	763	9 000	835
10 000	826	10 000	903
11 000	898	11 000	983
12 000	981	12 000	1 074
13 000	1 032	13 000	1 121
14 000	1 105	14 000	1 206
15 000	1 176	15 000	1 272
16 000	1 250	16 000	1 356
17 000	1 308	17 000	1 400
18 000	1 367	18 000	1 480

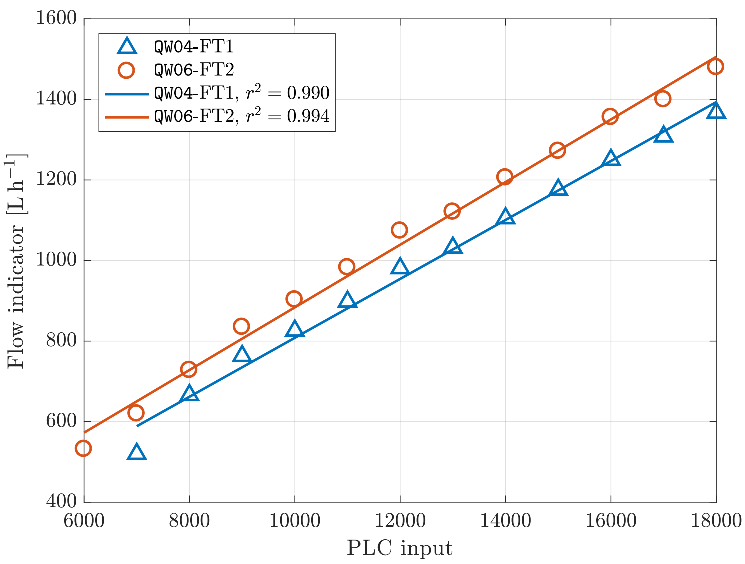


Figure 6: Linear fit of pump calibration data listed in Table 7.

The linear approximations appear reasonable and offer the relationships in Equation (6) between the volumetric flow rates and the corresponding set-points where P1 and P2 are in units $\mathrm{cm^3\,s^{-1}}$.

$$\mathrm{P1} \propto S\,0.0203, \quad \mathrm{P2} \propto S\,0.0216 \tag{6}$$

When starting the pumps initially, it is recommended to set the set-point of the corresponding control valve to $32\,000$ (lowest pressure drop) and to specify a pump set-point of $32\,000$. Otherwise the pump may not have sufficient power to overcome the pressure difference between its inlet and the effluent orifice. At set-points below a certain threshold the pumps are liable to stop altogether.

Control Valves V1 and V2

The 3-way valves are designed for control purposes hence they exhibit an approximately linear relationship between the set-point and the actual split factor. The split factor is the ratio of the volumetric flow rate which flows through the bent path of the valve. The total inlet through each of the 3-way valves is measured by flow transmitters. The volumetric flow rate straight through the valve may be measured by the bucket-stopwatch method in which a bucket of volume $500\,\mathrm{mL}$ captures the effluent and the time to fill is recorded. Triple measurement is recommended to ensure accuracy. When calibrating the valves it is important that the system is in steady state, i.e. that FT1 and FT2 readings are stable, and that stiction is avoided. Stiction is the phenomenon that a valve may not actually change position when subject to a small change in its set-point. This issue may be avoided by applying large intermediate set-point changes[3]. It is also important that valve calibration is performed at the flow rates at which the experiments are to be conducted since the split factor depends on the upstream pressure and hence the influent flow rate.

Sample calibration data is listed in Tables 8 and 9. A linear fit to the data is presented in Figure 7.

Table 8: Calibration data for V1, 23rd of June 2016.

QW08	FT1 $[\mathrm{L\,h^{-1}}]$	Time to fill $500\,\mathrm{mL}$ $[\mathrm{s}]$			Avg. Flow Rate $[\mathrm{L\,h^{-1}}]$	Split Factor
25 600	1 273	14.42	14.40	14.48	124.9	0.902
25 280	1 299	10.70	10.48	10.78	167.0	0.870
24 320	1 298	9.45	9.50	9.50	189.8	0.854
24 000	1 304	8.83	9.26	9.18	198.0	0.848
23 680	1 301	8.63	8.18	7.90	218.5	0.832
23 360	1 304	7.50	7.17	7.47	243.9	0.813
22 400	1 310	6.88	6.77	6.77	264.4	0.798
20 800	1 306	5.12	5.15	5.21	348.8	0.733
20 800	1 300	5.05	4.93	5.23	355.0	0.727
20 480	1 318	4.31	4.36	4.32	415.7	0.685
20 160	1 298	4.85	5.00	4.93	365.4	0.719
19 840	1 307	4.19	4.35	4.33	419.6	0.679
19 520	1 295	4.54	4.45	4.82	391.0	0.698
19 200	1 305	4.26	4.22	4.13	428.2	0.672

Table 9: Calibration data for V2, 23rd of June 2016.

QW10	FT2 $[\mathrm{L\,h^{-1}}]$	Time to fill $500\,\mathrm{mL}$ $[\mathrm{s}]$			Avg. Flow Rate $[\mathrm{L\,h^{-1}}]$	Split Factor
24 000	1 060	15.12	15.02	15.37	118.7	0.888
23 680	1 029	15.17	14.99	14.85	120.0	0.883
23 360	1 031	14.19	14.09	13.68	128.7	0.875
23 040	1 031	12.63	12.95	13.01	139.9	0.864
22 720	1 036	11.72	11.50	11.37	156.1	0.849
22 400	1 035	10.90	10.82	10.95	165.3	0.840
22 080	1 036	9.73	9.97	9.92	182.3	0.824
19 520	1 055	6.20	6.20	6.21	290.2	0.725
19 200	1 060	6.30	5.91	6.48	288.9	0.727
18 880	1 047	5.70	5.95	5.80	309.5	0.704
18 560	1 044	5.50	5.31	5.50	331.1	0.683
18 240	1 041	5.23	5.33	5.48	336.7	0.677
17 920	1 039	5.25	5.16	5.13	347.5	0.666
17 600	1 038	5.16	5.21	5.11	348.8	0.664
17 280	1 035	4.83	4.76	4.93	371.9	0.641

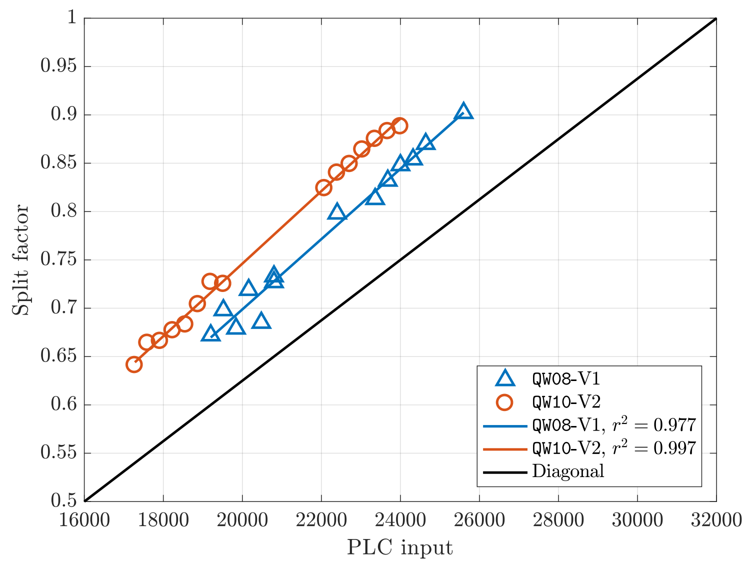


Figure 7: Linear fit of valve calibration data listed in Tables 8 and 9.

The linear approximations fit the data well. An ideal control valve would have a calibration curve which coincides with the diagonal. Proportionalities between set-points and the corresponding split factors are stated in Equation (7). The left hand side of either equation is the fraction of the influent volumetric flow rate through the valve which flows through the bent path

$$\mathrm{V1} \propto S\,3.64 \cdot 10^{-5}, \quad \mathrm{V2} \propto S\,3.75 \cdot 10^{-5}. \tag{7}$$

Another calibration procedure could be to record the steady state liquid levels for a given setting of V1 and V2. At steady state the split fractions are related to the liquid levels by Equations (8) and (9) assuming Bernoulli flow

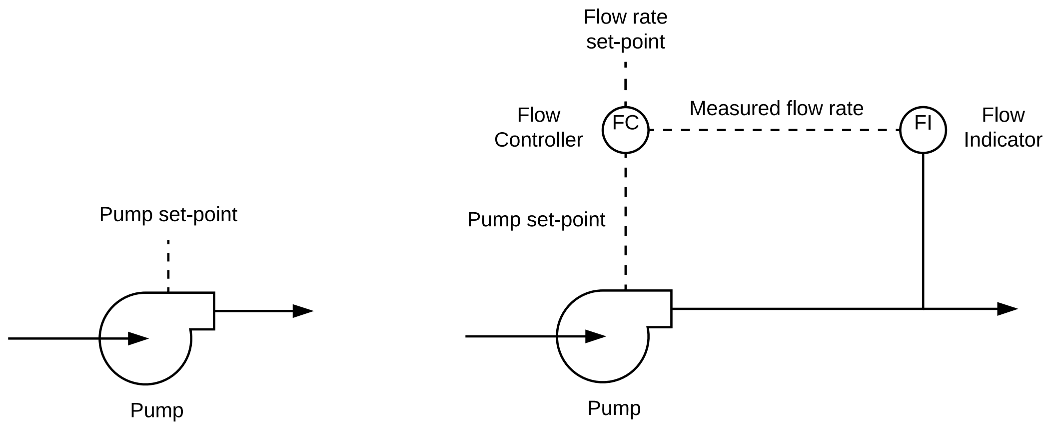
$$\gamma_1 = \frac{\sqrt{h_1}}{\sqrt{h_1} + \sqrt{h_4}} \text{ for } F_2 = 0 \text{ and } F_1 \neq 0 \tag{8}$$

$$\gamma_2 = \frac{\sqrt{h_2}}{\sqrt{h_2} + \sqrt{h_3}} \text{ for } F_1 = 0 \text{ and } F_2 \neq 0, \tag{9}$$

where F_1 is the flow rate through P1 and F_2 is the flow rate through P2. h_i is the liquid level in tank according to the numbering in Figure 4.

2.4 Feedback Control of Pump Throughput

Instead of relying on the pumps giving a certain throughput in response to a given set-point as illustrated in Figure 8a one may construct a feedback loop to regulate the throughput to a certain set-point. This configuration is illustrated in Figure 8b.



(a) Open loop. (b) Closed loop.

Figure 8: Control of pump throughput.

Consider for example `IW04` (FT1) as measured variable, `QW04` (P1) as manipulated variable and the desired pump throughput as the set-point. With a feedback regulator in place one would no longer manipulate `QW04` directly when changes in the pump throughput are called for. Instead one would update the set-point of the feedback loop and then the feedback regulator would adjust `QW04` such that `IW04` (the rate measured by FT1) matches the desired set-point. The key benefit is that calibration of the pump throughput to the measured flow rate is circumvented and consequently errors committed on accounts of errors in the calibration or actuator drift are avoided. Instead one has to decide on a regulator tuning.

Normalized open loop step response data for 10%, 20% and 30% step changes in both the positive and negative direction are shown for the pairs `QW04`–`IW04` (P1–FT1) and `QW06`–`IW12` (P2–FT2) in Figure 9. The responses were approximated with first-order transfer functions yielding time constants in the range 5.8 to $7.2\,\mathrm{s}$.

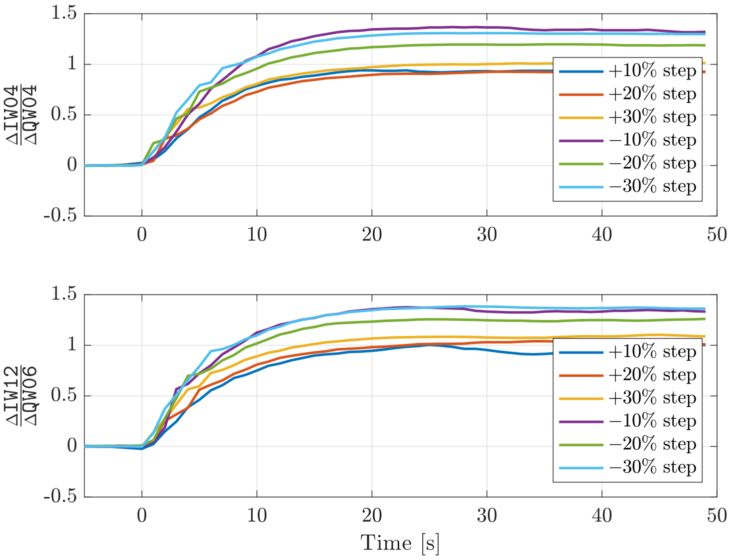


Figure 9: Normalized step response data for QW04–IW04 (P1–FT1) and QW06–IW12 (P2–FT2). Nominal steady state $12\,800$ for both pairs. Excitation at $t = 0$.

Setting $K_c = 0.5$ and $\tau_I = 4.8\,\mathrm{s}$ yielded satisfactory set-point tracking and disturbance rejection when abruptly changing the 3-way valve position as shown in Figure 10. The controller parameters for the P1–FT1 pair were communicated to the PLC by setting the value of QW36 to $12\,550$ (0011000100000110 in binary), QW40 to $0.5 \cdot 320$, QW42 to $\frac{4.8}{60} \cdot 320$ and QW44 and QW46 to zero. For the P2–FT2 pair QW36 was set to $29\,190$ (0111001000000110 in binary).

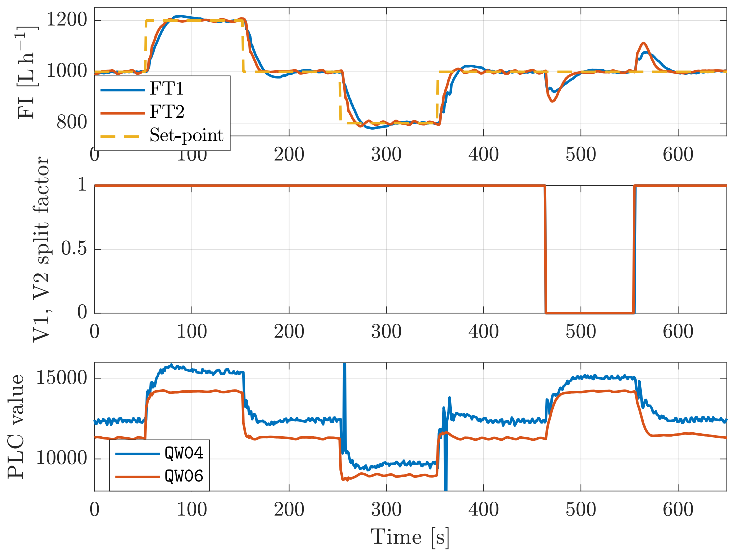


Figure 10: Closed loop response to set-point changes and disturbances for QW04–IW04 (P1–FT1) and QW06–IW12 (P2–FT2). Both loops are excited simultaneously.

A first-order transfer function provided a satisfactory fit to the closed loop response to set-point changes and yielded time constants of $9.8\,\mathrm{s}$ for P1–FT1 and $7.4\,\mathrm{s}$ for P2–FT2. This dynamic may be included in a model for predictive control purposes, enabling the controller to take the additional dynamics into account when computing optimal control inputs.

3 Communication

Communication with the four tank process is possible using either the OPC-DA or the OPC-UA standard. Minimal examples which show how to connect, read and write variables are presented in the following for both Matlab and Python. Matlab only offers OPC connectivity on Windows whereas Python offers OPC-DA connectivity on Windows and OPC-UA on any platform. It is recommended to use OPC-UA because it is a more recent standard and because it is inherently multi-platform. An elaborate example of a Python OPC-UA client with live plotting capabilities is listed in Appendix B.2. A similar example in Matlab is listed in Appendix B.3.

3.1 Minimal Examples

The reader is referred to comments in the code for comments on the code listed in the following minimal examples. The common idea is to connect to the OPC server, identify the desired variables in the OPC namespace, read or write the variables and then finally to close the connection.

Matlab, OPC-DA

```
% Connect to OPC-DA server
da = opcda('localhost', 'S7200.OPCServer');
connect(da);
% Get handles for IW04 (FT1) and QW04 (P1)
% The browsenamespace(da) function opens a GUI where the
% namespace may be browsed.
grp = addgroup(da);
IW04 = additem(grp, 'Microwin.CPU224.IW04');
QW04 = additem(grp, 'Microwin.CPU224.QW04');
% Read value of IW04
read(IW04)
% Write value to QW04
write(QW04, 0)
% Disconnect
disconnect(da);
```

Matlab, OPC-UA

```
% Connect to OPC-UA server
ua = opcua('opc.tcp://kt-pr-4tank:4840/four_tank_process/');
connect(ua);
% Browse namespace to find IW04 (FT1) and QW04 (P1)
% The ua.browseNamespace function opens a GUI where the
% namespace may be browsed.
S7200    = findNodeByName(ua.Namespace,'S7200.OPCServer');
Microwin = findNodeByName(S7200,'Microwin');
CPU224   = findNodeByName(Microwin,'CPU224');
IW04     = findNodeByName(CPU224,'IW04');
QW04     = findNodeByName(CPU224,'QW04');
% Read value of IW04
readValue(IW04)
% Write value to QW04
writeValue(QW04,0);
% Disconnect
disconnect(ua);
```

Python, OPC-DA

```
import OpenOPC
# Connect to OPC-DA server
da = OpenOPC.client()
# da.servers() returns a list of available servers.
da.connect('S7200.OPCServer')
# Once connected you can browse the namespace using
# the da.list() function.
# Read value of IW04
IW04 = da.read('Microwin.CPU224.IW04')
print(IW04)
# Write value to QW04
da.write(('Microwin.CPU224.QW04',0))
# Disconnect
da.close()
```

Python, OPC-UA

```
from opcua import ua, Client
# Connect to OPC-UA server
ua = Client('opc.tcp://kt-pr-4tank:4840/four_tank_process/')
ua.connect()
# Browse namespace to find IW04 (FT1) and QW04 (P1)
# You may browse the namespace in a
# GUI using the opcua-client software.
objects = ua.get_root_node().get_child('0:Objects')
S7200 = objects.get_child('2:S7200.OPCServer')
Microwin = S7200.get_child('2:Microwin')
CPU224 = Microwin.get_child('2:CPU224')
IW04 = CPU224.get_child('2:IW04')
QW04 = CPU224.get_child('2:QW04')
# Read value of IW04
print(IW04.get_value())
# Write value to QW04
QW04.set_value(0)
# Disconnect
ua.disconnect();
```

4 Simulation OPC-UA Server

A simulation OPC-UA server which emulates the actual four tank process is implemented in Python to aid the development of regulators communicating using the OPC-UA standard, the code is listed in Appendix B.1. The test server implements all of the functionality of the actual process which is described in Section 2. Mock measurements are generated using a mathematical model of the process and the emulator outputs these values corresponding to the sensor calibrations described in Section 2.3. This setup is illustrated in Figure 11 where the simulation model is encapsulated in an OPC server hence appearing indiscernible from the actual plant.

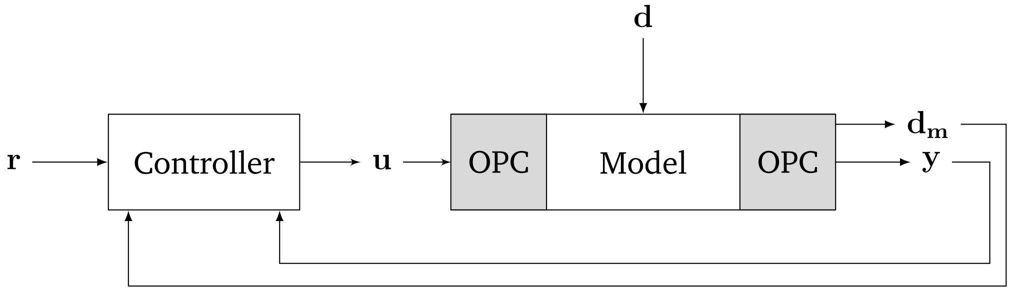


Figure 11: System considered in the implementation phase.

The only discrepancy in comparison with the OPC-UA server offered by the actual process is a "RESET" tag. If the tag is written a value besides "0" then the server will reset to its initial state.

If a regulator works as expected when applied on the test OPC-UA server then there is a good chance that it will also work when implemented on the actual process.

5 Implementation

Based on the preceding sections, an MPC based on a linearized first-principles model[1] has been implemented successfully on the four tank process. The MPC formulation is stated in Equations (10a) to (10e) and the parameters in Equation (11).

$$\min_{\mathbf{u}} \ \frac{1}{2}\sum_{k=1}^{N_{\mathrm{mpc}}} ||\mathbf{z}_k - \mathbf{r}_k||^2_{\mathbf{Q}_z} + ||\mathbf{u}_{k-1} - \mathbf{u}_{k-2}||^2_{\mathbf{Q}_{\Delta u}} \tag{10a}$$

subject to

$$\mathbf{x}_{k+1} = \mathbf{A}_{\mathrm{d}} + \mathbf{B}_{\mathrm{d}}\mathbf{u}_k + \mathbf{E}_{\mathrm{d}}\mathbf{d}_k, \qquad k = 0, 1, 2, .., N_{\mathrm{MPC}} - 1 \tag{10b}$$

$$\mathbf{z}_k = \mathbf{C}_{\mathrm{d},\,z}\mathbf{x}_k, \qquad k = 1, 2, 3, ..., N_{\mathrm{MPC}} \tag{10c}$$

$$\mathbf{u}_{\min,\,k} \leq \mathbf{u}_k \leq \mathbf{u}_{\max,\,k}, \qquad k = 0, 1, 2, ..., N_{\mathrm{MPC}} - 1 \tag{10d}$$

$$\Delta\mathbf{u}_{\min,\,k} \leq \mathbf{u}_{k+1} - \mathbf{u}_k \leq \Delta\mathbf{u}_{\max,\,k}, \qquad k = 0, 1, 2, ..., N_{\mathrm{MPC}} - 1 \tag{10e}$$

$$\mathbf{Q}_z = 5 \cdot 10^3 \mathbf{I},\ \mathbf{Q}_{\Delta u} = \mathbf{I},\ |\Delta u| \leq 100\,\mathrm{cm}^3\,\mathrm{s}^{-1}, \qquad (11)$$
$$170\,\mathrm{cm}^3\,\mathrm{s}^{-1} \leq u \leq 500\,\mathrm{cm}^3\,\mathrm{s}^{-1},\ T_s = 5\,\mathrm{s}$$

The prediction and control horizons are set to 200 and 190 respectively such that the control inputs for the final 11 instants of the prediction horizon are constant. A video showing the MPC regulating the plant is available[4]. A snapshot from the video is presented in Figure 12. The tanks are shown on the left hand side and on the right hand side is a live plot showing recent measurements and predictions.

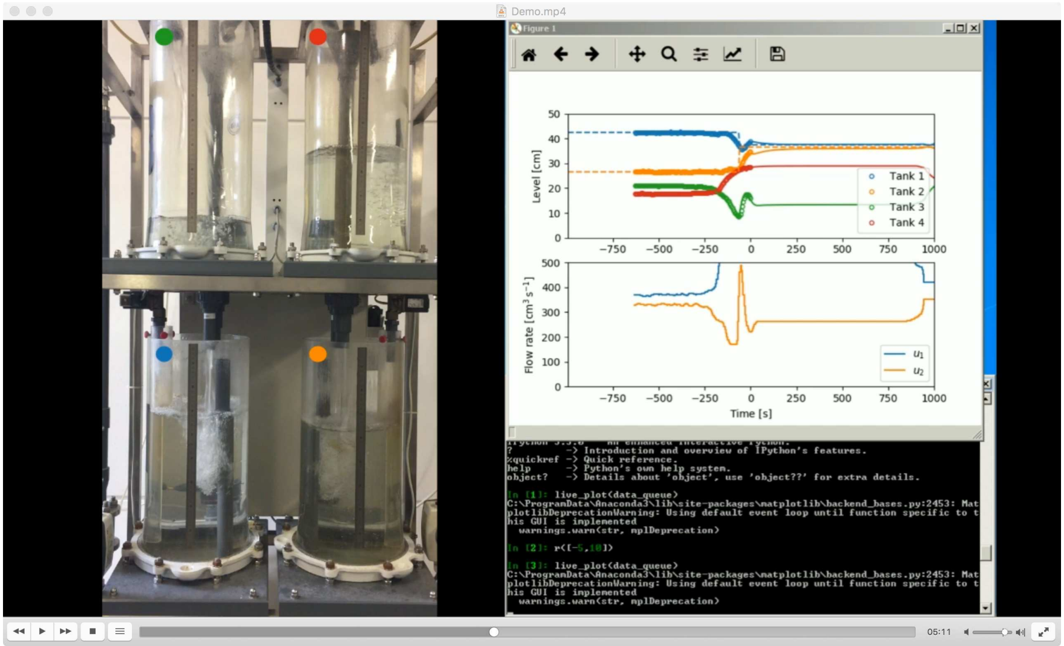


Figure 12: Snapshot from video of MPC controlling the liquid levels in the bottom tanks of the four tank process.

References

[1] Karl Henrik Johansson. The Quadruple-Tank Process: A Multivariable Laboratory Process with an Adjustable Zero. *IEEE Transactions on Control Systems Technology*, 8(3):456–465, 2000.

[2] OPC Foundation. Home Page – OPC Foundation. URL `https://opcfoundation.org/`. Accessed 24th of August 2017.

[3] Ali Ahammad Shoukat Choudhury, Chikezie Nwaoha, and Sharad Vishwasrao. *Valves*, pages 9–25. John Wiley & Sons, Inc., 2012.

[4] Eskild Schroll-Fleischer and John Bagterp Jørgensen. 02619 Model Predictive Control, 2017. URL `http://courses.compute.dtu.dk/02619`. Accessed 29th of August 2017.

A Installation of Python with OPC-UA Connectivity

A.1 Windows

1. Download Anaconda 64 bit Python 3.6 at `https://www.continuum.io/downloads`.
2. Install Anaconda. Use default options when prompted. For assistance, see `https://docs.continuum.io/anaconda/install/windows`.
3. Navigate to Start, Anaconda3 (64-bit) and run "Anaconda Prompt".
4. In the prompt, issue the command[1]:

   ```
   conda install python=3.5
   ```

5. In the prompt, issue the command:

   ```
   conda install -c anaconda cvxopt
   ```

6. In the prompt, issue the command:

   ```
   pip install freeopcua opcua-client
   ```

7. You have now set up Python. Always call Python code form the "Anaconda Prompt".

A.2 Ubuntu

1. Download Anaconda 64 bit Python 3.6 at `https://www.continuum.io/downloads`.
2. Install Anaconda. Use default options when prompted. For assistance, see `https://docs.continuum.io/anaconda/install/linux`.
3. Open a terminal window.
4. In the terminal window, issue the command:

   ```
   conda install -c anaconda cvxopt
   ```

5. In the terminal window, issue the command:

   ```
   pip install freeopcua opcua-client
   ```

6. You have now set up Python.

[1] Downgrading to Python 3.5 is required because `cvxopt` (convex optimization solver) does not yet support Python 3.6 on Windows.

A.3 macOS

1. Download Anaconda 64 bit Python 3.6 at `https://www.continuum.io/downloads`.
2. Install Anaconda. Use default options when prompted. For assistance, see `https://docs.continuum.io/anaconda/install/mac-os`.
3. Open a terminal window.
4. In the terminal window, issue the command:

   ```
   conda install -c anaconda cvxopt
   ```

5. In the terminal window, issue the command:

   ```
   pip install freeopcua opcua-client
   ```

6. You have now set up Python.

A.4 How to Run the Sample Code

Download the code listed in Appendix B from [4] or use the code listed in the appendix. Firstly the simulation server is started and then a client may be started.

To start the simulation server issue

```
python simulation_server.py
```

When the server is done starting up it will display "Server reset" to indicate that it has reset to the specified initial steady state and that it is ready for a client to connect. The Python client example (Appendix B.2) may be started by issuing

```
python client_template.py
```

A live plot will open showing the measurements as they are recorded from the OPC simulation server. Similarly to the Python example the Matlab example opens a live plot showing measurements as they are recorded.

B Sample Code

The code is also available for download online[4]. For comments on the code listed in the following, the reader is referred to the comments given in the code.

B.1 simulation_server.py

```python
# Name: simulation_server.py
# Author: Eskild Schroll-Fleischer <esksch@dtu.dk>
# Date: 30th of August 2017
#
# Description:
# Simulation server which emulates the four tank process in B228 using a process model
# to generate mock measurements. The server communicates according to the OPC-UA standard.
# The state may be reset by writing anything but 0 to the RESET tag.
# The server may be stopped by issuing CTRL-C.
#
# The code is organized as follows:
# 1. First-principles model of the four tank system
# 2. Configuration
# 3. Populate OPC-UA address space
# 4. (a) If the RESET tag value is different from 0 then the server is reset to the initial state
# 4. (b) Check whether sample time has passed and if so, execute process functionality
# 4. (c) Execute PID control loops
# 4. (d) Reflect writables in readables
# 4. (e) Simulate process model one sample time
# 4. (f) Publish results of simulation to OPC-UA server
# 4. (g) Process safety interlocks

# Import standard python packages
import time
import numpy as np
from opcua import ua, Server
from scipy.integrate import odeint

## 1. First-principles model of the four tank system
class FourTankSystem:
    def __init__(self,x0=[0, 0, 0, 0]):
        '''Set initial conditions and plant parameters.'''
        # Initial state
        self.x = np.array(x0) # [cm]
        self.t = 0

        # Parameters
        self.gamma = [0.403, 0.31] # [%]
        self.A = 380.1327 # [cm^2]
        self.a = 1.2272 # [cm^2]
        self.g = 981.0 # [cm/s^2]
        self.rho = 1.0 # [g/cm^3]
    def ode(self, x, t, u, d):
        '''Ordinary differential equation model.'''
        # Influent from pump and disturbances
        qin = np.array([
          self.gamma[0] *u[0], # Valve 1 to tank 1 [cm^3/s]
          self.gamma[1] *u[1], # Valve 2 to tank 2 [cm^3/s]
        (1-self.gamma[1])*u[1], # Valve 2 to tank 3 [cm^3/s]
        (1-self.gamma[0])*u[0], # Valve 1 to tank 4 [cm^3/s]
        ]);
        # Liquid levels
        h = x/(self.rho*self.A) # [cm]
        qout = self.a*np.sqrt(2*self.g*h)*(np.add(d,1))
        # Influent from other tanks
        qoutin = np.array([
        qout[2],
        qout[3],
        0,
        0
        ])
        # Mass balance
        # from pump + from tanks -effluent
        dxdt = self.rho*(qin + qoutin -qout)
        return dxdt
```

```
    def y(self, x):
        '''Measurement function.'''
        return x/(self.rho*self.A)
    def step(self, dt, u, d):
        '''Simulate dt seconds of the ODE model.'''
        # Explicit solver does not use Jacobian so theres is no reason to include it
        sol = odeint(self.ode, self.x, [0, dt], args=(u,d,)) # [initial, final]
        self.x = sol[1] # Save final as current state
        self.t += dt
        return self.x
FTS = FourTankSystem()

# Dimensions of variables
nx = 4
ny = 4
nu = 2
nz = 2
nd = 4

## 2. Configuration
OPC_UA_SERVER = 'opc.tcp://localhost:4840/four_tank_process/'
# Certificates may be generated on unix platforms by issuing:
# openssl req -x509 -newkey rsa:2048 -keyout private_key.pem -out certificate.pem -days 355 -nodes
# openssl x509 -outform der -in certificate.pem -out certificate.ders
OPC_UA_CERTIFICATE = 'certificate.der'
OPC_UA_PRIVATE_KEY = 'private_key.pem'
OPC_UA_URI = 'http://dtu.dk'
t_step = 0.2 # [s]
# The following two dictionaries map comprehensible process variable designations
# to their OPC-UA counterpart tags.
process_to_tag_read = { 'LT1' :'IW00',
            'LT3' :'IW02',
            'FT1' :'IW04',
            'LT2' :'IW08',
            'LT4' :'IW10',
            'FT2' :'IW12',
            'P1' :'IW24',
            'P2' :'IW26',
            'V1' :'IW28',
            'V2' :'IW30',
            'L1SP':'IW34',
            'L1PV':'IW36',
            'L1OP':'IW38',
            'L2SP':'IW40',
            'L2PV':'IW42',
            'L2OP':'IW44',
            'L3SP':'IW46',
            'L3PV':'IW48',
            'L3OP':'IW50',
            'L4SP':'IW52',
            'L4PV':'IW54',
            'L4OP':'IW56',
            'MV14':'IW62',}
process_to_tag_write = {'P1' :'QW04',
            'P2' :'QW06',
            'V1' :'QW08',
            'V2' :'QW10',
            'L1SP':'QW14',
            'L1KC':'QW16',
            'L1TI':'QW18',
            'L1TD':'QW20',
            'L1KF':'QW22',
            'L1CF':'QW24',
            'L2SP':'QW26',
            'L2KC':'QW28',
            'L2TI':'QW30',
            'L2TD':'QW32',
            'L2KF':'QW34',
            'L2CF':'QW36',
            'L3SP':'QW38',
            'L3KC':'QW40',
            'L3TI':'QW42',
            'L3TD':'QW44',
            'L3KF':'QW46',
            'L3CF':'QW48',
            'L4SP':'QW50',
            'L4KC':'QW52',
            'L4TI':'QW54',
```

```
            'L4TD':'QW56',
            'L4KF':'QW58',
            'L4CF':'QW60',
            'MV1' :'QX30',
            'MV2' :'QX31',
            'MV3' :'QX32',
            'MV4' :'QX33',}
PV_table = [None,'IW00','IW02','IW04',None,'IW08','IW10','IW12',None,None,None,None,None,None,None,None]
U_table = [None,'QW04','QW06','QW08','QW10',None,'QW14','QW26','QW38','QW50',None,None,None,None,None,None]

# Safety interlock. The server state resets if any liquid level exceeds h_safety_max
h_safety_max = 47.5 # [cm]

# Initial state
x0 = [14838.58763902, 10927.10345127, 6547.14018111, 6183.18306935] # [g]
u0 = np.array([1322, 1177])/3.6
d0 = np.array([0.1, 0.1, 0, 0])
valve0 = np.array([0.403, 0.31]) # [%]

# Calibration
signal_range = 32000
controller_range = 320
pump_cal = np.array([0.0203,0.0216]) # [(cm^3/s)/signal]
valve_cal = np.array([signal_range,signal_range]) # [split fraction/signal]
ft_cal = np.array([5/288, 5/288]) # [(cm^3/s)/signal]
lt_cal = 3.19e-3 # [cm/signal]
y_var = 0.5**2 # [(cm)^2]
u_var = 1.4**2 # [(cm^3/s)^2]
Q = y_var*np.eye(ny) # Measurement noise dispersion matrix
R = u_var*np.eye(nu) # Process noise dispersion matric
tau_FT = 5 # [s] Time constant of flow transmitter


# Instantiate server and mathematical model object
server = Server()
# Apply configuration
server.set_endpoint(OPC_UA_SERVER)
# Certificates are required in order for Matlab OPC Toolbox to be able to connect.
# The error has been reported to Mathworks and they are fixing the bug for
# Matlab 2017b.
server.load_certificate(OPC_UA_CERTIFICATE)
server.load_private_key(OPC_UA_PRIVATE_KEY)
idx = server.register_namespace(OPC_UA_URI)
objects = server.get_objects_node()

## 3. Populate OPC-UA address space
S7200 = objects.add_object(idx, 'S7200.OPCServer')
Microwin = S7200.add_folder(idx, 'Microwin')
CPU224 = Microwin.add_folder(idx, 'CPU224')
master_to_slave_OPCDA_tags = ['QW{i:02d}'.format(i=i) for i in range(0,64,2)]\
+ ['QX{i:02d}'.format(i=i) for i in range(30,34)]
master_to_slave_OPCUA_tags = [CPU224.add_variable(idx,
                        OPCDA_tag,
                        ua.Variant(0, ua.VariantType.UInt16))
              for OPCDA_tag in master_to_slave_OPCDA_tags]
# Set writable tags writable.
[node.set_writable() for node in master_to_slave_OPCUA_tags]
slave_to_master_OPCDA_tags = ['IW{i:02d}'.format(i=i) for i in range(0,64,2)]
slave_to_master_OPCUA_tags = [CPU224.add_variable(idx,
                        OPCDA_tag,
                        ua.Variant(0, ua.VariantType.UInt16))
              for OPCDA_tag in slave_to_master_OPCDA_tags]
# Create a map of process variable designation -> OPC-UA tag object
opcua_tags = dict(zip(master_to_slave_OPCDA_tags+slave_to_master_OPCDA_tags,
           master_to_slave_OPCUA_tags+slave_to_master_OPCUA_tags))
# A reset tag is added to enable remote reset of the server state.
reset_tag = CPU224.add_variable(idx, 'RESET', ua.Variant(1, ua.VariantType.UInt16))
reset_tag.set_writable()

# Start the server event loop
server.start()

# Set up states for the four PID loops
loop_states = [ {'integral':0,'previous_error':0,'u0':None,},
       {'integral':0,'previous_error':0,'u0':None,},
       {'integral':0,'previous_error':0,'u0':None,},
       {'integral':0,'previous_error':0,'u0':None,},]
```

```python
try:
  t0 = time.time()
  while True:
    ## 4. (a) If the RESET tag value is different from 0 then the server is reset to the initial state
    if reset_tag.get_value() != 0:
      # Reset server
      [tag.set_value(0) for tag in opcua_tags.values()]
      FTS.x = x0;
      [opcua_tags[process_to_tag_write[tag]].set_value(value) for tag, value in zip(['P1','P2'],u0/pump_cal)]
      [opcua_tags[process_to_tag_write[tag]].set_value(value) for tag, value in zip(['V1','V2'],valve0*valve_cal)]
      [opcua_tags[process_to_tag_write[tag]].set_value(1) if value != 0 else 0 for tag, value in zip(['MV1','MV2','MV3','MV4'],d0)]

      FT = u0/ft_cal
      reset_tag.set_value(0)
      print('Server reset')
    ## 4. (b) Check whether sample time has passed and if so, execute process functionality
    time.sleep( max([ (t0+t_step-time.time()) , 0.1 ]) )
    if time.time() -t0 >= t_step:
      t0 = t0 + t_step
      ## 4. (c) Execute PID control loops
      # Reflect writes to loop set points in the readable variables
      loop_set_points = [opcua_tags[process_to_tag_write[node]].get_value() for node in ['L1SP','L2SP','L3SP','L4SP',]]
      [opcua_tags[process_to_tag_read[node]].set_value(value) for node, value in zip(['L1SP','L2SP','L3SP','L4SP',],loop_set_points)]
      for i, loop in enumerate(['L1','L2','L3','L4']):
        loop_configuration = opcua_tags[process_to_tag_write[loop+'CF']].get_value()
        # If the 1st bit is 1 then the loop is in auto, otherwise in manual
        if (loop_configuration & (1<<1))>>1 == 1:
          # The loop is active.
          # It is direct if the 2nd bit is 0, inverse if it is 1
          if (loop_configuration & (1<<2))>>2 == 1:
            K_sign = -1
          else:
            K_sign = 1
          # Determine manipulated variable
          U_id = (loop_configuration & 0b1111<<8)>>8
          U_tag = opcua_tags[U_table[U_id]]
          # Set the reference value of the manipulated variable
          # if the loop is newly configured.
          if loop_states[i]['u0'] is None:
            loop_states[i]['u0'] = U_tag.get_value()
          # Determine measured variable for feedback control
          PV_id = (loop_configuration & 0b1111<<12)>>12
          PV = opcua_tags[PV_table[PV_id]].get_value()
          # Retrieve set point and control law parameters, Kc, Ti, Td, Kf
          nodes = [loop+item for item in ['KC','TI','TD','KF',]]
          Kc, Ti, Td, Kf = [opcua_tags[process_to_tag_write[node]].get_value()/controller_range for node in nodes]
          SP = loop_set_points[i]
          # Compute PID-FF control law
          error = K_sign*(PV-SP)/signal_range
          integral = loop_states[i]['integral'] + error*t_step
          derivative = (error-loop_states[i]['previous_error'])/t_step
          # Units of tau are converted from [min] to [s]:
          output = Kc*(error+integral/(Ti*60)+derivative*(Td*60))
          loop_states[i]['integral'] = integral
          loop_states[i]['previous_error'] = error
          output = int(loop_states[i]['u0']+output*signal_range)
          # Write PV and output to readable variables
          opcua_tags[process_to_tag_read[loop+'PV']].set_value(PV)
          opcua_tags[process_to_tag_read[loop+'OP']].set_value(output)
          # Write output to writable variable
          U_tag.set_value(output)
        else:
          # The control loop is inactive. Reset integral and previous error
          loop_states[i]['integral'] = 0
          loop_states[i]['previous_error'] = 0
          loop_states[i]['u0'] = None
      ## 4. (d) Reflect writables in readables
      # Reflect state of relays in IW62
      magnetic_valve_state = [opcua_tags[process_to_tag_write[node]].get_value()>0 for node in ['MV1','MV2','MV3','MV4',]]
      # Convert list of true, false to binary e.g. [True,True,False,True] -> 0b1101
      magnetic_valve_state_as_binary = int(''.join(str(int(item)) for item in magnetic_valve_state[::-1]), 2)
      # Create bitmask with 1 corresponding to magnetic valve state in IW62
      mask = 0b1111<<8
      IW62 = int(opcua_tags['IW62'].get_value())
      IW62 = (IW62 & ~mask) | (magnetic_valve_state_as_binary<<8 & mask)
      opcua_tags['IW62'].set_value(IW62)

      # Reflect actuator states in readable variables
```

```
      actuator_states = [opcua_tags[process_to_tag_read[node]].set_value(opcua_tags[process_to_tag_write[node]].get_value()) for node in ['P1',
             'P2','V1','V2',]]

      ## 4. (e) Simulate process model
      # Generate measurement and process noise
      v = np.random.multivariate_normal(np.zeros(ny),Q)
      w = np.random.multivariate_normal(np.zeros(nu),R)
      # Simulate
      u = [int(opcua_tags[process_to_tag_write[node]].get_value()) for node in ['P1','P2',]]
      d = [0.1 if e else 0 for e in magnetic_valve_state]
      u = u*pump_cal + w
      FT = np.exp(-t_step/tau_FT)*(FT -u/ft_cal) + u/ft_cal
      # Simulate
      y = FTS.y(FTS.step(t_step, u, d))
      LT = (y+v)/lt_cal

      ## 4. (f) Publish results of simulation to OPC-UA server
      [opcua_tags[process_to_tag_read[node]].set_value(int(value)) for node, value in zip(['FT1','FT2',],FT)]
      [opcua_tags[process_to_tag_read[node]].set_value(int(value)) for node, value in zip(['LT1','LT2','LT3','LT4',],LT)]

      ## 4. (g) Process safety interlocks
      # If the liquid level exceeds a certain mark then reset.
      if max(y) > h_safety_max:
        reset_tag.set_value(1)
finally:
  server.stop()
```

B.2 client_template.py

```
# Name: client_template.py
# Author: Eskild Schroll-Fleischer <esksch@dtu.dk>
# Date: 30th of August 2017
#
# Description:
# MPC regulator for the four tank process in B228 at the Technical University of Denmark.
# Communicates with the process equipment using OPC-UA.
# Data aquisition, Kalman filter and MPC are executed in a background thread at regular
# intervals. The controller set point may be changed during operation using the r(x)
# function in the embedded prompt. A live plot may be started using the
# live_plot(data_queue) function, it may be closed by CTRL-C.
#
# The code is organized as follows:
# 1. Configuration
# 2. Prepare Kalman filter and MPC here
# 3. Connect to OPC-UA server and discover nodes
# 4. Open CSV file for logging
# 5. Establish time-zero and read current values
# 6. (a) Poll server for new measurements
# 6. (b) Read measurements, inputs and known disturbances
# 6. (c) Filtering and MPC execution here
# 6. (d) Update data for animation plot
# 7. Plot

# Import standard python packages
import sys, time, datetime, csv, queue, atexit, threading
from opcua import Client
import numpy as np
from numpy.matlib import repmat
from scipy.optimize import fsolve
import matplotlib.pyplot as plt
# Use qt5 backend for more realiable plotting with matplotlib
import matplotlib.pyplot as p
p.switch_backend('Qt5Agg')

try:
    from IPython import embed
except ImportError:
    import code
    def embed():
        vars = globals()
        vars.update(locals())
        shell = code.InteractiveConsole(vars)
        shell.interact()

## 1. Configuration
OPC_UA_SERVER = 'opc.tcp://localhost:4840/four_tank_process/'
LOG_FILE = 'log.csv'
# Length of discrete time step [s]
t_step = datetime.timedelta(seconds=1)
# Number of discrete time steps to keep in history
n_hist = 50
# Number of discrete time steps to forecast
n_horizon = 10

# Calibration
signal_range = 32000
controller_range = 320
pump_cal = np.array([0.0203,0.0216]) # [(cm^3/s)/signal]
valve_cal = np.array([signal_range,signal_range]) # [split fraction/signal]
ft_cal = np.array([5/288, 5/288]) # [(cm^3/s)/signal]
lt_cal = 3.19e-3 # [cm/signal]

# The following two dictionaries map comprehensible process variable designations
# to their OPC-UA counterpart tags.
process_to_tag_read = { 'LT1' :'IW00',
            'LT3' :'IW02',
            'FT1' :'IW04',
            'LT2' :'IW08',
            'LT4' :'IW10',
            'FT2' :'IW12',
            'P1' :'IW24',
            'P2' :'IW26',
            'V1' :'IW28',
            'V2' :'IW30',
```

```
            'MV14':'IW62',}
process_to_tag_write = {'P1w' :'QW04',
            'P2w' :'QW06',
            'V1w' :'QW08',
            'V2w' :'QW10',
            'MV1w':'QX30',
            'MV2w':'QX31',
            'MV3w':'QX32',
            'MV4w':'QX33',}

# Inverted mappings are generated which map from the comprehensible
# process variable designations to their corresponding OPC-UA tags.
tag_to_process_read = {v: k for k, v in process_to_tag_read.items()}
tag_to_process_write = {v: k for k, v in process_to_tag_write.items()}

# Dimensions of variables
ny = 4
nu = 2
nz = 2
nd = 4

##
## 2. Prepare Kalman filter and MPC here
##

# Set these values!
ys = np.array([0,0,0,0])
us = np.array([0,0])
ds = np.array([0,0,0,0])

# Default to keeping current steady state
r_future = np.zeros((1,nz))

def regulator(data_queue):
  global r_future
  # Get reference to current thread instance
  this = threading.currentThread()

  # Preallocate measurement and estimate history matrices to be used in a ring-buffer scheme
  r = np.zeros((n_hist+n_horizon,nz))
  y_hist = np.empty((n_hist,ny))
  y_est = np.empty((n_hist,ny))
  y_pred = np.empty((n_horizon,ny))
  u_hist = np.empty((n_hist,nu))
  u_pred = np.empty((n_horizon,nu))
  for array in [y_hist, y_est, y_pred, u_hist, u_pred]:
    array[:] = np.NAN

  # 3. Connect to OPC-UA server and discover nodes
  client = Client(OPC_UA_SERVER)
  # Connect and discover nodes
  client.connect()
  root = client.get_root_node()
  objects = root.get_child('0:Objects').get_child('2:S7200.OPCServer').get_child('2:Microwin').get_child('2:CPU224')
  opcua_tags = {}
  for object in objects.get_children():
    # In the present case the tags are on the form "Microwin.CPU224.VAR".
    # Hence the last part after the final dot corresponds to the designations
    # in process_to_tag_read and process_to_tag_write.
    node_name = object.get_display_name().to_string()
    if node_name in tag_to_process_read.keys():
      opcua_tags[tag_to_process_read[node_name]] = object
    elif node_name in tag_to_process_write.keys():
      opcua_tags[tag_to_process_write[node_name]] = object

  # 4. Open CSV file for logging
  logfile = open(LOG_FILE, 'a')
  csvlog = csv.writer(logfile, delimiter=';', quoting=csv.QUOTE_MINIMAL)

  try:
    # 5. Establish time-zero and read current values. The process is assumed to be in
    # steady state.
    t0 = opcua_tags['LT4'].get_data_value().ServerTimestamp
    y0 = np.array([opcua_tags[e].get_value() for e in ['LT1','LT2','LT3','LT4',]])
    u0 = np.array([opcua_tags[e].get_value() for e in ['P1','P2',]])
    plt.ion()
    t_start = t0
    while getattr(this, 'do_run', True):
```

```
        # 6. (a) Poll server for new measurements and act when sufficient time has passed
        time.sleep(0.1)
        t = opcua_tags['LT4'].get_data_value().ServerTimestamp
        if t -t0 >= t_step:
          #print(t-t0)
          t0 = t
          # 6. (b) Read measurements, inputs and known disturbances as well as extra
          # data not directly used by the regulator. Data is logged continuously.
          y = [opcua_tags[e].get_value() for e in ['LT1','LT2','LT3','LT4',]]
          u = [opcua_tags[e].get_value() for e in ['P1','P2',]]
          d = [0.1 if (opcua_tags['MV14'].get_value() & 1<<i) != 0 else 0 for i in range(8,12)]
          extra = [opcua_tags[e].get_value() for e in ['FT1','FT2','V1','V2']]
          # Log data to disk
          csvlog.writerow([(t0-t_start).total_seconds()]+y+list(r[0,])+u+d+extra)

          # Dimensional variables from deviation variables
          y = ys + (np.array(y)-y0)*lt_cal
          u = us + (np.array(u)-u0)*pump_cal

          ##
          ## 6. (c) Filtering and MPC execution here
          ##

          # 6. (d) Update data for animation plot
          # Roll history and trajectory
          y_hist = np.roll(y_hist,-ny)
          u_hist = np.roll(u_hist,-nu)
          r = np.roll(r,-nz)
          y_hist[-1,] = y
          u_hist[-1,] = u
          r[-1,] = r_future

          # Submit new data to queue for live_plot to consume
          data_queue.put((r, y_hist, y_est, u_hist, y_pred, u_pred))
  finally:
    client.disconnect()
    logfile.close()

## 7. Plot
def live_plot(data_queue):
  # Empty the queue of its contents
  while True:
    try:
      data_queue.get(block=False)
    except queue.Empty:
      break
  # Get data from queue
  r, y_hist, y_est, u_hist, y_pred, u_pred = data_queue.get()
  # Prepare time axis which is constant at all times
  t_hist = np.linspace(-(n_hist-1),0,n_hist) *t_step.total_seconds()
  t_hist_pred = np.linspace(-(n_hist-1),n_horizon,n_hist+n_horizon) *t_step.total_seconds()
  # Open plot window and clear it.
  f = plt.figure(1)
  f.clf()
  # Upper subplot
  plt.subplot(2,1,1)
  # Plot measurements
  p1 = plt.plot(t_hist, y_hist, 'o', ms=4, mfc='none')
  # Reset color order
  plt.gca().set_prop_cycle(None)
  # Plot filtered measurements
  p2 = plt.plot(t_hist_pred, np.concatenate((y_est,y_pred)))
  # Reset color order
  plt.gca().set_prop_cycle(None)
  # Plot set point
  p3 = plt.plot(t_hist_pred, r, '--')
  # Axis specification
  plt.ylim([0,60])
  plt.xlim([-(n_hist-1)*t_step.total_seconds(), n_horizon*t_step.total_seconds()])
  plt.legend(['Tank 1','Tank 2','Tank 3','Tank 4',],loc='lower left')
  plt.ylabel('Level $[\mathrm{cm}]$')
  # Lower subplot
  plt.subplot(2,1,2)
  #plt.cla() ###
  # Plot manipulated variable as stairs
  p4 = plt.plot(t_hist_pred, np.concatenate((u_hist,u_pred)), drawstyle='steps-pre')
  # Axis specification
  plt.ylim([0,500])
```

```
  plt.xlim([-(n_hist-1)*t_step.total_seconds(), n_horizon*t_step.total_seconds()])
  plt.legend(['$u_1$','$u_2$'],loc='lower left')
  plt.ylabel('Flow rate $[\mathrm{cm^3\,s^{-1}}]$')
  plt.xlabel('Time $[\mathrm{s}]$')
  # Display plot
  plt.show()
  # Live update plot until keyboard interrupt (CTRL-C) is issued.
  try:
    while True:
      plt.pause(0.1)
      # Get latest data
      try:
        r, y_hist, y_est, u_hist, y_pred, u_pred = data_queue.get(True, 0.1)
      except queue.Empty:
        continue
      # Update the plots
      for i, p in enumerate(p1):
        p.set_ydata(y_hist[:,i])
      y_ = np.concatenate((y_est,y_pred))
      for i, p in enumerate(p2):
        p.set_ydata(y_[:,i])
      for i, p in enumerate(p3):
        p.set_ydata(r[:,i])
      y_ = np.concatenate((u_hist,u_pred))
      for i, p in enumerate(p4):
        p.set_ydata(y_[:,i])
  except KeyboardInterrupt:
    plt.close(1)

# Use this function to manipulated set-point from cmd window
def r(x):
  global r_future
  r_future = r_future + x

def end_thread(thread):
  thread.do_run = False
  if thread.is_alive():
    thread.join()

if __name__ == '__main__':
  data_queue = queue.Queue()
  thread = threading.Thread(target=regulator,args=(data_queue,),daemon=True)
  thread.start()
  atexit.register(end_thread, thread)
  live_plot(data_queue)
  embed()
```

B.3 client_template.m

```
% Name: client_template.m
% Author: Eskild Schroll-Fleischer <esksch@dtu.dk>
% Date: 30th of August 2017
%
% Description:
% MPC regulator for the four tank process in B228 at the Technical University of Denmark.
% Communicates with the process equipment using OPC-UA.
% Data aquisition, Kalman filter and MPC are executed in a background thread at regular
% intervals using a timer. The controller set point may be changed during operation by
% modifying r_future in the prompt. The regulator may be started by issuing
%  start(th)
% and stopped by issuing
%  stop(th)
%
% The code is organized as follows:
% 1. Configuration
% 2. Prepare Kalman filter and MPC here
% 3. Read variables to establish initial conditions
% 4. Create timer object to read variables periodically
% 5. (a) Read measurements, inputs and known disturbances
% 5. (b) Filtering and MPC execution here
% 5. (c) Update data for animation plot
% 6. Plot

%% Preamble
set(0,'defaultlinelinewidth',1.7)
set(0,'DefaultAxesFontSize',14)
set(0,'DefaultAxesXGrid','on','DefaultAxesYGrid','on','DefaultAxesZGrid','on')
set(groot, 'defaultAxesTickLabelInterpreter','latex');
set(groot, 'defaultLegendInterpreter','latex');
set(0,'defaultTextInterpreter','latex');
set(0, 'DefaultFigurePosition', [0 0 500 600]);

%% 1. Configuration
OPC_UA_URL = 'opc.tcp://localhost:4840/four_tank_process/';
% Length of discrete time step [s]
regulator.t_step = 1;
% Number of discrete time steps to keep in history
regulator.n_hist = 50;
% Number of discrete time steps to forecast
regulator.n_horizon = 10;
% Prepare time axis
regulator.t_hist = linspace(-(regulator.n_hist-1)*regulator.t_step,0,regulator.n_hist);
regulator.t_hist_pred = linspace(-(regulator.n_hist-1)*regulator.t_step,regulator.n_horizon*regulator.t_step,regulator.n_hist+regulator.n_horizon);

% Calibration
signal_range = 32000;
controller_range = 320;
regulator.pump_cal = [0.0203, 0.0216];
regulator.valve_cal = signal_range;
regulator.ft_cal = 5/288;
regulator.lt_cal = 3.19e-3;

% Connect to OPC-UA server and discover nodes
ua = opcua(OPC_UA_URL);
connect(ua);
% Discover nodes in the namespace
S7200 = findNodeByName(ua.Namespace,'S7200.OPCServer');
Microwin = findNodeByName(S7200,'Microwin');
CPU224 = findNodeByName(Microwin,'CPU224');
nodes = CPU224.Children;
%                   LT1 LT2 LT3 LT4 P1 P2 FT1 FT2 V1 V2 MV14
readable_indices = [37  41  38  42  49 50 39  43  51 52 68];
%                   P1  P2  V1  V2 MV1 MV2 MV3 MV4
writable_indices = [3   4   5   6  33  34  35  36];
nodes = nodes([readable_indices writable_indices]);
LT1_ = 1; LT2_ = 2; LT3_ = 3; LT4_ = 4; P1r_ = 5; P2r_ = 6; FT1_ = 7; FT2_ = 8;
V1_ = 9; V2_ = 10; MV14_ = 11; P1w_ = 12; P2w_ = 13; V1w_ = 14; V2w_ = 15;
MV1_ = 16; MV2_ = 17; MV3_ = 18; MV4_ = 19;

regulator.y_ = nodes([LT1_,LT2_,LT3_,LT4_]);
regulator.u_ = nodes([P1w_,P2w_]);
regulator.d_ = nodes(MV14_);

% Dimensions of variables
```

```
regulator.ny = 4;
regulator.nu = 2;
regulator.nz = 2;
regulator.nd = 4;

%%
%% 2. Prepare Kalman filter and MPC here
%%

%% 3. Read variables to establish initial conditions
regulator.y0 = double(cell2mat(readValue(regulator.y_))');
regulator.u0 = double(cell2mat(readValue(regulator.u_))');
regulator.d0 = double(0.1*bitget(readValue(regulator.d_)',[8:11]));
% Initial conditions do not necessarily have to be steady state
regulator.ys = regulator.y0*regulator.lt_cal;
regulator.us = regulator.u0.*regulator.pump_cal;
regulator.ds = regulator.d0;

%% 4. Create timer object to read variables periodically
th = timer;
fh = figure(1);
set(th,'timerfcn',@(~,~) timer_function(regulator,fh),'period',1,'executionmode','fixedrate')

% Preallocate measurement and estimate history matrices to be used in a ring-buffer scheme.
global y_hist y_est y_pred u_hist u_pred r r_future
y_hist = nan(regulator.n_hist,regulator.ny);
y_est = nan(regulator.n_hist,regulator.ny);
y_pred = nan(regulator.n_horizon,regulator.ny);
u_hist = nan(regulator.n_hist,regulator.nu);
u_pred = nan(regulator.n_horizon,regulator.nu);
r = zeros(regulator.n_hist+regulator.n_horizon,regulator.nz);

% Default to keeping current steady state
r_future = zeros(1,regulator.nz);

function timer_function(reg,fig)
    global y_hist y_est y_pred u_hist r r_future
    %% 5. (a) Read measurements, inputs and known disturbances
    y = double(cell2mat(readValue(reg.y_))');
    u = double(cell2mat(readValue(reg.u_))');
    d = double(0.1*bitget(readValue(reg.d_)',[8:11]));

    % Dimensional variables from deviation variables
    y = reg.ys + (y-reg.y0)*reg.lt_cal;
    u = reg.us + (u-reg.u0).*reg.pump_cal;

    %%
    %% 5. (b) Filtering and MPC execution here
    %%

    %% 5. (c) Update data for animation plot
    % Roll history and trajectory
    y_hist(1:end-1,:) = y_hist(2:end,:);
    y_hist(end,:) = y;
    u_hist(1:end-1,:) = u_hist(2:end,:);
    u_hist(end,:) = u;
    r(1:end-1,:) = r(2:end,:);
    r(end,:) = r_future;

    %% 6. Plot
    fig;
    clf
    % Upper subplot
    subplot(2,1,1);
    % Plot measurements
    plot(reg.t_hist,y_hist,'o','MarkerSize',4)
    hold on;
    % Reset color order
    ax=gca;ax.ColorOrderIndex = 1;
    % Plot filtered measurements
    plot(reg.t_hist_pred, [y_est;y_pred])
    % Reset color order
    ax=gca;ax.ColorOrderIndex = 1;
    % Plot set point
    plot(reg.t_hist_pred,r+reg.ys(1:2),'--')
    % Axis specification
    ylim([0 60])
    xlim([min(reg.t_hist) max(reg.t_hist_pred)])
```

```
    legend({'Tank $1$','Tank $2$','Tank $3$','Tank $4$'})
    ylabel('Level $[\mathrm{cm}]$')
    % Lower subplot
    subplot(2,1,2);
    % Plot manipulated variable as stairs
    stairs(reg.t_hist,u_hist)
    % Axis specification
    ylim([0 500])
    xlim([min(reg.t_hist) max(reg.t_hist_pred)])
    legend({'$u_1$','$u_2$'})
    ylabel('Flow rate $[\mathrm{cm^3\,s^{-1}}]$')
    xlabel('Time $\mathrm{[s]}$')
end

start(th)
```

C Datasheets

C.1 Bürkert 6213

burkert FLUID CONTROL SYSTEMS

Servo-assisted 2/2 way diaphragm valve

- Servo-assisted diaphragm with diameter of up to DN 40
- Spring coupled diaphragm opens without differential pressure
- Vibration-proof, screwed coil system
- Damped design for quiet closing
- Press mould housing with high surface quality

Type 6213EV can be combined with...

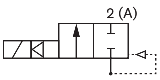
Type 2508
Cable plug

Type 2513
Cable plug
(ATEX Cat. 3 GD)

DTS 1000115690 EN Version: N Status: RL (released | freigegeben | validé) printed: 28.10.2016

The 6213 EV valve is a servo-assisted solenoid valve of the S.EV series. The spring coupling of the diaphragm supports the opening process of the valve. In its standard version, the valve is suitable for use in liquids. A minimum differential pressure is required for complete opening. A special version (HP00) which opens the valve without differential pressure is available for gas and vacuum applications. Various diaphragm material combinations are available depending on the application. The standard brass housing satisfies all European drinking water requirements. Lead-free or dezincification-resistant brass types are available for other markets. The housing offering is rounded out by a stainless steel version. The solenoid coils are moulded with a chemically resistant epoxy. For reduced energy requirement, all coils can be delivered with electronic power reduction. In combination with a plug in accordance with DIN EN 17301-803 Form A, the valves satisfy protection class IP65 – in combination with a stainless steel housing NEMA 4X .

Circuit function A



Servo-assisted 2/2 way valve; normally closed, with 2 way pilot control

Technical data	
Orifice	Standard DN 10 - 40 mm HP00: DN13-20
Body material	Brass acc. to DIN EN 50930-6, stainless steel 1.4408 (316), nickel-plated brass (5μm)
Inner part of valve Brass body Stainless steel body	 Brass, stainless steel and PPS Stainless steel and PPS
Seal material	NBR, FKM, EPDM
Medium NBR FKM EPDM	 Neutral fluids, water, hydraulic oil, oil without additives Per-solutions, hot oils with additives Oil and fat-free fluids and gases
Ambient temperature	Max. +55 °C
Medium viscosity	Max. 21 mm^2/s
Medium temperature NBR FKM EPDM	 -10 to +80 °C 0 to +90 °C with polyamide coil / 0 - 120 °C with epoxy coil -30 to +90 °C with polyamide coil -30 to +100 °C with epoxy coil
Voltages	Standard 024/DC, 024/50, 230/50, 110/50, 120/60 HP00: 24V (50-60Hz), 230V (50-60Hz)
Voltage tolerance	±10%
Duty cycle	100% continuous rating
Electrical connection	Tag connector acc. to DIN EN 175301-803 Form A (previously DIN 43650) (see ordering chart for accessories, page 7)
Protection class	IP 65 with cable plug
Installation	As required, preferably with actuator upright

Response times[1)]	0.1 - 4 seconds (depending on orifice and differential pressure)

[1)] Measured at valve outlet at 6 bar and +20°C
Opening: pressure build-up 0 to 90%
Closing: Pressure drop 100 to 10%

Technical data

Power consumption

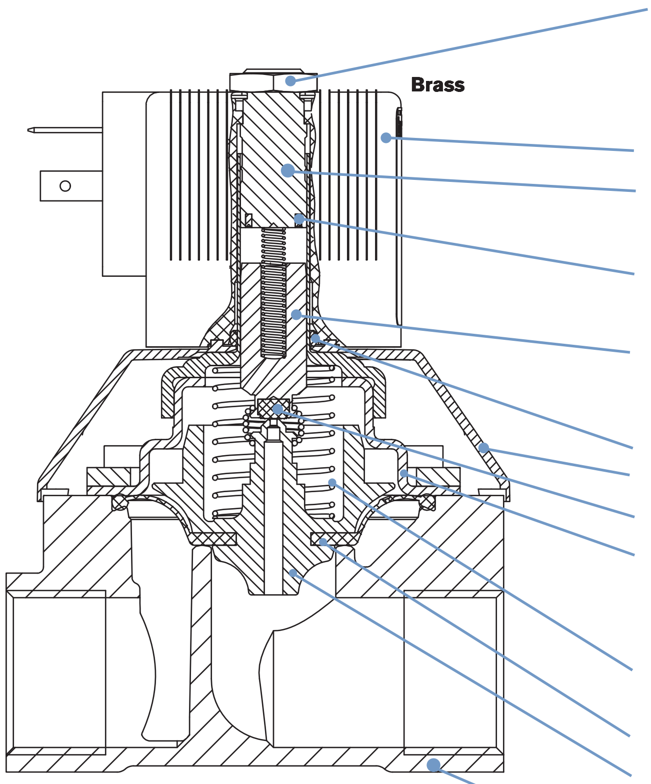
Orifice DN	Port Connection	Coil size width [mm] AC	DC	Power consumption [1)] Inrush AC [VA]	Hold (hot coil) AC [VA/W]	DC [W]	Insulation class coil [2)] Seal material FKM	Seal material NBR and EPDM	Weight [kg] Brass Coil AC	Brass Coil DC
10	G1/4. G3/8	32	40	34	14/8	10 (11)	H	B	0.33	0.41
10	G1/2	32	40	34	14/8	10 (11)	H	B	0.37	0.44
13	G1/2	32	40	36	14/8	10 (11)	H	B	0.46	0.54
13	G3/4	32	40	36	14/8	10 (11)	H	B	0.49	0.57
20	G3/4	32	40	38	14/8	10 (11)	H	B	0.74	0.82
20	G1	32	40	38	14/8	10 (11)	H	B	0.95	1.03
25	G1	42	65	150	37/16	28 (29)	H	H	1.6	2.2
25	G11/4	42	65	150	37/16	28 (29)	H	H	1.7	2.3
40	G11/4	42	65	190	37/16	28 (29)	H	H	3.2	3.7
40	G11/2	42	65	190	37/16	28 (29)	H	H	3.2	3.7
40	G2	42	65	190	37/16	28 (29)	H	H	3.38	3.9

HP00 Power consumption

Orifice DN	Port Connection	Coil size width [mm] AC/DC	Power consumption [1)] Inrush AC [VA]	Hold (hot coil) AC [VA/W]	DC [W]	Insulation class coil [2)] Seal material FKM	Seal material NBR and EPDM	Weight [kg] Brass Coil AC	Brass Coil DC
13	G1/2	42	125	37/16	16 (21)	H	H	0.80	0.81
13	G3/4	42	125	37/16	16 (21)	H	H	0.86	0.87
20	G3/4	42	140	37/16	16 (21)	H	H	1.13	1.14
20	G1	42	140	37/16	16 (21)	H	H	1.30	1.31

[1)] Values in brackets applies at coil temperature 20 °C
[2)] H Epoxy coil, B Polyamide coil

Materials



Locknut:
Brass version: Steel (surface thick-film passivated acc. to Rohs)
Stainless steel version: 1.4305 PTFE coated

Coil: Polyamide or Epoxy

Stopper:
DN 10-40 mm: 1.4113

Shading ring (only AC version):
with Brass body: Copper (Cu)
with Stainless steel body: Silver (Ag)

Magnetic core:
DN 10-40 mm: 1.4113

O-Ring: FKM

Bonnet: PA6

Plunger seal: NBR, FKM, EPDM

Cover:
DN 10-25 mm: 1.4301
DN 40: Brass, nickel-plated brass (5μm), stainless steel 1.4408

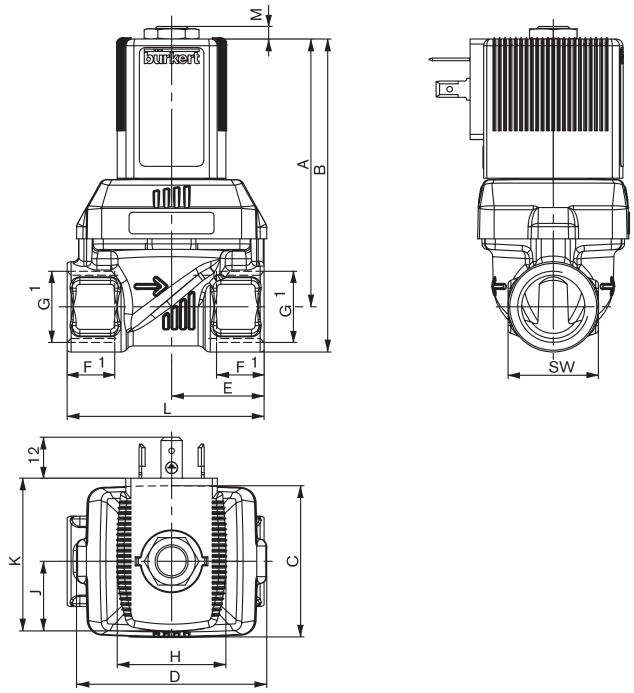
Spring: 1.4310

Diaphragm NBR, FKM, EPDM

Diaphragm support: PPSGF40 in combination with brass and accordingly stainless steel parts

Valve body: Brass, nickel-plated brass(5μm), stainless steel 1.4408 burkert

Dimensions [mm]



Dimensions (AC-coil, 32mm)

					E	* G		* NPT		* Rc					L		
DN	A	B	C	D	(MS/VA)	F1	G1	F2	G2	F3	G3	H	J	K	(MS/VA)	SW	M
	67.4	78.4			22	12	G 1/4	10	NPT 1/4	9.7	Rc 1/4						
10	67.4	78.4	36	46	22	12	G 3/8	10.3	NPT 3/8	10.1	Rc 3/8	32	20.5	45	50	22	3.7
	69.4	82.9			24.5	14	G1/2	13.7	NPT 1/2	13.2	Rc 1/2				50/55	27	
13	78.9	92.4	44.5	56	27.2/32.5	14	G 1/2	13.7	NPT 1/2	13.2	Rc 1/2	32	20.5	45	58/65	27	3.7
	80.9	96.9			32.5	16	G 3/4	14	NPT 3/4	14.5	Rc 3/4				65	32	
20	93.4	109.4	65	76.6	37	16	G 3/4	14	NPT 3/4	14.5	Rc 3/4	32	20.5	45	80	32	3.7
	95.9	116.4			37.5	18	G 1	16.8	NPT 1	16.8	Rc 1				80	41	

Dimensions (DC-coil, 40mm)

					E	* G		* NPT		* Rc					L		
DN	A	B	C	D	(MS/VA)	F1	G1	F2	G2	F3	G3	H	J	K	(MS/VA)	SW	M
	67.4	78.4			22	12	G 1/4	10	NPT 1/4	9.7	Rc 1/4						
10	67.4	78.4	36	46	22	12	G 3/8	10.3	NPT 3/8	10.1	Rc 3/8	40	23.5	51	50	22	3.7
	69.4	82.9			24.5	14	G1/2	13.7	NPT 1/2	13.2	Rc 1/2				50/55	27	
13	79.3	92.8	44.5	56	27.2/32.5	14	G 1/2	13.7	NPT 1/2	13.2	Rc 1/2	40	23.5	51	58/65	27	3.7
	81.3	97.3			32.5	16	G 3/4	14	NPT 3/4	14.5	Rc 3/4				65	32	
20	93.8	109.8	65	76.6	37	16	G 3/4	14	NPT 3/4	14.5	Rc 3/4	40	23.5	51	80	32	3.7
	96.3	116.8			37.5	18	G 1	16.8	NPT 1	16.8	Rc 1				80	41	

Dimensions (AC-coil, 42mm / DC-coil 65mm)

					E	* G		* NPT		* Rc					L		
DN	A	B	C	D	(MS/VA)	F1	G1	F2	G2	F3	G3	H	J	K	(MS/VA)	SW	M
	158.3	193.3			64	24	G 2	17.6	NPT 2	23.4	Rc 2				132	70	
40	152.3	182.3	104.5	117	61	22	G1 1/2	17.3	NPT 1 1/2	19.1	Rc 1 1/2	65	37.5	72	126	60	7
	146.8	171.8			61	20	G1 1/4	17.3	NPT 1 1/4	19.1	Rc 1 1/4				126	50	
25	141.3	166.3	77	88	46	20	G1 1/4	17.3	NPT 1 1/4	19.1	Rc 1 1/4	65	37.5	72	95	50	7
	136.3	156.8			46	18	G 1	16.8	NPT 1	16.8	Rc 1				95	41	
	158.3	193.3			64	24	G 2	17.6	NPT 2	23.4	Rc 2				132	70	
40	152.3	182.3	104.5	117	61	22	G1 1/2	17.3	NPT 1 1/2	19.1	Rc 1 1/2	42	27	55.5	126	60	7
	146.8	171.8			61	20	G1 1/4	17.3	NPT 1 1/4	19.1	Rc 1 1/4				126	50	
25	141.3	166.3	77	88	46	20	G1 1/4	17.3	NPT 1 1/4	19.1	Rc 1 1/4	42	27	55.5	95	50	7
	136.3	156.8			46	18	G 1	16.8	NPT 1	16.0	Rc 1				95	41	

Dimensions [mm] *(cont.)*

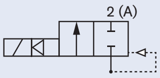
HP00 Version
Dimensions (coil, 42mm)

					2E	* G		* NPT		* Rc					L		
DN	**A**	**B**	**C**	**D**	**(MS/VA)**	**F1**	**G1**	**F2**	**G2**	**F3**	**G3**	**H**	**J**	**K**	**(MS/VA)**	**SW**	**M**
20	119.3	139.8	65	76.6	37.5	18	G 1	16.8	NPT 1	16.8	Rc 1	42	27	55.5	80	41	7
	116.8	132.8			37	16	G 3/4	14	NPT 3/4	14.5	Rc 3/4					32	
13	104.3	120.3	44.5	56	32.5	16	G 3/4	14	NPT 3/4	14.5	Rc 3/4				65	32	
	102.6	115.6			27.2/32.5	14	G 1/2	13.7	NPT 1/2	13.2	Rc 1/2				58/65	27	
					27.2/32.5										58/65	27	

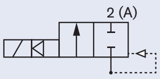
Ordering chart for valves (other versions on request)

Valves with brass body

DN 10 -40 mm

Circuit function	Port connection	Orifice [mm]	Kv value water [m³/h] 1) 4)	Pressure range [bar] 2)	Weight [kg] (DC) 3)	Item no. per voltage/frequency [V/Hz]		
						024/DC	024/50	230/50
	Brass-body, NBR Diaphragm, polyamide coil, medium temperature -10...+80°C							
A 2/2 way valve NC 	G 1/4	10	1.3	0 - 10	0.3 (0.5)	221 674	221 675	221 677
	G 3/8	10	1.9	0 - 10	0.3 (0.5)	221 598	221 599	221 601
	G 1/2	10	1.9	0 - 10	0.4 (0.5)	221 606	221 607	221 609
	G 1/2	13	3.6	0 - 10	0.4 (0.5)	221 602	221 603	221 605
	G 3/4	13	3.6	0 - 10	0.5 (0.6)	221 618	221 619	221 621
	G 3/4	20	8.3	0 - 10	0.7 (0.8)	221 630	221 631	221 633
	G 1	20	8.3	0 - 10	0.9 (1.0)	221 634	221 635	221 637
	Brass-body, NBR Diaphragm, epoxy coil, medium temperature -10...+80°C							
	G 1	25	11	0 - 10	1.6 (2.2)	227 533	221 725	221 728
	G 1 1/4	25	11	0 - 10	1.7 (2.3)	227 534	221 729	221 732
	G 1 1/4	40	23	0 - 10	2.9 (3.4)	270 903	270 895	270 899
	G 1 1/2	40	30	0 - 10	3.2 (3.7)	227 539	221 750	221 753
	G 2	40	30	0 - 10	3.4 (3.9)	227 541	221 754	221 757
	Brass-body, FKM Diaphragm, epoxy coil, medium temperature 0...120°C							
	G 1/4	10	1.3	0 - 10	0.3 (0.5)	221 678	221 679	221 681
	G 3/8	10	1.9	0 - 10	0.3 (0.5)	221 610	221 611	221 613
	G 1/2	10	1.9	0 - 10	0.4 (0.5)	221 614	221 615	221 617
	G 1/2	13	3.6	0 - 10	0.4 (0.5)	221 622	221 623	221 625
	G 3/4	13	3.6	0 - 10	0.5 (0.6)	221 626	221 627	221 629
	G 3/4	20	8.3	0 - 10	0.7 (0.8)	221 638	221 639	221 641
	G 1	20	8.3	0 - 10	0.9 (1.0)	221 642	221 643	221 645
	G 1	25	11	0 - 10	1.6 (2.2)	227 537	221 733	221 736
	G 1 1/4	25	11	0 - 10	1.7 (2.3)	227 538	221 737	221 740
	G 1 1/4	40	23	0 - 10	2.9 (3.4)	270 905	270 906	270 908
	G 1 1/2	40	30	0 - 10	3.2 (3.7)	227 544	227 724	227 726
	G 2	40	30	0 - 10	3.4 (3.9)	227 545	227 728	227 730
	Brass-body, EPDM Diaphragm, polyamide coil, medium temperature -30...+90°C							
	G 1/4	10	1.3	0 - 10	0.3 (0.4)	221 670	221 671	221 673
	G 3/8	10	1.9	0 - 10	0.3 (0.4)	221 646	221 647	221 649
	G 1/2	10	1.9	0 - 10	0.4 (0.5)	221 650	221 651	221 653
	G 1/2	13	3.6	0 - 10	0.4 (0.5)	221 654	221 655	221 657
	G 3/4	13	3.6	0 - 10	0.5 (0.6)	221 658	221 659	221 661
	G 3/4	20	8.3	0 - 10	0.7 (0.8)	221 662	221 663	221 665
	G 1	20	8.3	0 - 10	0.9 (1.0)	221 666	221 667	221 669
	Brass-body, EPDM Diaphragm, epoxy coil, medium temperature -30...+100°C							
	G 1	25	11	0 - 10	1.6 (2.2)	227 535	221 717	221 720
	G 1 1/4	25	11	0 - 10	1.7 (2.3)	227 536	221 721	221 724
	G 1 1/4	40	23	0 - 10	2.9 (3.4)	270 904	270 890	270 894
	G 1 1/2	40	30	0 - 10	3.2 (3.7)	227 542	221 741	221 745
	G 2	40	30	0 - 10	3.4 (3.9)	227 543	221 746	221 749

DN 13-20 mm HPOO version

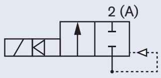
Circuit function	Port connection	Orifice [mm]	Kv value water [m³/h] 1)	Pressure range [bar] 2)	Weight [kg] (DC)	Item no. per voltage/frequency [V/Hz]		
						024/DC	024/50-60	230/50-60
	Brass-body, FKM Diaphragm, epoxy coil, medium temperature 0...+120°C							
A 2/2 way valve NC 	G 1/2	13	3.6	0 - 10	0.8	221 706	221 705	231 574
	G 3/4	20	8.3	0 - 10	1.3	221 712	221 711	221 713
	G 1	20	8.3	0 - 10	1.4	221 715	221 714	221 716
	Brass-body, EPDM Diaphragm, epoxy coil, medium temperature -30...+100°C							
	G 1/2	13	3.6	0 - 10	0.8	221 694	221 693	221 695
	G 3/4	20	8.3	0 - 10	1.3	208 422	221 699	189 592
	G 1	20	8.3	0 - 10	1.4	221 703	221 702	221 704

1) Measured at +20°C, 1 bar 2) pressure at valve inlet and free outlet.
2) Pressure data [bar]: Overpressure with respect to atmospheric pressure.
3) The values in brackets regarding the weight apply to the DC version.
4) A minimum differential pressure of 0.5 bar is required for full (100%) opening.

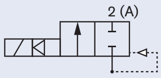
Ordering chart for valves (other versions on request)

Valves with Stainless steel body;

DN 10 -40 mm

Circuit function	Port connection	Orifice [mm]	Kv value water [m³/h] 1) 4)	Pressure range [bar] 2)	Weight [kg] (DC) 3)	Item no. per voltage/frequency [V/Hz] 024/DC	024/50	230/50
A 2/2 way valve NC	**Stainless steeel-body, NBR Diaphragm, polyamide coil, medium temperature -10...80°C**							
2 (A) 	G 3/8	10	1.9	0 - 10	0.3 (0.4)	222 150	222 151	222 152
	G 1/2	13	3.6	0 - 10	0.4 (0.5)	222 156	222 157	222 158
	G 3/4	20	8.3	0 - 10	0.7 (0.8)	222 168	222 169	222 170
	G 1	20	8.3	0 - 10	0.9 (1.0)	222 171	222 172	222 173
	Stainless steel body, NBR Diaphragm, epoxy coil, medium temperature -10...+80°C							
	G 1	25	11	0 - 10	1.6 (2.2)	227 546	228 429	222 193
	G 1 1/4	25	11	0 - 10	1.7 (2.3)	227 547	228 432	222 197
	G 1 1/2	40	30	0 - 10	3.2 (3.7)	227 552	228 435	222 201
	G 2	40	30	0 - 10	3.4 (3.9)	227 554	228 438	222 205
	Stainless steel body, FKM Diaphragm, epoxy coil, medium temperature 0...120°C							
	G 3/8	10	1.9	0 - 10	0.3 (0.4)	221 758	221 759	221 761
	G 1/2	13	3.6	0 - 10	0.4 (0.5)	221 762	221 763	221 765
	G 3/4	20	8.3	0 - 10	0.7 (0.8)	222 122	222 123	222 125
	G 1	20	8.3	0 - 10	0.9 (1.0)	222 126	222 127	222 129
	G 1	25	11	0 - 10	1.6 (2.2)	227 550	228 430	222 143
	G 1 1/4	25	11	0 - 10	1.7 (2.3)	227 551	228 433	222 145
	G 1 1/2	40	30	0 - 10	3.2 (3.7)	227 557	228 436	222 147
	G 2	40	30	0 - 10	3.4 (3.9)	227 558	228 439	222 149
	Stainless steeel-body, EPDM Diaphragm, polyamide coil, medium temperature -30...90°C							
	G 3/8	10	1.9	0 - 10	0.3 (0.4)	222 153	222 154	222 155
	G 1/2	13	3.6	0 - 10	0.4 (0.5)	222 159	222 160	222 161
	G 3/4	20	8.3	0 - 10	0.7 (0.8)	222 174	222 175	222 176
	G 1	20	8.3	0 - 10	0.9 (1.0)	222 177	222 178	222 179
	Stainless steeel-body, EPDM Diaphragm, epoxy coil, medium temperature -30...+100°C							
	G 1	25	11	0 - 10	1.6 (2.2)	227 548	228 431	222 195
	G 1 1/4	25	11	0 - 10	1.7 (2.3)	227 549	228 434	222 199
	G 1 1/2	40	30	0 - 10	3.2 (3.7)	227 555	228 437	222 203
	G 2	40	30	0 - 10	3.4 (3.9)	227 556	228 440	222 207

DN 13-20 mm HPOO version

Circuit function	Port connection	Orifice [mm]	Kv value water [m³/h] 1)	Pressure range [bar] 2)	Weight [kg] (DC)	Item no. per voltage/frequency [V/Hz] 024/DC	024/50-60	230/50-60
A 2/2 way valve NC	**Stainless steel body, FKM Diaphragm, epoxy coil, medium temperature 0...120°C**							
2 (A) 	G 1/2	13	3.6	0 - 10	0.8	208 694	220 585	205 351
	G 3/4	20	8.3	0 - 10	1.3	222 137	222 136	222 138
	G 1	20	8.3	0 - 10	1.4	222 140	222 139	222 141
	Stainless steeel-body, EPDM Diaphragm, epoxy coil, medium temperature -30...100°C							
	G 1/2	13	3.6	0 - 10	0.8	213 132	222 166	220 584
	G 3/4	20	8.3	0 - 10	1.3	222 186	222 187	222 188
	G 1	20	8.3	0 - 10	1.4	222 189	222 190	222 191

1) Measured at +20°C, 1 bar 2) pressure at valve inlet and free outlet.
2) Pressure data [bar]: Overpressure with respect to atmospheric pressure.
3) The values in brackets regarding the weight apply to the DC version.
4) A minimum differential pressure of 0.5 bar is required for full (100%) opening.

Please note that the cable plug has to be ordered separately, see Ordering chart for accessory and separate datasheet, Type 2508

Further versions on request

Port connection
NPT, Rc

Temperature
Special temperature ranges

Voltages
further Voltages available

Body material
Brass dezincification resistant
nickel-plated brass (5µm)

Approvals
drinking water approval acc. to KTW/W270
VDE Approval acc. to DIN EN 60730 (VDE0631)
Watermark Licence
UL(UL-listed) approval (MH10753)
UR(UL-recognized) approval
NEMA 250 Type 4X

Orifice DN1o in brass and stainless steel is also available in explosion proof version
Explosion protected approvals

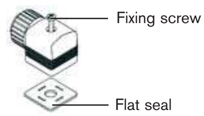
ATEX: PTB 14 ATEX 2023 X
II 2G Ex mb IIC T4 Gb
II 2D Ex mb IIIC T135 °C Db

IECEx: IECEx PTB 14.0049 X
Ex mb IIC T4 Gb
Ex mb IIIC T135 °C Db

Ordering chart for accessories

Cable plug Type 2508 according to DIN EN 175301-803 Form A

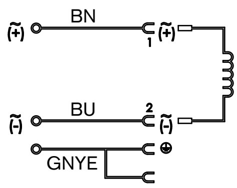
Circuitry	Voltage / frequency	Item no.
None (standard)	0 - 250 V AC/DC	008 376
further versions see datasheet Type 2508		



The delivery of a cable plug includes the flat seal and the fixing screw.
For further versions see datasheet Type 2508

Cable plug Type 2513 acc. to DIN EN 175301-803, Form A

Meets the requirements of ATEX category 3 GD



Cable length [mm]	Item no. [in mm]
12000	260 893
5000	260 892
3000	260 891
300	260 890

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C.2 Grundfos 25-60 N 180

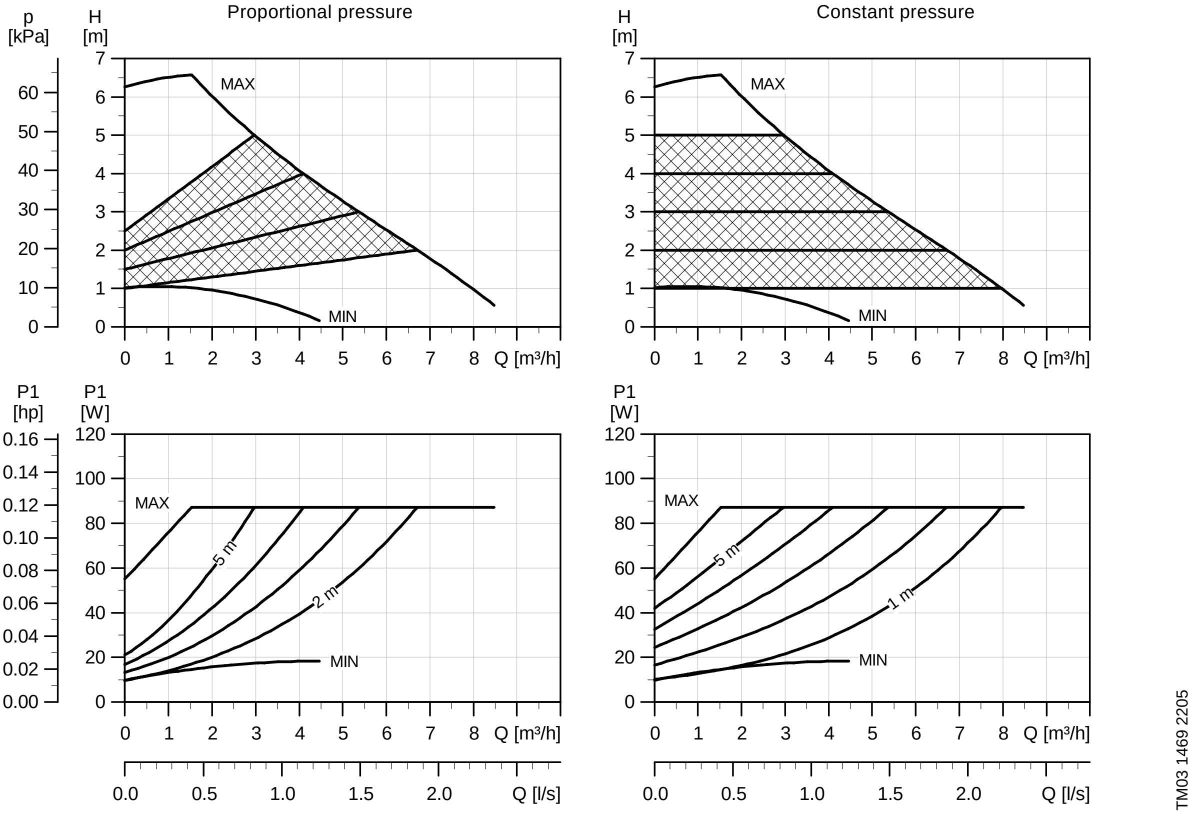
GRUNDFOS **DATA BOOKLET**

MAGNA, UPE

Series 2000 circulator pumps

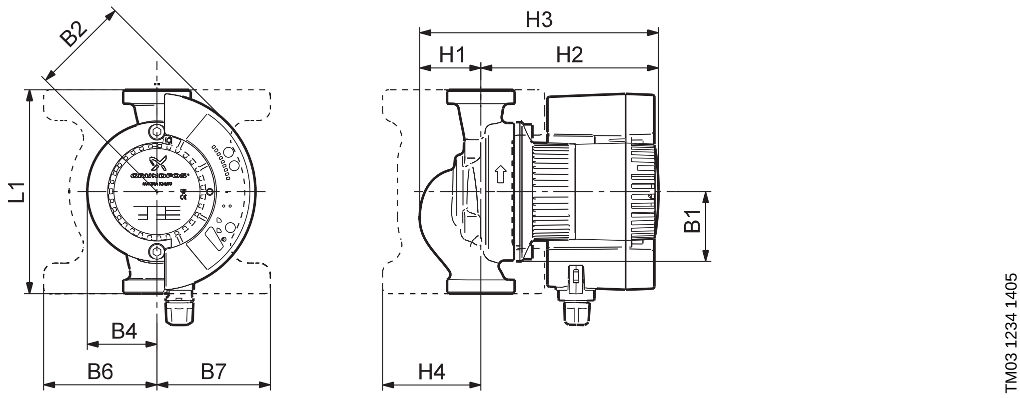
BE > THINK > INNOVATE >

MAGNA 25-60



Electrical data

U_n [V]		P_1 [W]	$I_{1/1}$ [A]
1 x 230-240 V	Min.	10	0.09
	Max.	85	0.60



Dimensions and weights

Pump type	Dimensions [mm]												Weight [kg]	Ship. vol.
	L1	B1	B2	B4	B6	B7	H1	H2	H3	H4	D1	G	Gross	$[m^3]$
MAGNA 25-60	180	62	87	62	100	100	54	157	211	85	25	1 1/2	5.3	0.012

C.3 Danfoss MAGFLO MAG 5000

Overview

Transmitter MAG 5000/6000 compact version (left) and 19" insert version (right)

The MAG 5000 and 6000 are transmitters engineered for high performance, easy installation, commissioning and maintenance. The transmitters evaluate the signals from the SITRANS F M sensors type MAG 1100, MAG 1100 F, MAG 3100, MAG 3100 P and MAG 5100 W.

Transmitter types:

- MAG 5000: Max. measuring error ± 0.4 % ± 1 mm/s (incl. sensor)
- MAG 6000: Max. measuring error ± 0.2 % ± 1 mm/s (incl. sensor, see also sensor specifications) and with additional features such as: "plug & play" add-on bus modules; integrated batch functions.

Benefits

- Superior signal resolution for optimum turn down ratio
- Digital signal processing with many possibilities
- Automatic reading of SENSORPROM data for easy commissioning
- User configurable operation menu with password protection.
- 3 lines, 20 characters display in 11 languages.
- Flow rate in various units
- Totalizer for forward, reverse and net flow as well as additional information available
- Multiple functional outputs for process control, minimum configuration with analogue, pulse/frequency and relay output (status, flow direction, limits)
- Comprehensive self-diagnostic for error indication and error logging (see under SITRANS F M diagnostics)
- Batch control (MAG 6000 only)
- Custody transfer approval: PTB, OIML R 117, OIML R 49, MI-001, PTB K 7.2 and OE12/C 040 for chilled water
- MAG 6000 with add-on bus modules for HART, FOUNDATION Fieldbus H1, DeviceNet, Modbus RTU/RS 485, PROFIBUS PA and DP

Application

The SITRANS F M flowmeters are suitable for measuring the flow of almost all electrically conductive liquids, pastes and slurries. The main applications can be found in:

- Water and waste water
- Chemical and pharmaceutical industries
- Food and beverage industries
- Power generation and utility

Design

The transmitter is designed as either IP67 NEMA 4X/6 enclosure for compact or wall mounting or 19" version as a 19" insert as a base to be used in:

- 19" rack systems
- Panel mounting IP20/NEMA 1 (prepared for IP65/NEMA 2 display side)
- Back of panel mounting IP20/NEMA 1
- Wall mounting IP66/NEMA 4X

Several options on 19" versions are available such as:

- Transmitters mounted in safe area for Ex ATEX approved flow sensors (incl. barriers)
- Transmitters with electrode cleaning unit on request

Function

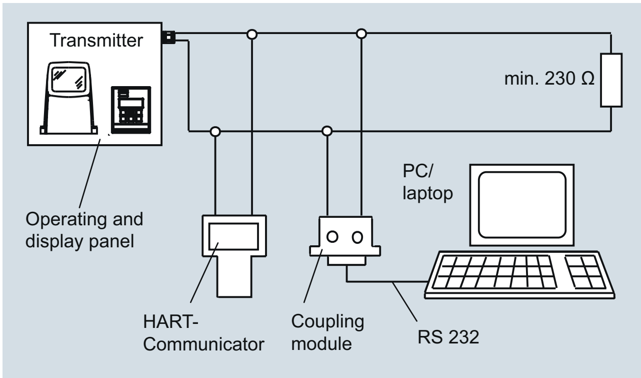
The MAG 5000/6000 are transmitters with a built-in alphanumeric display in several languages. The transmitters evaluate the signals from the associated electromagnetic sensors and also fulfil the task of a power supply unit which provides the magnet coils with a constant current.

Further information on connection, mode of operation and installation can be found in the data sheets for the sensors.

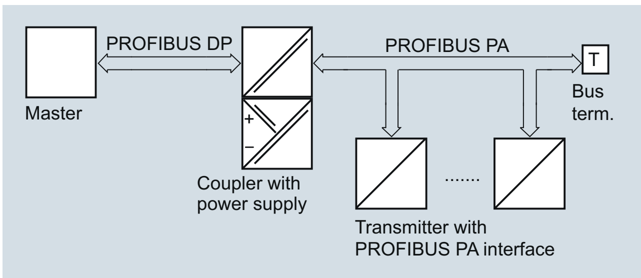
Displays and controls

Operation of the transmitter can be carried out using:

- Control and display unit
- HART communicator
- PC/laptop and SIMATIC PDM software via HART communication
- PC/laptop and SIMATIC PDM software using PROFIBUS or Modbus communication



HART communication



PROFIBUS PA communication

3

Technical specifications

Mode of operation and design	
Measuring principle	Electromagnetic with pulsed constant field
Empty pipe	Detection of empty pipe (special cable required in remote mounted installation)
Excitation frequency	Depend on sensor size
Electrode input impedance	$> 1 \times 10^{14}\ \Omega$
Input	
Digital input	11 ... 30 V DC, R_i = 4.4 KΩ
• Activation time	50 ms
• Current	$I_{11\ V\ DC}$ = 2.5 mA, $I_{30\ V\ DC}$ = 7 mA
Output	
Current output	
• Signal range	0 ... 20 mA or 4 ... 20 mA
• Load	< 800 Ω
• Time constant	0.1 … 30 s, adjustable
Digital output	
• Frequency	0 ... 10 kHz, 50 % duty cycle (uni/bidirectional)
• Pulse (active)	24 V DC, 30 mA, 1 KΩ ≤ R_i ≤ 10 KΩ, short-circuit-protected (power supplied from flowmeter)
• Pulse (passive)	3 … 30 V DC, max. 110 mA, 200 Ω ≤ R_i ≤ 10 KΩ (powered from connected equipment)
• Time constant	0.1 … 30 s, adjustable
Relay output	
• Time constant	Changeover relay, same as current output
• Load	42 V AC/2 A, 24 V DC/1 A
Low flow cut off	0 ... 9.9 % of maximum flow
Galvanic isolation	All inputs and outputs are galvanically isolated.
Max. measuring error (incl. sensor and zero point)[1)]	
• MAG 5000	0.4 % ±1 mm/s
• MAG 6000	0.2 % ±1 mm/s
Rated operation conditions	
Ambient temperature	
• Operation	• Display version: -20 ... +60 °C (-4 ... +140 °F) • Blind version: -20 ... +60 °C (-4 ... +140 °F) • MI-001 version -25 ... +55 °C (-13 ... +131 °F) • Custody transfer (CT) version -20 ... +50 °C (-4 ... +122 °F)
• Storage	-40 ... +70 °C (-40 ... +158 °F)
Mechanical load (vibration)	
Compact version	18 ... 1000 Hz, 3.17 g RMS, sinusoidal in all directions to IEC 60068-2-36
19“ insert	1 ... 800 Hz, 1 g, sinusoidal in all directions to IEC 60068-2-36
Degree of protection	
Compact version	IP67/NEMA 4X/6 to IEC 529 and DIN 40050 (1 mH_2O 30 min.)
19“ insert	IP20/NEMA 1 to IEC 529 and DIN 40050
EMC performance	IEC/EN 61326-1 (all environments) IEC/EN 61326-2-5
Display and keypad	
Totalizer	Two eight-digit counters for forward, net or reverse flow
Display	Background illumination with alphanumeric text, 3 x 20 characters to indicate flow rate, totalized values, settings and faults; Reverse flow indicated by negative sign
Time constant	Time constant as current output time constant
Design	
Enclosure material	
• Compact version	Fiber glass reinforced polyamide; stainless steel AISI 316/1.4436 (IP65)
• 19" insert	Standard 19“ insert of aluminum/steel (DIN 41494), width: 21 TE, height: 3 HE
• Back of panel	IP20/NEMA 1; Aluminum
• Panel mounting	IP20/NEMA 1 (prepared for IP65/NEMA 2 display side); ABS plastic
• Wall mounting	IP66/NEMA 4X; ABS plastic
Dimensions	
Compact version	See dimensional drawings
19“ insert	See dimensional drawings
Weight	
Compact version	0.75 kg (2 lb)
19“ insert	See dimensional drawings
Power supply	• 115 ... 230 V AC +10 % -15 %, 50 ... 60 Hz • 11 ... 30 V DC or 11 ... 24 V AC
Power consumption	• 230 V AC: 17 VA • 24 V AC: 9 VA, I_N = 380 mA, I_{ST} = 8 A (30 ms) • 12 V DC: 11 W, I_N = 920 mA, I_{ST} = 4 A (250 ms) • 24 V DC: 8.4 VA, I_N = 350 mA, I_{ST} = 4 A (10 ms) I_{ST}= 4 A (250 ms): For solar panel please secure stable current supply
Certificates and approvals	
General purpose	• CE (LVD, EMC, PED, RoHS) • UL (c-UL-us)
Hazardous areas	• FM, CSA - NI Class I Div. 2 Groups A, B, C, D
Custody transfer	• Cold water: MI-001 • Chilled water - PTB K 7.2 (Germany) - OE12/C 040 (Austria) - TS 27.02 008 (Denmark)
Marine (only for remote version with MAG 5100 W, DN 50 ... DN 300)	• ABS • Bureau Veritas • DNV • GL • Lloyd’ s Register of Shipping
Others	• CMC/CPA (China) • C-TICK (Australia and New Zealand EMC) • EAC (Russia,Belarus, Kazakhstan) • KCC (South Korea)

Communication	
Standard	
• MAG 5000	Without serial communication or HART as option
• MAG 6000	Prepared for client-mounted add-on modules
Optional (MAG 6000 only)	HART, Modbus RTU/RS 485, FOUNDATION Fieldbus H1, DeviceNet, PROFIBUS PA, PROFIBUS DP as add-on modules
• MAG 5000/6000 CT	No communication moduls approved

1) For detailed accuracy specifications, see page 3/22

Safety barrier (e/ia)

Application	**For use with MAG 5000/6000 19" and MAG 1100 Ex/MAG 3100 Ex**		
Ex approval	MAG 1100 Ex [EEx e ia] IIB ATEX, EAC Ex		
	MAG 3100 Ex [EEx e ia] IIC ATEX, EAC Ex		
Cable parameter	Group	Capacity in µF	Inductance in mH
Electrode	IIC	≤ 4.1	≤ 80
	IIB	≤ 45	≤ 87
	IIA	≤ 45	≤ 87
Ambient temperature			
• During operation	-20 ... +50 °C (-4 ... +122 °F)		
• During storage	-20 ... +70 °C (-4 ... +158 °F)		
Enclosure			
• Material	Standard 19" insert in aluminum/steel (DIN 41494)		
• Width	21 TE (4.75")		
• Height	3 HE (5.25")		
• Rating	IP20 / NEMA 1 to EN 60529		
• Mechanical load	1 g, 1 … 800 Hz sinusoidal in all directions to EN 60068-2-36		

Selection and Ordering data

Transmitter MAG 5000

Description		Article No.	
Transmitter MAG 5000 Blind for compact and wall mounting; IP67/NEMA 4X/6, fibre glass reinforced polyamide			
• 11 ... 30 V DC/ 11 ... 24 V AC	⬟	**7ME6910-1AA30-0AA0**	
• 115 ... 230 V AC, 50/60 Hz	⬟	**7ME6910-1AA10-0AA0**	
Transmitter MAG 5000 Display for compact and wall mounting; IP67/NEMA 4X/6, fibre glass reinforced polyamide			
• 11 ... 30 V DC/ 11 ... 24 V AC	⬟	**7ME6910-1AA30-1AA0**	
• 115 ... 230 V AC, 50/60 Hz	⬟	**7ME6910-1AA10-1AA0**	
• 115 ... 230 V AC, 50/60 Hz, with HART	⬟	**7ME6910-1AA10-1BA0**	
Transmitter MAG 5000 CT for compact and wall mounting, approved for custody transfer (only with approval marks, no verification – only a complete flowmeter can be verified, i.e. sensor together with the transmitter); IP67/NEMA 4X/6, fibre glass reinforced polyamide			
• 11 ... 30 V DC/ 11 ... 24 V AC		**7ME6910-1AA30-1AB0**	
• 115 ... 230 V AC, 50/60 Hz		**7ME6910-1AA10-1AB0**	
Transmitter MAG 5000 for 19" rack and wall mounting			
• 11 ... 30 V DC/ 11 ... 24 V AC	⬟	**7ME6910-2CA30-1AA0**	
• 115 ... 230 V AC, 50/60 Hz	⬟	**7ME6910-2CA10-1AA0**	

⬟ We can offer shorter delivery times for configurations designated with the Quick Ship Symbol ⬟. For details see page 10/11 in the appendix.

Transmitter MAG 6000

Description		Article No.	
Transmitter MAG 6000 Blind for compact and wall mounting; IP67/NEMA 4X/6, fibre glass reinforced polyamide			
• 11 ... 30 V DC/ 11 ... 24 V AC	⬟	**7ME6920-1AA30-0AA0**	
• 115 ... 230 V AC, 50/60 Hz	⬟	**7ME6920-1AA10-0AA0**	
Transmitter MAG 6000 for compact and wall mounting; IP67/NEMA 4X/6, fibre glass reinforced polyamide			
• 11 ... 30 V DC/ 11 ... 24 V AC	⬟	**7ME6920-1AA30-1AA0**	
• 115 ... 230 V AC, 50/60 Hz	⬟	**7ME6920-1AA10-1AA0**	
Transmitter MAG 6000 for compact and wall mounting; IP65/NEMA 4, stainless steel AISI 316/1.4436 (only for sensor with stainless steal terminal box) (for remote version order stainless steal terminal box separately)			
• 11 ... 30 V DC/ 11 ... 24 V AC		**7ME6920-1QA30-1AA0**	
• 115 ... 230 V AC, 50/60 Hz		**7ME6920-1QA10-1AA0**	
Transmitter MAG 6000 CT for compact and wall mounting, approved for custody transfer, without verification (no approval marks - only a complete flowmeter can be verified, i.e. sensor together with the transmitter); IP67/NEMA 4X/6, fibre glass reinforced polyamide			
• 11 ... 30 V DC/ 11 ... 24 V AC		**7ME6920-1AA30-1AD0**	
• 115 ... 230 V AC, 50/60 Hz		**7ME6920-1AA10-1AD0**	
Spare part transmitter for CT systems produced before 12/2016 or with firmware version 3.03			
• 11 ... 30 V DC/ 11 ... 24 V AC		**7ME6920-1AA30-1AB0**	
• 115 ... 230 V AC, 50/60 Hz		**7ME6920-1AA10-1AB0**	
Transmitter MAG 6000 SV for compact and wall mounting; special excitation frequency 44 Hz for Batch application DN ≤ 25/1" IP67/NEMA 4X/6, fibre glass reinforced polyamide			
11 ... 30 V DC/ 11 ... 24 V AC		**7ME6920-1AB30-1AA0**	
115 ... 230 V AC, 50/60 Hz		**7ME6920-1AB10-1AA0**	

Description		Article No.	
Transmitter MAG 6000 for 19“ rack and wall mounting			
• 11 ... 30 V DC/ 11 ... 24 V AC	⬟	**7ME6920-2CA30-1AA0**	
• 115 ... 230 V AC, 50/60 Hz	⬟	**7ME6920-2CA10-1AA0**	
Transmitter MAG 6000 SV for 19“ rack and wall mounting; special excitation frequency 44 Hz for Batch application DN ≤ 25/1“			
• 11 ... 30 V DC/ 11 ... 24 V AC		**7ME6920-2CB30-1AA0**	
• 115 ... 230 V AC, 50/60 Hz		**7ME6920-2CB10-1AA0**	
MAG 6000 19" insert, complete mounted with IP66/ NEMA 4X wall mounting enclosure in ABS plastic; 115 ... 230 V AC, 50/60 Hz; cable gland PG13.5		**7ME6920-2EA10-1AA0**	
MAG 6000 SV 19” insert with safety barrier for Ex-approved sensors, complete mounted with IP66/NEMA 4X wall mounting enclosure in ABS plastic, 115 ... 230 V AC, 50/60 Hz; cable gland PG13.5			
• For ATEX 2G D sensors		**7ME6920-2MA11-1AA0**	
MAG 6000 SV 19” insert, complete mounted with IP66/NEMA 4X wall mounting enclosure in ABS plastic, special excitation frequency 44 Hz for Batch application DN ≤ 25/1“; cable gland PG13.5			
• 11 … 30 V DC, 11 … 24 V AC		**7ME6920-2EB30-1AA0**	
• 115 … 230 V AC, 50/60 Hz		**7ME6920-2EB10-1AA0**	

⬟ We can offer shorter delivery times for configurations designated with the Quick Ship Symbol ⬟. For details see page 10/11 in the appendix.

Operating instructions for SITRANS F M MAG 5000/6000

Description	Article No.
For SITRANS F M MAG 5000/6000 IP67	
• English	**A5E02338368**
• German	**A5E02944982**
For SITRANS F M MAG 5000/6000 19"	
• English	**A5E02082880**

All literature is available to download for free, in a range of languages, at www.siemens.com/processinstrumentation/documentation

Communication modules for MAG 6000

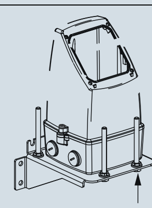
Description		Article No.	
HART (not for MAG 6000 I)	⬟	**FDK:085U0226**	
Modbus RTU/RS 485	⬟	**FDK:085U0234**	
PROFIBUS PA Profile 3	⬟	**FDK:085U0236**	
PROFIBUS DP Profile 3	⬟	**FDK:085U0237**	
DeviceNet	⬟	**FDK:085U0229**	
FOUNDATION Fieldbus H1		**A5E02054250**	

Operating instructions for SITRANS F add-on modules

Description	Article No.
HART	
• English	**A5E03089708**
PROFIBUS PA/DP	
• English	**A5E00726137**
• German	**A5E01026429**
Modbus	
• English	**A5E00753974**
• German	**A5E03089262**
FOUNDATION Fieldbus	
• English	**A5E02318728**
• German	**A5E02488856**
DeviceNet	
• English	**A5E03089720**

All literature is available to download for free, in a range of languages, at www.siemens.com/processinstrumentation/documentation

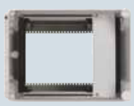
Accessories for MAG 5000 and MAG 6000

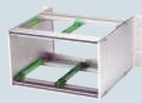
Description		Article No.	
Accessory kit for remote use of sensor with two 5-pin terminal blocks		**A5E34827189**	
Wall mounting unit for MAG 5000/6000 IP67/NEMA 4X/6, terminal box in polyamide[1]			
• 4 x M20 cable glands	⬟	**FDK:085U1018**	
• 4 x ½“ NPT cable glands	⬟	**FDK:085U1053**	
Special wall mounting unit for MAG 5000/6000 IP67/ NEMA 4X/6, mounting bracket in stainless steel AISI 316 (1.4401), terminal box in polyamide			
• 4 x M20 cable glands	⬟	**A5E36699697**	
• 4 x ½“ NPT cable glands	⬟	**A5E36699699**	
Sun lid for MAG 5000/6000 transmitter (Frame and lid)		**A5E02328485**	
Standard coil or electrode cable, 3 x 1.5 mm²/ 18 gage, single shielded with PVC jacket, Temp. range: -30 ... +70 °C (-22 ... +158 °F)			
• 5 m (16.5 ft)	⬟	**A5E02296523**	
• 10 m (33 ft)	⬟	**FDK:083F0121**	
• 20 m (65 ft)	⬟	**FDK:083F0210**	
• 30 m (98 ft)	⬟	**A5E02297309**	
• 40 m (130 ft)	⬟	**FDK:083F0211**	
• 50 m (164 ft)	⬟	**A5E02297317**	
• 60 m (200 ft)	⬟	**FDK:083F0212**	
• 100 m (330 ft)		**FDK:083F0213**	
• 150 m (500 ft)		**FDK:083F3052**	
• 200 m (650 ft)		**FDK:083F3053**	
• 500 m (1650 ft)		**FDK:083F3054**	

⬟ We can offer shorter delivery times for configurations designated with the Quick Ship Symbol ⬟. For details see page 10/11 in the appendix.

[1] For stainless steel wall mounting kit, order:
- M20: FDK:085U1018 and A5E00836867
- ½ NPT: FDK:085U1053 and A5E00836868

Transmitter MAG 5000/6000

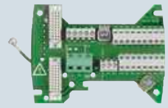
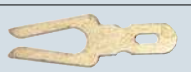
Description		Article No.	
Special electrode cable[1) (empty pipe detection or low conductivity), 3 x 0.25 mm², double shielded with PVC jacket; Temperature range : -30 ... +70 °C (-22 ... +158 °F)			
• 10 m (33 ft)	⬟	**FDK:083F3020**	
• 20 m (65 ft)	⬟	**FDK:083F3095**	
• 40 m (130 ft)		**FDK:083F3094**	
• 60 m (200 ft)		**FDK:083F3093**	
• 100 m (330 ft)		**FDK:083F3092**	
• 150 m (500 ft)		**FDK:083F3056**	
• 200 m (650 ft)		**FDK:083F3057**	
• 500 m (1650 ft)		**FDK:083F3058**	
Low-noise electrode coax cable for low conductivity and high vibration levels, 3 x 0.13 mm²			
• 2 m (6.6 ft)		**A5E02272692**	
• 5 m (16.5 ft)		**A5E02272723**	
• 10 m (33 ft)		**A5E02272730**	
Cable kit including standard coil cable (3 x 1.5 mm²/ 18 gage, single shielded with PVC jacket) and special electrode cable[1) (3 x 0.25 mm², double shielded with PVC jacket); Temperature range: -30 ... +70 °C (-22 ... +158 °F)			
• 5 m (16.5 ft)	⬟	**A5E02296329**	
• 10 m (33 ft)	⬟	**A5E01181647**	
• 15 m (49 ft)	⬟	**A5E02296464**	
• 20 m (65 ft)	⬟	**A5E01181656**	
• 25 m (82 ft)	⬟	**A5E02296490**	
• 30 m (98 ft)	⬟	**A5E02296494**	
• 40 m (130 ft)	⬟	**A5E01181686**	
• 50 m (164 ft)	⬟	**A5E02296498**	
• 60 m (200 ft)		**A5E01181689**	
• 100 m (330 ft)		**A5E01181691**	
• 150 m (500 ft)		**A5E01181699**	
• 200 m (650 ft)		**A5E01181703**	
• 500 m (1650 ft)		**A5E01181705**	
Potting kit for IP68/NEMA 6P sealing of sensor junction box	⬟	**FDK:085U0220**	
19“ safety barrier (21 TE)[1) [EEx e ia] IIC for MAG 1100 Ex sensors and MAG 3100 Ex sensors 12 ... 24 V, 115 ... 230 V, incl. back plate (A5E02559810)		**FDK:083F5034**	
Front panel mounting enclosure IP65/NEMA 2 in ABS plastic for 19“ insert (21 TE)		**FDK:083F5030**	
Front panel mounting enclosure IP65/NEMA 2 in ABS plastic for 19“ insert (42 TE)		**FDK:083F5031**	

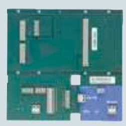
Description	Article No.	
Panel mounting enclosure IP20/NEMA 1 in aluminium for 19“ insert (21 TE)	**FDK:083F5032**	
Panel mounting enclosure IP20/NEMA 1 in aluminium for 19“ insert (42 TE)	**FDK:083F5033**	
Wall mounting enclosure IP66/NEMA 4X in ABS plastic for 19“ insert (cable glands and connection board not included)		
• 21 TE	**FDK:083F5037**	
• 42 TE	**FDK:083F5038**	
Front cover (7TE) for panel mounting enclosure	**FDK:083F4525**	
Sun shield for MAG 5000/6000 transmitters in remote design	**A5E01209496**	
Sun Shield for MAG 5000/ 6000 transmitter in compact design on MAG 3100 (DN 15 ... 2000/½" ... 78") or MAG 5100 W (DN 150 ... 1200/6" ... 48")	**A5E01209500**	

⬟ We can offer shorter delivery times for configurations designated with the Quick Ship Symbol ⬟. For details see page 10/11 in the appendix.

1) Special cables cannot be used with 19" safety barrier

Spare parts

Description	Article No.	
Connection board (for polyamide terminalbox)		
• 12 ... 24 V	**A5E02559817**	
• 115 ... 230 V	**A5E02559816**	
Connection board (for stainless steel terminal-box)		
• 12 ... 24 V	**A5E02604280**	
• 115 ... 230 V	**A5E02604272**	
Connection board MAG 5000/6000 19" insert for panel mounting enclosure, 12 ... 24 V/115 ... 230 V	**A5E02559809**	
Connection board MAG 5000/6000 19" insert with safety barrier for panel mounting enclosure, 12 ... 24 V/115 ... 230 V	**A5E02559810**	
Connection board MAG 5000/6000 19" insert with safety barrier for panel mounting enclosure, 12 ... 24 V/115 ... 230 V (only for sensors produced before October 2007)	**A5E02559811**	
Connection board MAG 5000/6000 19" insert with cleaning unit for panel mounting enclosure, 12 ... 24 V/115 ... 230 V	**FDK:083F4123**	
SENSORPROM memory unit (Sensor code and serial numbers must be specified on order)		
• 2 kB (for MAG 5000/6000/ MAG 6000 I)		
- 1 pc.	**FDK:085U1005**	
- 10 pcs.	**FDK:083F5052**	
• 250 B (for MAG 2500/3000)	**FDK:085U1008**	
Display unit for MAG 5000/6000		
• Black neutral front	**FDK:085U1038**	
• Siemens front	**FDK:085U1039**	
HW key	**On request**	

Description	Article No.	
Cable glands (polyamide), 4 pcs.		 ½" NPT M20
• M20	⬟ **A5E00822490**	
• ½" NPT	⬟ **A5E00822501**	
• PG 13.5, 2 pcs.	**FDK:083G0228**	
Sealing screws for sensor/ transmitter, 2 pcs	**FDK:085U0221**	
Terminal box, in polyamide, inclusive lid, terminal blocks, gasket and screws		
• M20	**FDK:085U1050**	
• ½" NPT	**FDK:085U1052**	
Terminal box lid, in polyamide	**FDK:085U1003**	
Terminal box, in stainless steel, inclusive lid, terminal blocks, gasket and screws, for MAG 6000 in stainless steel and for all Ex sensors,		
• M20	**A5E00836867**	
• ½" NPT	**A5E00836868**	
Terminal box (3A) for MAG 1100 F in polyamide, inclusive lid, terminal blocks, gasket and screws		
• M20	**A5E00822478**	
• ½" NPT	**A5E00822479**	
Gasket for terminal box lid in polyamide and MAG 5000/6000 IP67/ NEMA 4X/6 (5 pc.)	**A5E37086797**	
Spare part kit for remote use of sensor with 20 pcs. 5-pin terminal blocks	**A5E34346873**	
Connection board MAG 5000/6000 19" insert for wall mounting enclosure, 12 ... 24 V / 115 ... 230 V	**A5E02559813**	
Connection board MAG 5000/ 6000 19" insert with safety barrier for wall mounting enclosure, 12 ... 24 V/115 ... 230 V	**A5E02559814**	
Connection board MAG 5000/ 6000 19" insert with safety barrier for wall mounting enclosure, 12 ... 24 V/115 ... 230 V (only for sensors produced before October 2007)	**A5E02559812**	
Connection board MAG 5000/ 6000 19" insert with cleaning unit for wall mounting enclosure, 12 ... 24 V/115 ... 230 V	**A5E02559815**	
SENSORPROM programmer with RS 232 interface	**FDK:083H4246**	

⬟ We can offer shorter delivery times for configurations designated with the Quick Ship Symbol ⬟. For details see page 10/11 in the appendix.

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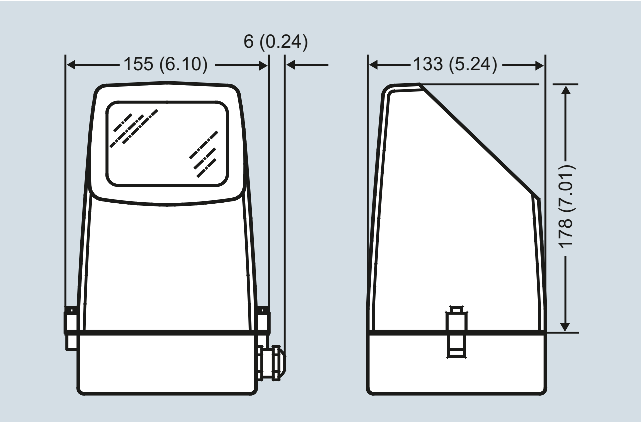
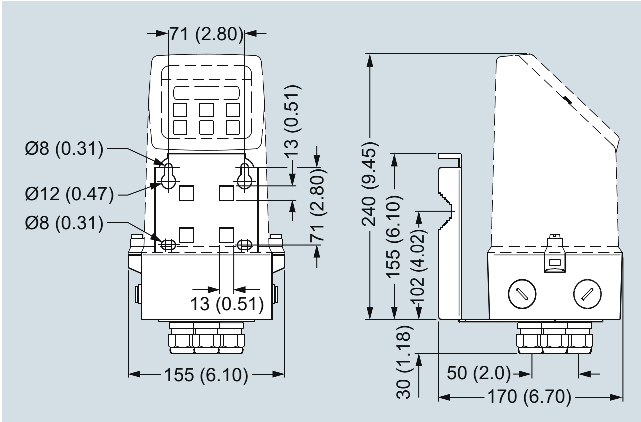
Dimensional drawings

Transmitter IP67/NEMA 4X/6 compact polyamide

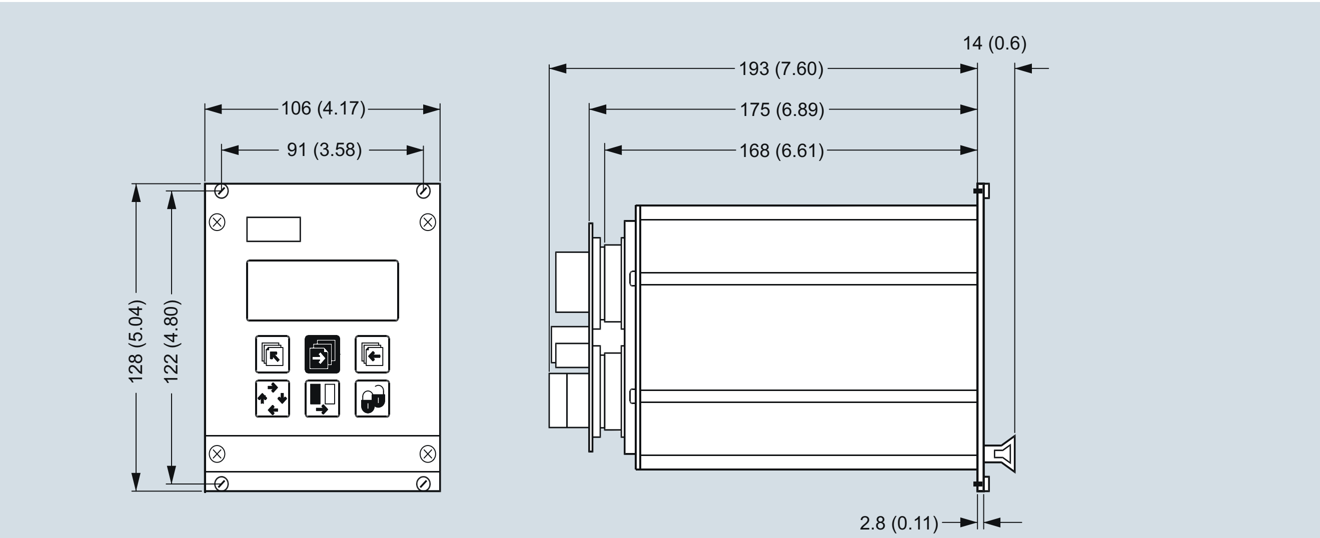


Transmitter compact mounted, dimensions in mm (inch)



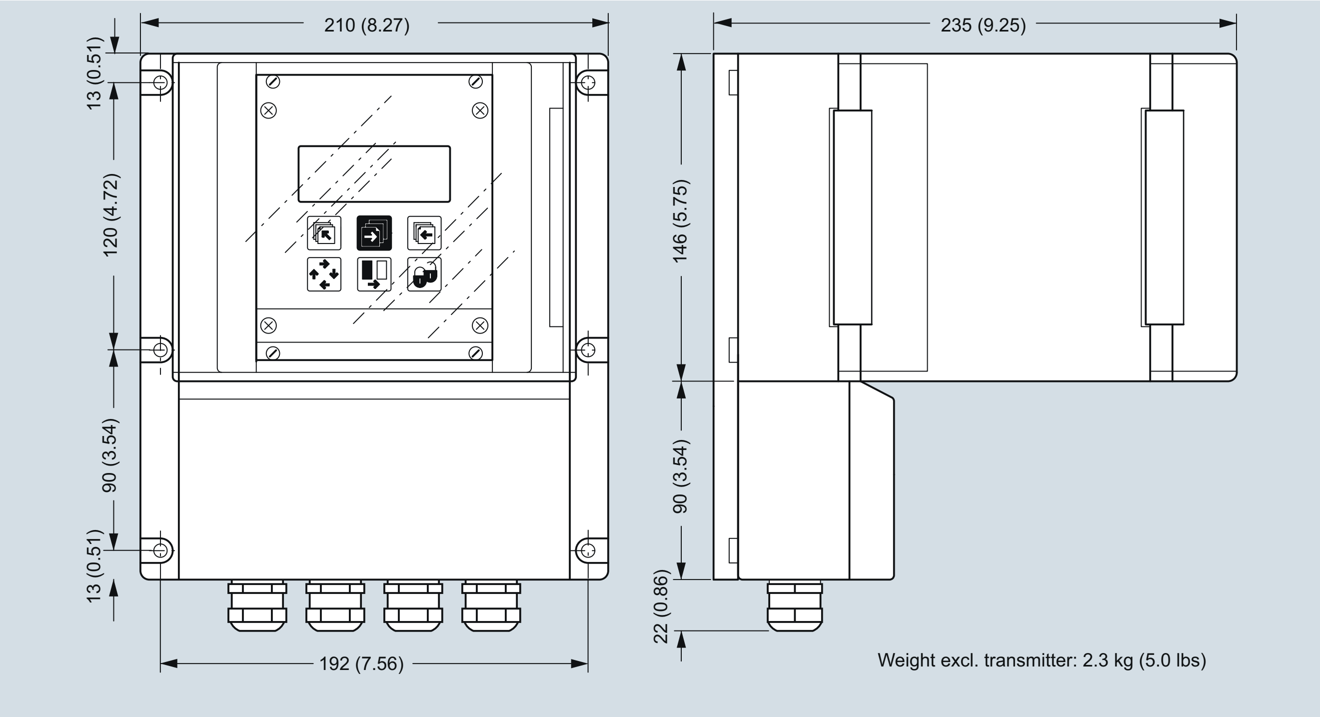
Transmitter wall mounted, dimensions in mm (inch)

Transmitter, 19" IP20/NEMA 1 standard unit



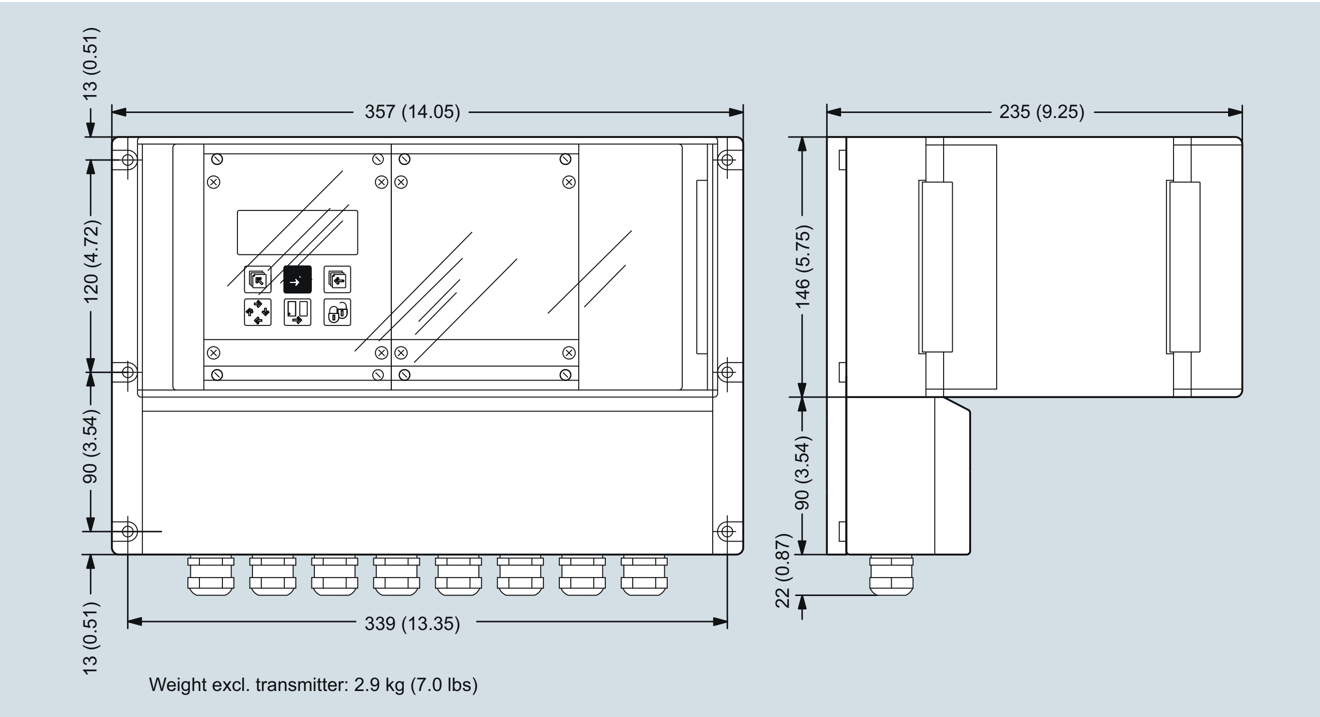
Dimensions in mm (inch)

Transmitter, wall mounting IP66/NEMA 4X, 21 TE



Dimensions in mm (inch)

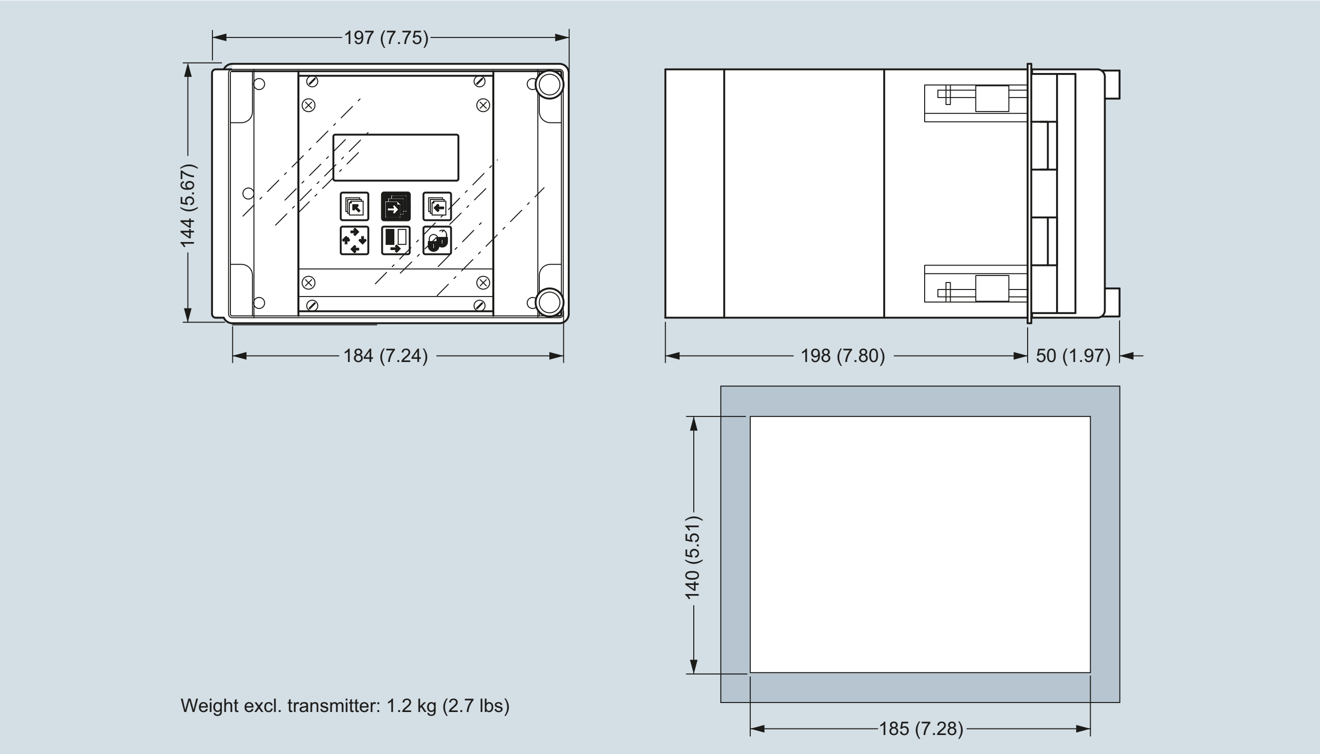
Transmitter, wall mounting IP66/NEMA 4X, 42 TE



Dimensions in mm (inch)

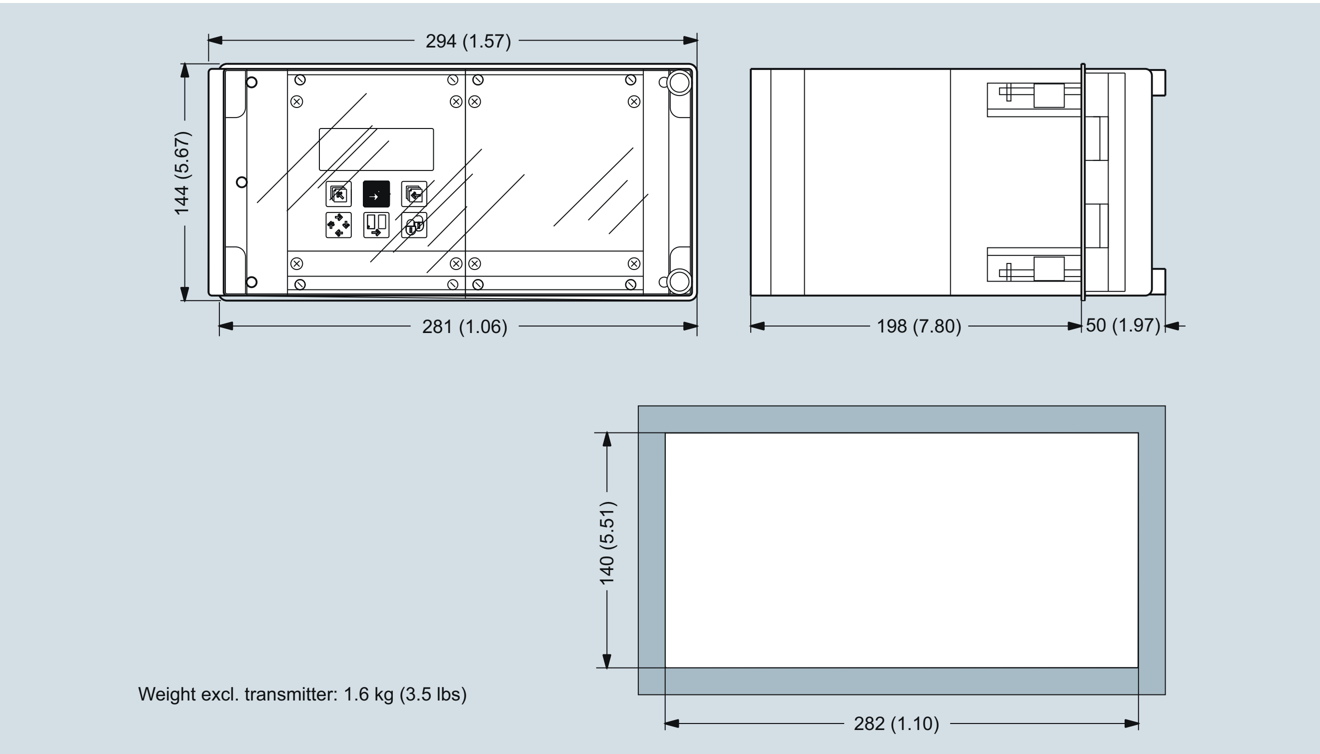
Transmitter MAG 5000/6000

Transmitter, panel front IP20/NEMA 1, 21 TE



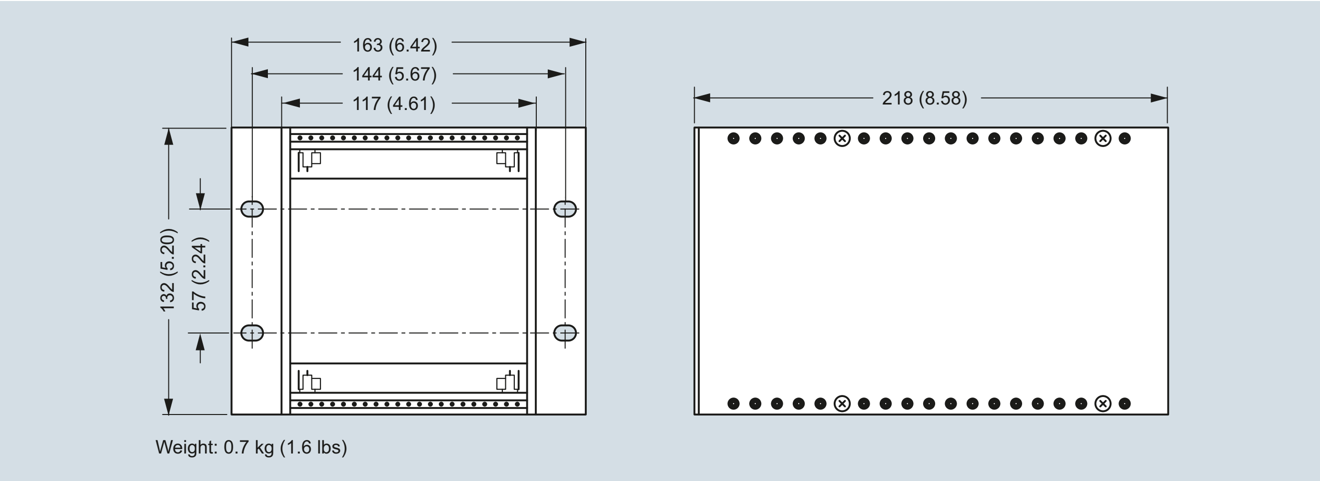
Dimensions in mm (inch)

Transmitter, panel front IP20/NEMA 1, 42 TE



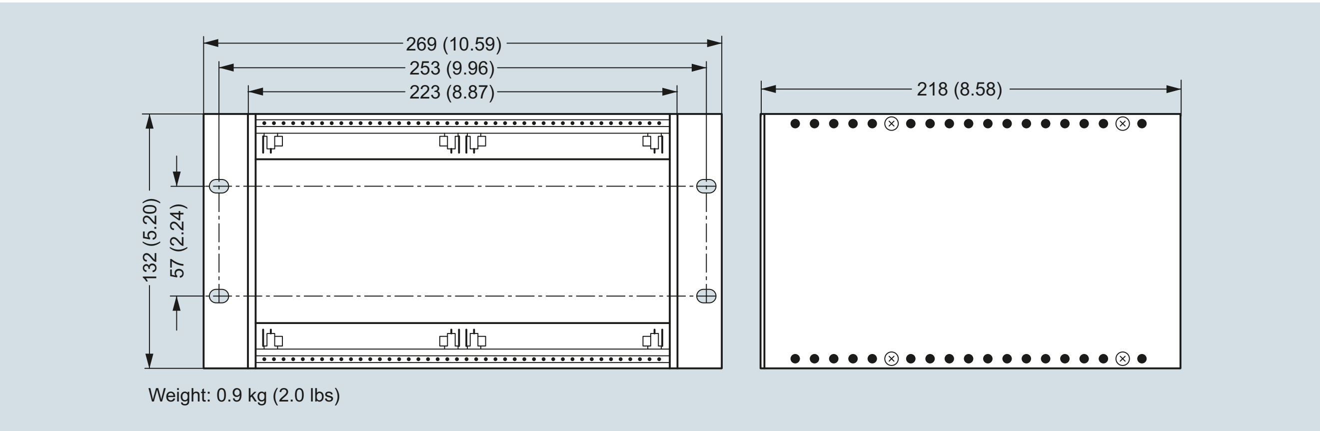
Dimensions in mm (inch)

Transmitter, back of panel IP20/NEMA 1, 21 TE



Dimensions in mm (inch)

Transmitter, back of panel IP20/NEMA 1, 42 TE



Dimensions in mm (inch)

3

Schematics

Electrical connection

Grounding

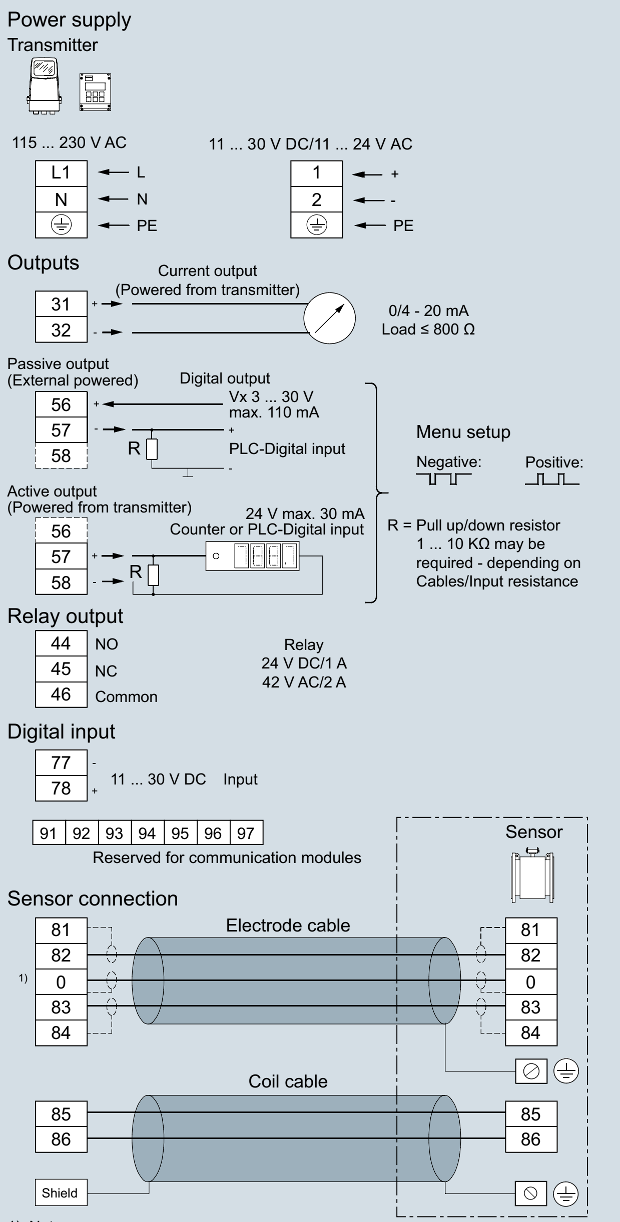
PE must be connected due to safety class 1 power supply.

Mechanical counters

When mounting a mechanical counter to terminals 57 and 58 (active output), a 1000 μF capacitor must be connected to the terminals 56 and 58. Capacitor + is connected to terminal 56 and capacitor - to terminal 58.

Output cables

If the output cable length is long in noisy environment, we recommend to use shielded cable.



1) Note:
Special cable with individual wire shields (shown as dotted lines) are only required when using empty pipe function or long cables.

C.4 Samson 3226

Types 3226/5857, 3226/5824, 3226/5825, 3226/5757-7, 3226/5724-8, 3226/5725-7, 3226/5725-8 Electric Control Valves

Type 3226/2780 Pneumatic Control Valve

Type 3226 Three-way Valve

Application

Control valves available as mixing or diverting valves for use in heating, ventilation and air-conditioning systems

DN 15 to 50, G ½ to G 1 · PN 25 · Version up to 150 °C
(water and non-flammable gases)

Special features

- Type 3226 Three-way Valve designed as a **mixing valve** with male thread connection and welding ends or threaded ends (DN 15 to 50) or with female thread connection (G ½ to G 1)
- Type 3226 Three-way Valve designed as a **diverting valve** with male thread connection and welding ends or threaded ends (DN 15 to 50)
- Type 3226 Three-way Valve combined with Type 5857 and TROVIS 5757-7 (with special spring)
- Force-locking connection between valve and actuator
- Type 3226 Three-way Valve (mixing or diverting valve) in special version: DVGW-tested

Versions

Electric control valves		
Type 3226/5857	PN 25	DN 15 to 25 G ½ to G 1
Type 3226/5824	PN 25	DN 15 to 50 G ½ to G 1
Type 3226/5825 [1]	PN 25	DN 15 to 50 G ½ to G 1
Electric control valve with electric actuator with process controller for heating and cooling applications		
Type 3226/5757-7	PN 25	DN 15 to 25 G ½ to G 1
Type 3226/5724-8	PN 25	DN 15 to 50 G ½ to G 1
Type 3226/5725-7 [1]	PN 25	DN 15 to 50 G ½ to G 1
Type 3226/5725-8 [1]	PN 25	DN 15 to 50 G ½ to G 1
Pneumatic control valves		
Type 3226/2780-1	PN 25	DN 15 to 50 G ½ to G 1
Type 3226/2780-2 [2]	PN 25	DN 15 to 50 G ½ to G 1

1) Electric actuators with fail-safe action
2) Pneumatic actuator suitable for integrated positioner attachment

Fig. 1: *Type 3226/5824*
Version with female thread

Fig. 2: *Type 3226/2780-1*
Version with male thread connection and welding ends

Also available:

Type 3260 Three-way Valve with flanges ▶ Data Sheet T 5861

Principle of operation (Fig. 3)

The three-way valve in the version with male thread connection and welding ends or threaded ends can be used for both mixing or diverting valves. The valves vary in the plug arrangement and must be installed accordingly. The version with female thread connection can only be used for mixing valves.
The process medium flows through the three-way valve in the direction indicated by the arrow. The position of the plug (3) determines the cross-sectional area of flow between the plug and the seat (2). The plug follows the actuator stem, which is changed by the control signal acting on the actuator (8), owing to the force of the valve spring (5). The valve (1) and actuator (8) have a force-locking connection.
An intermediate insulating piece is available for insulated pipes.

Fail-safe position (Fig. 4)

For three-way valves mounted to an actuator with fail-safe action, the control valve has two different positions which become effective upon power supply failure:

Actuator stem extends

- Port B of the mixing valve closes on power supply failure
- Port A of the diverting valve closes on power supply failure

Actuator stem retracts

- Port A of the mixing valve closes on power supply failure
- Port B of the diverting valve closes on power supply failure

Electric actuators

The Types 5857, 5824 and 5825 Electric Actuators can be controlled by three-step signals, or, in the version with positioner, with signals from 0/4 to 20 mA or 0/2 to 10 V. Various optional accessories can be mounted onto the actuator. Type 5825 Actuator is able to perform a fail-safe action. Refer to Table 4.

Refer to the data sheets for more details on the electric actuators:

▶ **T 5857:** Type 5857 Electric Actuator
▶ **T 5824:** Types 5824 and 5825 Electric Actuators

Electric actuators with process controllers

The electric actuator with process controller consists of a **linear actuator with an integrated digital controller**. The TROVIS 5757-7, TROVIS 5724-8, TROVIS 5725-7 and TROVIS 5725-8 are suitable for heating and cooling applications. TROVIS 5724-8 and TROVIS 5725-8 have two PID control modules and are ready-wired.
TROVIS 5725-7 and TROVIS 5725-8 Actuators are able to perform a fail-safe action. Refer to Table 4.

Refer to the data sheets for more details on the electric actuators with process controller:

▶ **T 5757-7:** TROVIS 5757-7 Electric Actuator with Process Controller for heating and cooling applications
▶ **T 5725-7:** TROVIS 5725-7 Electric Actuator with Process Controller for heating and cooling applications
▶ **T 5724-8:** TROVIS 5724-8 and TROVIS 5725-8 Electric Actuator with Process Controller for heating and cooling applications

Pneumatic actuators

The Type 2780-1 Pneumatic Actuator uses a control signal from 0.4 to 1 bar and Type 2780-2 uses a control signal from 0.4 to 2 bar which is applied to the loading pressure connection. The pneumatic actuators require a supply pressure of at least 0.2 bar above the maximum bench range. The actuators are available for fail-safe action "actuator stem extends (FA)" or "actuator stem retracts (FE)".
The Type 2780-2 Pneumatic Actuator is suitable for integral positioner attachment.

Refer to the data sheets for more details on the pneumatic actuators:

▶ **T 5840:** Types 2780-1 and 2780-2 Pneumatic Actuators

Installation of the control valve

The control valves can be mounted in any position. However, the electric actuators must not be suspended downwards.
Make sure that the maximum ambient temperature of 50 °C for the actuator, mounted on the valve bonnet, is not exceeded. Make sure that the inlet and outlet flows of the plant are correctly assigned to ports A, B, and AB. Fig. 4 schematically illustrates a few typical applications.
Strainers must be installed upstream of the inlets of valves mounted on actuators with fail-safe action (e.g. Type 1 N or Type 1 FN).
If the control valve is to be insulated, the actuator and the coupling nut must not be insulated as well. Additionally, it must be ensured that the temperature does not exceed the maximum permissible ambient temperature. If necessary, an intermediate insulating piece must be used. Do not insulate it over 25 mm.

Ordering text

Type ... Control Valve:

❑ 3226/5857, ❑ 3226/5824-…, ❑ 3226/5825-…,

❑ 3226/5757-7, ❑ 3226/5724-8…, ❑ 3226/5725-7…,

❑ 3226/5725-8…, ❑ 3260/2780-1, ❑ 3226/2780-2

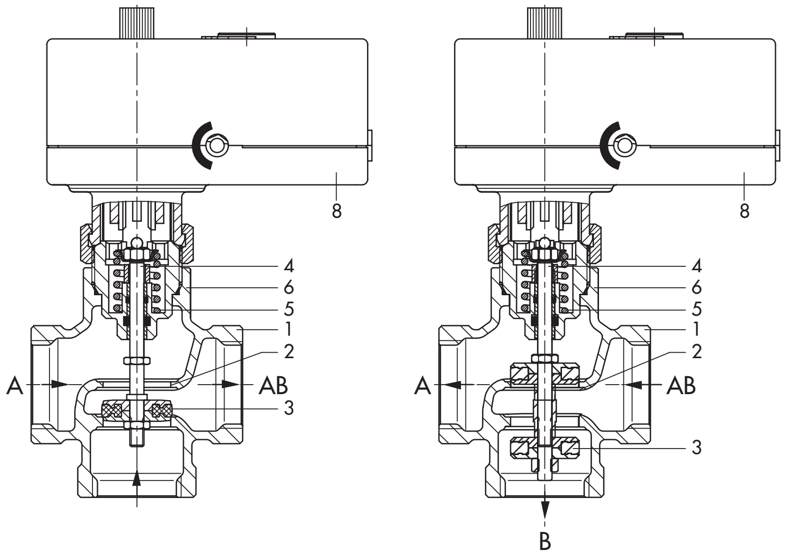
- Valve type: ❑ mixing valve, ❑ diverting valve
- End connections:
  ❑ male thread connection and welding ends DN …,
  ❑ male thread connection and threaded ends DN …,
  ❑ female thread G …
- Kvs coefficient: …
- DVWG version: ❑ yes, ❑ no

Further specifications on the electric actuator

- Control: ❑ three-step signal, ❑ positioner
- Power supply: …
- Electric additional equipment: …

Further specifications on the pneumatic actuator

- Signal pressure connection for Type 2780-1: ❑ G ⅛ , ❑ ⅛ NPT
- Fail-safe action: ❑ stem extends (FA), ❑ stem retracts (FE)



1 Valve body
2 Seat
3 Plug
4 Plug stem
5 Valve spring
6 Adapter
8 Actuator

Fig. 3: *Functional diagram of Type 3226/5857*
left: mixing valve, right: diverting valve

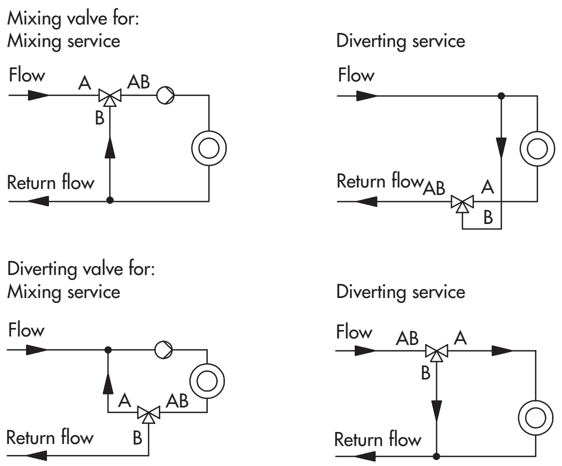


Fig. 4: *Typical installations*

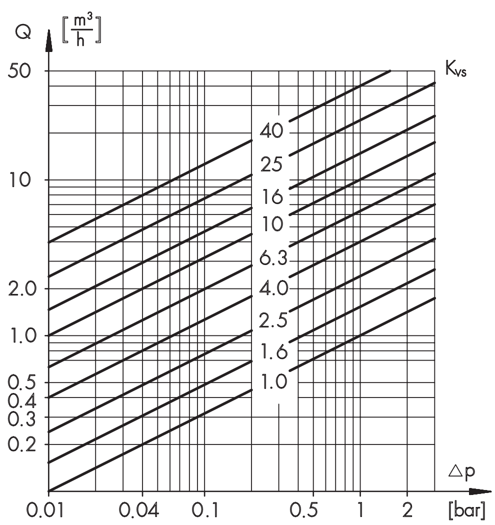


Fig. 5: *Flow rate diagram for water*

Table 1: *Technical data · All pressures in bar (gauge)*

Type 3226 Three-way Valve								
Nominal size	Mixing or diverting valve with male thread connection	DN	15	20	25	32	40	50
Thread size	Mixing valve with female thread	G	½	¾	1	–	–	–
Nominal pressure		PN	25					
DVGW version		PN	10					
Permissible temperature range		°C	+5 (–15) to 150 [1]					
DVGW version		°C	+5 to 90 °C					
Permissible differential pressure for actuators								
Type 5857, TROVIS 5757-7		bar	4	2.6	1.8	–	–	–
Type 5824, Type 5825, TROVIS 5724-8, TROVIS 5725-7, TROVIS 5725-8, Type 2780		bar	4	4	4	1.7	1.1	1.1
Rated travel		mm	6	6	6	12	12	12
Seat/plug seal			Soft seal					
Leakage class according to IEC 60534-4			Class I (≤ 0.01 % of K_{VS} coefficient)					
Compliance			CE · EAC					

[1] Use intermediate insulating piece (1990-1712)
– for medium temperatures between –15 and +5 °C (actuators according to Table 4)
– in networks with constant medium temperatures > 135 °C (TROVIS 5724-8, TROVIS 5725-7, TROVIS 5725-8, Type 5824 and Type 5825 Actuators)
– for liquids > 120 °C (TROVIS 5757-7 and Type 5857 Actuators)

Table 2: *Materials*

Type 3226 Three-way Valve	
Valve body	CC499K (CuSn5Zn5Pb2-C)
Plug	CW617N (CuZn40Pb2zh) with EPDM
Packing	O-rings made of EPDM
Welding ends	St 37
Threaded ends	Red brass

Table 3: *Nominal sizes and K_{VS} coefficients*

Type 3226 Three-way Valve												
Nominal size	Mixing or diverting valve with male thread connection	DN	15				20	25	32	40	50
Thread size	Mixing valve with female thread	G	½				¾	1	–	–	–
K_{VS} coefficient			1.0	1.6	2.5	4	6.3	10	16	25	40
Rated travel		mm	6	6	6	6	6	6	12	12	12

Table 4: *Possible combinations*

Type 3226 Three-way Valve/actuator												
Type/ TROVIS	Fail-safe action: Actuator stem		Details in	Nominal size DN						Thread size G		
	Extends	Retracts		15	20	25	32	40	50	½	¾	1
Electric actuators												
5857 [1]	–	–	▶ T 5857	•	•	•		–		•	•	•
5824-10	–	–	▶ T 5824	•	•	•		–		•	•	•
5824-13 [2]	–	–		•	•	•		–		•	•	•
5825-10	•	–		•	•	•		–		•	•	•
5825-13 [2]	•	–		•	•	•		–		•	•	•
5825-15	–	•		•	•	•		–		•	•	•
5824-20	–	–			–		•	•	•		–	
5824-23 [2]	–	–			–		•	•	•		–	
5825-20	•	–			–		•	•	•		–	
5825-23 [2]	•	–			–		•	•	•		–	
5825-25	–	•			–		•	•	•		–	
Electric actuators with process controller for heating and cooling applications												
5757-7 [1]	–	–	▶ T 5757-7	•	•	•		–		•	•	•
5724-810	–	–	▶ T 5724-8	•	•	•		–		•	•	•
5724-820	–	–			–		•	•	•		–	
5725-710	•	–	▶ T 5725-7	•	•	•		–		•	•	•
5725-715	–	•		•	•	•		–		•	•	•
5725-720	•	–			–		•	•	•		–	
5725-725	–	•			–		•	•	•		–	
5725-810	•	–	▶ T 5724-8	•	•	•		–		•	•	•
5725-820	•	–			–		•	•	•		–	
Pneumatic actuators												
2780-1	•	•	▶ T 5840	•	•	•	•	•	•	•	•	•
2780-2	•	•		•	•	•	•	•	•	•	•	•

1) The valve spring in the Type 3226 Valve intended for mounting on the Type 5857 and TROVIS 5757-7 Actuators is different from that of the Type 3226 intended for mounting on other actuators. Basically, actuators with a larger nominal thrust (e.g. Type 5824) may also be combined with valves for Type 5857 and TROVIS 5757-7 Actuators, however, not vice versa.

2) Version with half the transit time

Table 5: *Dimensions and weights*

Table 5.1: *Type 3226 Three-way Valve*

Valves with male thread connection							
Nominal size	DN	15	20	25	32	40	50
Length L	mm	65	70	75	100	110	130
Height H2	mm	51			61		
Height H3	mm	40	40	40	60	65	65
… with welding ends							
Thread size R	G	¾	1	1¼	1¾	2	2½
Pipe Ød	mm	21.3	26.8	33.7	42	48	60
Width across flats SW		30	36	46	59	65	82
Length L2	mm	210	234	244	268	294	330
Height H4	mm	112	122	124	149	162	175
Weight without actuator	kg (approx.)	3.2	3.6	4.0	6.1	7.0	8.0
… with threaded ends							
Male thread A	G	½	¾	1	1¼	1½	2
Width across flats SW		30	36	46	59	65	82
Length L3	mm	128	143	158	179	195	227
Height H5	mm	71.5	76.5	81.5	99	108	114
Weight without actuator	kg (approx.)	3.2	3.6	4.0	6.1	7.0	8.0
Valves with female thread							
Thread size	G	½	¾	1	–		
Length L1	mm	65	75	90	–		
Height H1	mm	40	40	40	–		
Height H2	mm	51			–		
AF1		27	34	46	–		
Weight without actuator	kg (approx.)	0.9	1.1	1.3	–		

Table 5.2: *Electric actuators*

	Type	5857	5824	5825
Weight	kg (approx.)	0.7	1.0	1.25

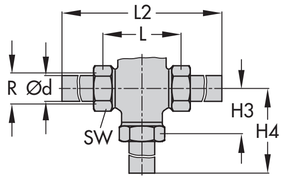
Table 5.3: *Electric actuators with process controllers*

	TROVIS	5757-7	5724-8	5725-7/-8
Weight	kg (approx.)	0.7	1.1	1.3

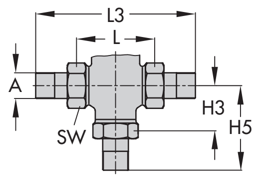
Table 5.4: *Pneumatic Actuators*

	Type	2780-1	2780-2
Weight	kg (approx.)	2	3.2

Type 3226 Three-way Valve with male thread connection and welding ends

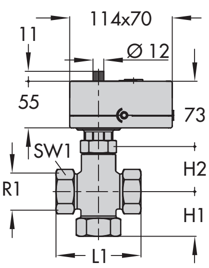


Type 3226 Three-way Valve with male thread connection and threaded ends

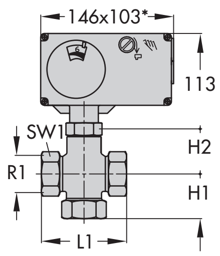


Type 3226 Three-way Valve with female thread

Electric control valves



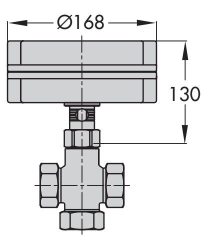
Type 3226/5857: DN 15 to 25
Type 3226/5757-7: DN 15 to 25



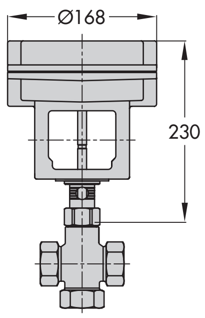
Type 3226/5824: DN 15 to 50
Type 3226/5825: DN 15 to 50
Type 3226/5724-8: DN 15 to 50
Type 3226/5725-7: DN 15 to 50
Type 3226/5725-8: DN 15 to 50

* Dimensions for actuators
Types 5824-x3/5825-x3:
146 x 136

Pneumatic control valves



Type 3226/2780-1: DN 15 to 50



Type 3226/2780-2: DN 15 to 50

Specifications subject to change without notice

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C.5 Samson 3760

Electropneumatic Positioner and Pneumatic Positioner Type 3760

Application

Single-acting positioners for direct attachment to pneumatic control valves. Supplied with an electric input signal of 4 to 20 mA or a pneumatic input signal of 0.2 to 1 bar (3 to 15 psi).

For travels from 5 to 15 mm

CE Ex JIS FM APPROVED

The positioners ensure a predetermined assignment of the valve stem position (controlled variable x) to the control signal (reference variable w). They compare the control signal issued by a controller with the travel of the control valve and issue an output signal pressure p_{st} (output variable y).

The positioners have the following special features: suitable for normal and split-range operation; reversible operating direction; excellent dynamic response; low supply air consumption, insensitive to mechanical vibration; compact, low-maintenance design; optionally available with inductive limit switch and, on request, output pressure limiter.

A version for hazardous areas with type of protection "Intrinsic safety" Ex II 2 G EEx ia IIC T6 according to ATEX is available for the proximity switch circuit and for the signal circuit of the electropneumatic positioner (see summary of explosion protection certificates).

Type of protection EEx d with Type 6116 i/p Converter (Fig. 2)

Direct attachment to Type 3277 Pneumatic Actuators with effective areas of 120, 240 and 350 cm² (see T 8310-1 EN).

Optionally available with a pressure gauge (scale 0 to 6 bar and 0 to 90 psi) to monitor the signal pressure. The pressure gauge housing is made of stainless steel; connection optionally nickel-plated or completely of stainless steel.

Versions

Type 3760 Electropneumatic Positioner (Fig. 1)
Version suitable for non-hazardous areas. Signal pressure ranges from 0 to 6 bar (0 to 90 psi); supply air from 1.4 to 6 bar (20 to 90 psi). Reference variable: standard version 4 to 20 mA.

Type 3760 Electropneumatic Positioner · Same version as above, except for its use in hazardous areas. Type of protection Ex II 2 G EEx ia IIC T6 for the signal circuit
Type of protection EEx d with Type 6116 i/p Converter (Fig. 2)
On request, also available with an intrinsically safe inductive limit switch.

Type 3760 Pneumatic Positioner

Reference variable 0.2 to 1 bar (3 to 15 psi), signal pressure ranges from 0.2 to approx. 6 bar (3 to approx. 90 psi); supply air from 1.4 to 6 bar (20 to 90 psi).
On request, also available with an intrinsically safe inductive limit switch.

Fig. 1 · Type 3760 Positioner

Fig. 2 · Micro-flow valve with EEx d positioner (Type 3760 with Type 6116 i/p Converter)

Principle of operation

The only difference between the positioners is that the electropneumatic positioner is equipped with an i/p converter (2).

Both positioners ensure a predetermined assignment of the valve stem position to the control signal. The controlled variable x is the valve travel. The reference variable w is either a DC signal (i) for the electropneumatic positioner (i/p) or a pneumatic signal (pe) for the pneumatic positioner (p/p). The DC signal and the pneumatic signal are both issued by a connected controller. The manipulated variable y is the positioner's output pressure (p_{st}).

The Type 3760 Positioners are designed for direct attachment to SAMSON Type 3277 Actuators.

In the electropneumatic positioner, the direct current signal i is transmitted from the controller to the i/p converter (2), where it is converted into a proportional air pressure p_e of 0.2 to 1 bar or 3 to 15 psi. In the pneumatic positioner, the control signal p_e provided as air pressure is directly transmitted to the measuring diaphragm (3).

The pneumatic control signal p_e produces a force at the measuring diaphragm (3) which is compared to the force of the range spring (7). The motion of the measuring diaphragm (3) is transmitted to the double plug (13) of the force switch (12) via the lever (4). As a result, a corresponding signal pressure p_{st} is produced. Any changes in the control signal p_e or the valve stem position causes changes in the signal pressure p_{st}. Thus, the plug stem of the valve moves to the position which corresponds to the reference variable.

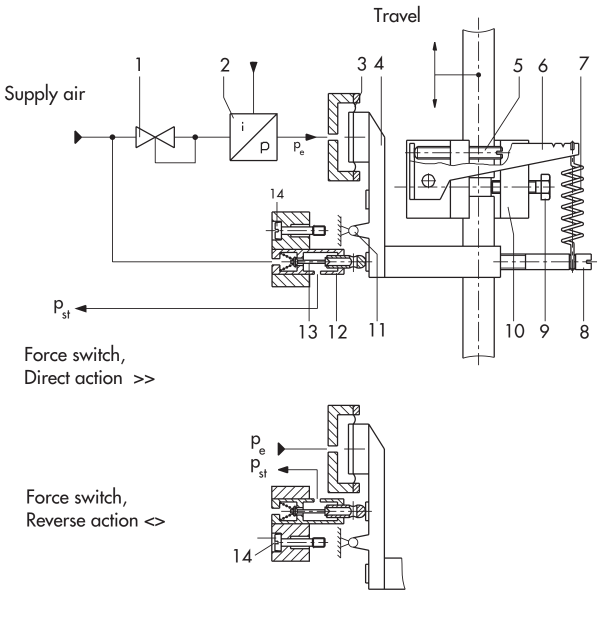
The positioners can be used for both standard and split-range operation. Note that the signal pressure range (range of the output pressure p_{st}) must match the spring range of the actuator.

In split-range operation, the output signal of a control station intended to control two control valves is divided in such a way that each actuator passes through its full travel at half the input span. For a span between 0.2 and 1 bar, for example, the first valve is adjusted to the first half (from 0.2 to 0.6 bar), the second is adjusted to the second half (from to 0.6 to 1 bar).

The adjustment screws for zero (5) and span (8) are used to set the lower and upper range values of the input signal. The range spring (7) must be chosen to match both the rated travel of the control valve and the nominal span of the reference variable.

Operating direction

When the pneumatic control signal p_e (reference variable) increases, the signal pressure p_{st} can be selected to be increasing (direct action >>) or decreasing (reverse action <>). The operating direction is determined by the position of the force switch (12) and can also be changed on site.



Legend

1 Pressure regulator
2 i/p converter
3 Measuring diaphragm
4 Diaphragm lever
5 Adjustment screw (zero)
6 Lever
7 Range spring
8 Adjustment screw (span)
9 Clamping screw
10 Clamp
11 Axis of rotation
12 Force switch
13 Double plug
14 Screw

Fig. 3 · Functional diagram of Type 3760 Positioner

Table 1 · Technical data

Travel range		5 to 15 mm (see Table 2 for range springs)
Reference variable Span for split-range operation 0 to 50 % or 50 to 100 %	Pneumatic	0.2 to 1 bar (3 to 15 psi)
	Electric	4 to 20 mA (Ex only) · R_i 250 7 %
		4 to 20 mA (non-Ex) · R_i 200 7 %
		0 to 20 mA · R_i 200 7 %
(R_i = internal resistance at 20 °C)		1 to 5 mA · R_i 880 7 %
Supply air		1.4 to 6 bar (20 to 90 psi)
		Max. particle size and density: Class 2 · Oil content: Class 3 · Pressure dew point: Class 3 or at least 10 K below the lowest ambient temperature to be expected
Signal pressure p_{st} (output)		Max. 0 to 6 bar (0 to 90 psi)
Characteristic		Linear, deviation from terminal-based conformity 1.5 %
Hysteresis		0.5 %
Sensitivity		< 0.1 %
Operating direction		Reversible
Air consumption in steady state		At 0.6 bar signal pressure and supply pressure up to 6 bar 100 l_n/h
Air output capacity		At p = 1.4 bar 1600 l_n/h · At p = 6 bar 5000 l_n/h
Transit times with Type 3277 Actuator (15 mm travel, 0.2 to 1 bar signal pressure)		120 cm²: 2 s · 240 cm²: 6 s · 350 cm²: 8 s
Permissible ambient temperature		–20 to +70 °C
(Note the limits in the EC Type Examination Certificate)		Down to –30 °C with metal cable gland Down to –40 °C with metal cable gland and Type 6112 i/p Converter The limits in the EC Type Examination Certificate additionally apply for explosion-protected versions –40 to 70 °C with Type 3760 used as pneumatic positioner without proximity switches
Influences	Temperature (zero)	0.03 %/°C
	Span	0.03 %/°C
	Vibrations	Between 5 to 120 Hz and 2 g 0.5 %
	Supply air	1 % between 1.4 and 6 bar
Variable position when turned 180°		< 3.5 %
Degree of protection		IP 54 (IP 65 special version)
Materials		Housing: Polyamide · External parts: Stainless steel 1.4571 and 1.4104 Measuring diaphragm: Fluorosilicone rubber · Cable gland: Polyamide, M20 x 1.5
Weight		0.6 kg
Additional equipment		
Inductive limit switch		Type SJ2 – SN
Control current circuit		Values corresponding to the downstream transistor relay
Hysteresis at rated travel		1 %

Table 2 · Range springs

Range spring	Reference variable (%)	Travel (mm)
1	0 to 100 Split-range 0 to 50 or 50 to 100	12/15 6/7.5
2	0 to 100	6/7.5
3	Split-range 0 to 50	12/15
4	Split-range 50 to 100	12/15
5	0 to 100	5
6	0 to 100	20
7	Split-range 0 to 50 or 50 to 100	5

Positioner attachment

The positioners are designed for direct attachment to Type 3277 Actuators with effective areas 350 cm² and smaller. They are secured directly to the actuator yoke using two screws.

No external piping is necessary for actuators with effective areas of 120 cm². The signal pressure pst from the positioner is transmitted to the desired diaphragm chamber via a switchover plate and internal air ducts.

Combination of positioner and actuator

Fig. 4 illustrates the different types of attachment. The specifications "left attachment" or "right attachment" apply when looking onto the switchover plate and the signal pressure connection. Depending on the intended attachment, the positioner is to be secured on either the right or the left side of the yoke.

Subsequent conversion, such as reversing the operating direction of the positioner control loop or modifying the actuator's fail-safe action, is possible. In this case, note that the positioner must also be attached in a different position.

Fail-safe action

The Type 3277 Pneumatic Actuator has the two fail-safe actions which move the valve stem to the predetermined position whenever the signal pressure decreases or the air supply fails.

Actuator stem extends:
Whenever the pressure acting on the surface of the diaphragm decreases or the air supply fails, the force of the compression springs in the actuator causes the actuator stem to extend.

Actuator stem retracts:

Whenever the pressure acting on the surface of the diaphragm decreases or the air supply fails, the force of the compression springs in the actuator causes the actuator stem to retract.

Further details can be found in Data Sheet T 8310-1 EN.

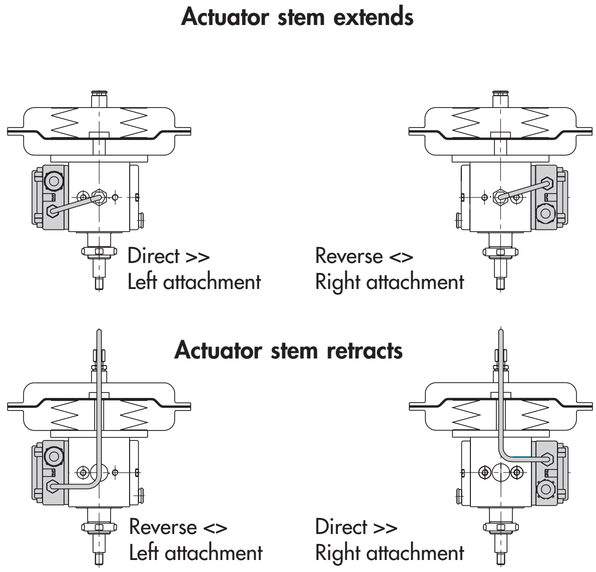


Fig. 4 · Attachment position

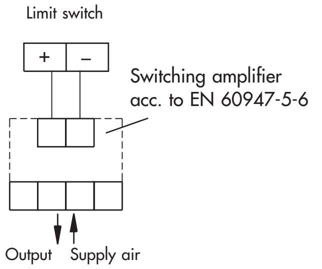
Summary of explosion protection certificates for Type 3760

Type of approval	Certificate number	Date	Comments
EC Type Examination Certificate	PTB 02 ATEX 2076	2002-07-18	Ex II 2 G EEx ia IIC T6; Inductive limit switches PTB 99 ATEX 2219 X; Type 3760-1
Statement of Conformity	PTB 03 ATEX 2181 X	2003-09-30	Ex II 3 G EEx nA II T6; Zone 2; Type 3760-8
CSA approval	LR 54227-23 Addendum LR 54227-32	1996-04-22 2005-09-16 1999-10-14	Class 1, Div. 1; Groups A, B, C, D NLRC approval also valid in USA Class I, Groups A, B, C, D Encl. 3; Inductive limit switches; Type 3760-3
FM approval	3020228 Revision	2005-02-28	Classes I, II, III; Div 1; Groups A, B, C, D, E, F, G Class I, Zone 0 AEx ia IIC T6; Class I; Div. 2; Groups A, B, C, D Class II; Div. 2; Groups F, G; Cl. III NEMA 3R With inductive limit switch; Type 6109 and Type 6112 i/p Module; Type 3760-3

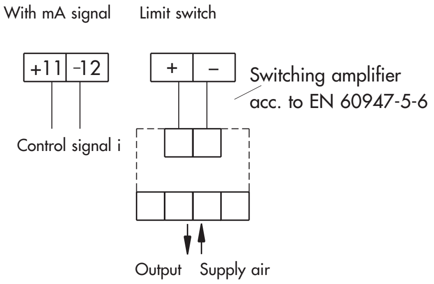
Refer to Data Sheet T 6116 EN for EEx d certificates for Type 6116 i/p Converter.

Electrical connections

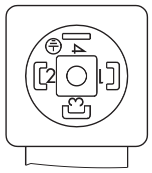
Pneumatic version



Electropneumatic version

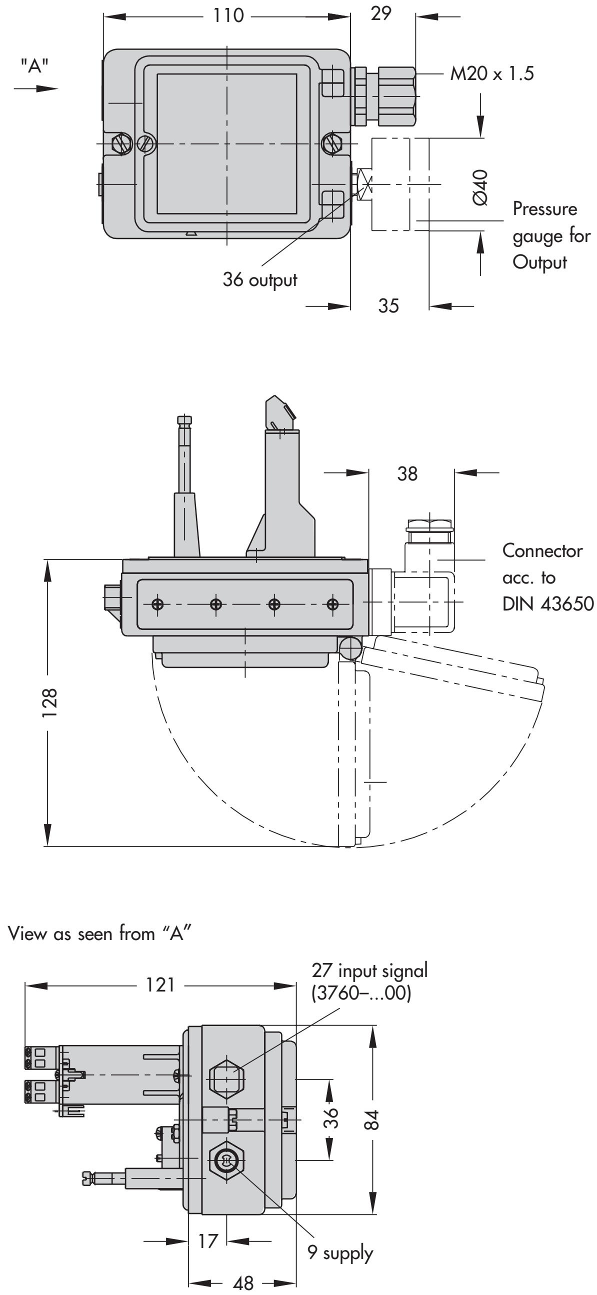


Connection with cable socket (DIN 43650)



Cable socket	Terminal	
1	+ 11	i/p converter
2	– 12	
3	+	Limit switch
4	–	

Dimensions in mm



Pneumatic connections G ⅛ or ⅛ NPT

Article code

Positioner	Type 3760-	x	x	x	x	x	x	0	0	0	0	0	0
Explosion protection													
Without		0			2/3								
Ⓔx II 2 G EEx ia IIC T6 acc. to ATEX		1			0								
FM/CSA intrinsically safe/non incendive		3			0								
Ⓔx II 3 G EEx nA II T6 acc. to ATEX		8			0								
Limit switches													
Without			0										
1 x inductive, SJ2 SN			1										
Pneumatic connection													
ISO 228/1 - G ⅛				1									
⅛ - 27 NPT				2									
Electrical connection													
Without					0	0	0						
Cable gland M20 x 1.5, blue (plastic)					1								
Cable gland M20 x 1.5, black (plastic)					2								
Connector DIN 43650-AF3-PG11					3								
i/p module													
Without						0	0						
Type 6109						1	1						
Type 6112						2	1/2/3						
Reference variable													
0.2 ... 1.0 bar / 3 ... 15 psi							0						
4 ... 20 mA							1						
0 ... 20 mA							2						
1 ... 5 mA							3						

Accessories

Adapter ½ NPT for electrical connections

Additional specifications

Range spring 1/ ... 7/
Pressure gauge Without/with
Gauge housing CrNiMo steel,
Connection optionally nickel-plated/completely CrNiMo steel

Specifications subject to change without notice.

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Internet: http://www.samson.de

2010-02

C.6 Siemens SITRANS 7MF1563

Application

The transmitters 7MF1560 and 7MF1563 are used to measure the absolute and relative pressures or the level of liquids and gases, the transmitter 7MF1562 to measure the relative pressure of gases, liquids and steam.

They are used in the chemical, pharmaceutical and food industries, in mechanical engineering, shipbuilding, water supply and conservation etc.

An application example for the 7MF1562 is the measurement of compressed air containing oil in compressors or compressor stations.

Design

The pressure transmitters contain a piezo-resistive measuring cell with stainless steel diaphragm (7MF1560) or a thin-film cell with ceramic diaphragm (7MF1562 and 7MF1563) which can also be used for corrosive media, and an electronics board, fitted together in a stainless steel (7MF1560 and 7MF1563) or brass (7MF1562) housing. With the transmitter 7MF1560, the measuring cell and the electronics are potted together.

The transmitter has a process connection G½A (male thread), or G1/8A (female thread) to DIN 16 288 made of stainless steel or brass.

The electrical connection is via a plug (DIN 43 650) with Pg 9 cable inlet.

Mode of operation

The silicon measuring cell of the transmitter has a piezo-resistive bridge on which the operating pressure is transmitted via silicone oil and a stainless steel seal diaphragm. The transmitters 7MF1562 and 7MF1563 have a thin-film strain gauge which is mounted on a ceramic diaphragm.

Every measuring cell is temperature-compensated.

The voltage output by the measuring cell is converted by an amplifier into an output current of 4 to 20 mA.

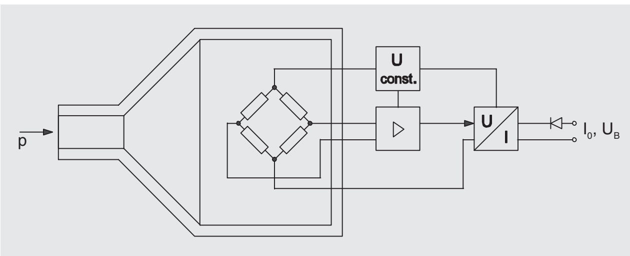


Fig. 1/161 Pressure transmitters 7MF1560, 7MF1562 and 7MF1563, mode of operation

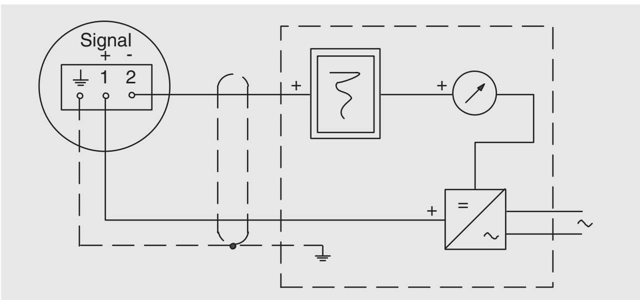


Fig. 1/162 Pressure transmitters 7MF1560, 7MF1562 and 7MF1563, connection diagram

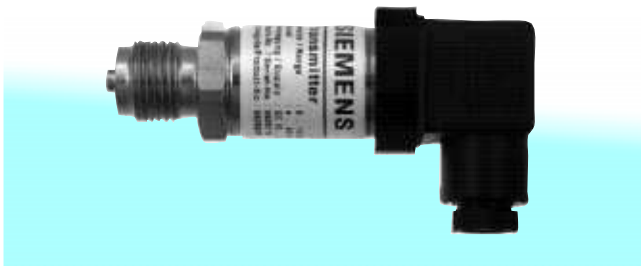


Fig. 1/163 Pressure transmitters 7MF1560, 7MF1562 and 7MF1563

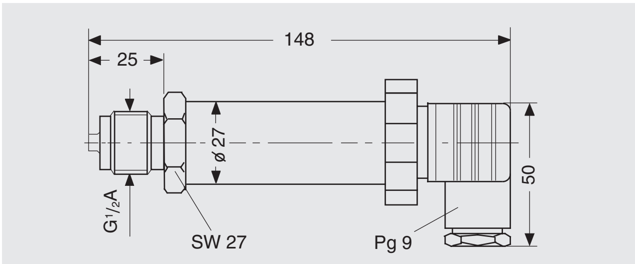


Fig. 1/164 Pressure transmitter 7MF1560, dimensions

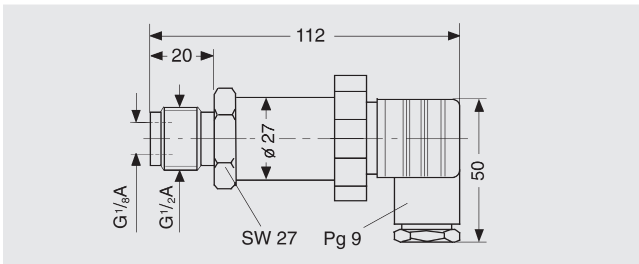


Fig. 1/165 Pressure transmitter 7MF1562, dimensions

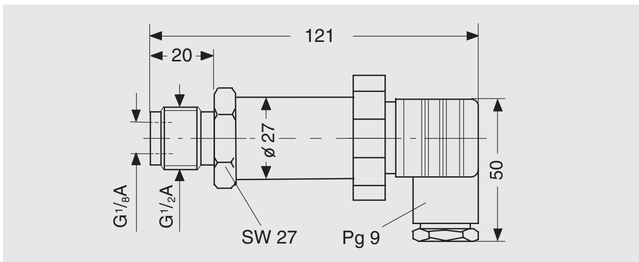


Fig. 1/166 Pressure transmitter 7MF1563, dimensions

Technical data

	7MF1560	7MF1562	7MF1563
Application		See page 1/135	
Mode of operation and system design		See page 1/135	
Measuring principle	Piezo-resistive	Thin-film strain gauge	Thin-film strain gauge
Input			
Measured variable	Pressure and absolute pressure	Pressure	Pressure and absolute pressure
Measuring range	0 to 400 bar	0 to 25 bar	0 to 400 bar
Output			
Output signal		4 to 20 mA	
Load		$(U_B - 10\ V) / 0.02\ A$	
Characteristic		Linear rising	
Accuracy			
Error in measurement (at 25 °C, including conformity error, hysteresis and repeatability)	0.2 % of full-scale value - typical	0.5 % of full-scale value - typical	0.25 % of full-scale value - typical
Response time T_{99}		< 0.1 s	
Long-term drift			
• Start-of-scale value	0.2 % of full-scale value/year	0.3 % of full-scale value/year - typical	0.25 % of full-scale value/year
• Span	0.2 % of full-scale value/year	0.3 % of full-scale value/year - typical	0.25 % of full-scale value/year
Ambient temperature effect			
• Start-of-scale value	0.25 %/10 K of full-scale value	0.3 %/10 K of full-scale value - typical	0.25 %/10 K of full-scale value
• Span	0.25 %/10 K of full-scale value	0.3 %/10 K of full-scale value - typical.	0.25 %/10 K of full-scale value
Vibration influence		0.05 %/g to 500 Hz in all directions (to IEC 68-2-64)	
Power supply influence		0.01 %/V	
Rated operating conditions			
Ambient conditions			
• Ambient temperature		-25 to +85 °C	
• Storage temperature		-50 to +100 °C	
• Degree of protection (to EN 60 529)		IP 65	
• Electromagnetic compatibility			
- Emitted interference		To EN 50 081	
- Noise immunity		To EN 50 082	
Medium conditions			
• Process temperature limits		-30 °C to +120 °C	
• Process pressure limits		See overload pressure (ordering data on page 1/137)	
Design			
Weight (without options)	Approx. 0.3 kg	Approx. 0.2 kg	Approx. 0.25 kg
Dimensions		See dimensional drawings on page 1/135	
Material			
• Wetted parts materials			
- Measuring cell	Stainless steel, mat. No. 1.4571	Al_2O_3 - 96 %	Al_2O_3 - 96 %
- Process connection	Stainless steel, mat. No. 1.4571	Brass, mat. No. 2.0402	Stainless steel, mat. No. 1.4571
- O-ring	Fully-welded design	Viton	Viton
• Non-wetted parts materials			
- Housing	Stainless steel, mat. No. 1.4571	Brass, mat. No. 2.0402	Stainless steel, mat. No. 1.4571
- Plug connector		Plastic housing, to DIN 43 650, form A	
Process connection	G½A - male thread (DIN 16 288), remote seals on request	G½A - male thread G$^{1}/_{8}$A - female thread	G½A - male thread G$^{1}/_{8}$A - female thread
Electrical connection (to DIN 43 650)		Pg 9	
Power supply			
Terminal voltage on transmitter	10 to 40 V DC	10 to 36 V DC	10 to 36 V DC

Ordering data

Order No. Order code

Transmitter SITRANS P, Z series

	Order No.
7MF1560, for pressure and absolute pressure	**7MF1560-■■■ 0 0 + ■■■**
7MF1562, for pressure	**7MF1562-■■■ 0 0 + ■■■**
7MF1563, for pressure and absolute pressure Two-wire system, rising characteristic	**7MF1563-■■■ 0 0 + ■■■**

Measuring range	Overload pressure 7MF1560	Overload pressure 7MF1562	Overload pressure 7MF1563	7MF1560 Pressure	7MF1560 Absolute pressure	7MF1562 Pressure	7MF1563 Pressure	7MF1563 Absolute pressure	Order code
0 to 250 mbar	4 bar			**2AD**	**4AD**	–	–	–	
0 to 400 mbar	4 bar			**2AE**	**4AE**	–	–	–	
0 to 600 mbar	4 bar			**2AG**	**4AG**	–	–	–	
0 to 1 bar	4 bar		7 bar	**3BA**	**5BA**	–	**3BA**	**5BA**	
0 to 1.6 bar	7 bar		7 bar	**3BB**	**5BB**	–	**3BB**	**5BB**	
0 to 2.5 bar	14 bar		12 bar	**3BD**	**5BD**	–	**3BD**	**5BD**	
0 to 4 bar	14 bar		12 bar	**3BE**	**5BE**	–	**3BE**	**5BE**	
0 to 6 bar	14 bar		25 bar	**3BG**	**5BG**	–	**3BG**	**5BG**	
0 to 10 bar	34 bar		25 bar	**3CA**	**5CA**	–	**3CA**	**5CA**	
0 to 16 bar	34 bar	32 bar	50 bar	**3CB**	**5CB**	**3CB**	**3CB**	**5CB**	
0 to 25 bar	70 bar	64 bar	120 bar	**3CD**		**3CD**	**3CD**		
0 to 40 bar	140 bar		120 bar	**3CE**		–	**3CE**		
0 to 60 bar	140 bar		250 bar	**3CG**		–	**3CG**		
0 to 100 bar	340 bar		250 bar	**3DA**	–	–	**3DA**	–	
0 to 160 bar	340 bar		500 bar	**3DB**	–	–	**3DB**	–	
0 to 250 bar	700 bar		500 bar	**3DD**	–	–	**3DD**	–	
0 to 400 bar	700 bar		600 bar	**3DE**	–	–	**3DE**	–	
Other version Add Order code and plain text: Measuring range: ... to ... (m)bar				**9AA**	**9AB**	**9AA**	**9AA**	**9AB**	**H1Y**

Available ex stock

C.7 Siemens S7-200 CPU 224

SIEMENS

Product data sheet 6ES7214-1AD23-0XB0

SIMATIC S7-200, CPU 224, COMPACT UNIT,
DC POWER SUPPLY 14 DI DC/10 DO DC,
8/12 KB CODE/8 KB DATA,
PROFIBUS DP EXTENDABLE

-

Supply voltage	
24 V DC	Yes
permissible range, lower limit (DC)	20.4 V
permissible range, upper limit (DC)	28.8 V
Load voltage L+	
Rated value (DC)	24 V
permissible range, lower limit (DC)	20.4 V
permissible range, upper limit (DC)	28.8 V
Input current	
Inrush current, max.	12 A ; at 28.8 V
from supply voltage L+, max.	700 mA ; 110 to 700 mA, output current for expansion modules (DC 5 V) 660 mA
Encoder supply	
24 V encoder supply	
24 V	Yes ; permissible range: 15.4 to 28.8 V
Short-circuit protection	Yes ; electronic at 280 mA
Output current, max.	280 mA
Memory	
Type of memory	other

Number of memory modules (optional)	1 ; pluggable memory module, content identical with integral EEPROM; can additionally store recipes, data logs and other files
Data and program memory	
Data memory, max.	8 kbyte
Program memory, max.	12 kbyte ; 8 KB with active run-time edit
Backup	
present	Yes ; Program: Entire program maintenance-free on integral EEPROM, programmable via CPU; data: Entire DB 1 loaded from PG/PC maintenance-free on integral EEPROM, current values of DB 1 in RAM, retentive memory bits, timers, counters, etc. maintenance-free via high-performance capacitor; optional battery for long-term buffering
Battery	
Backup battery	
Battery operation	
Backup time, max.	100 h ; (min. 70 h at 40 °C); 200 days (typ.) with optional battery module
CPU processing times	
for bit operations, max.	0.22 µs
Counters, timers and their retentivity	
S7 counter	
Number	256
of which retentive with battery	
adjustable	Yes ; via high-performance capacitor or battery
lower limit	1
upper limit	256
Counting range	
lower limit	0
upper limit	32767
S7 times	
Number	256
of which retentive with battery	
adjustable	Yes ; via high-performance capacitor or battery
upper limit	64
Time range	
lower limit	1 ms
upper limit	54 min ; 4 timers: 1 ms to 30 s; 16 timers: 10 ms to 5 min; 236 timers: 100 ms to 54 min
Data areas and their retentivity	
Flag	
Number, max.	32 byte

Retentivity available	Yes ; M 0.0 to M 31.7
of which retentive with battery	0 to 255, via high-performance capacitor or battery, adjustable
of which retentive without battery	0 to 112 in EEPROM, adjustable
Hardware configuration	
Expansion devices, max.	7 ; Only expansion modules of the S7-22x series can be used. Due to the limited output current, the use of expansion modules may be limited.
Connectable programming devices/PCs	SIMATIC PG/PC, standard PC
Expansion modules	
Analog inputs/outputs, max.	35 ; max. 28 inputs and 7 outputs (EM) or max. 0 inputs and 14 outputs (EM)
Digital inputs/outputs, max.	168 ; max. 94 inputs and 74 outputs (CPU + EM)
AS-Interface inputs/outputs max.	62 ; AS-Interface A/B slaves (CP 243-2)
Digital inputs	
Number of digital inputs	14
m/p-reading	Yes ; optionally, per group
Input voltage	
Rated value, DC	24 V
for signal "0"	0 to 5 V
for signal "1"	min. 15 V
Input current	
for signal "1", typ.	2.5 mA
Input delay (for rated value of input voltage)	
for standard inputs	
Parameterizable	Yes ; all
at "0" to "1", min.	0.2 ms
at "0" to "1", max.	12.8 ms
for interrupt inputs	
Parameterizable	Yes ; I 0.0 to I 0.3
for counter/technological functions	
Parameterizable	Yes ; (E0.0 to E1.5) 30 kHz
Cable length	
Cable length, shielded, max.	500 m ; Standard input: 500 m, high-speed counters: 50 m
Cable length unshielded, max.	300 m ; not for high-speed signals
Digital outputs	
Number of digital outputs	10 ; Transistor
short-circuit protection	No ; to be provided externally
Limitation of inductive shutdown voltage to	1 W
Switching capacity of the outputs	

with resistive load, max.	0.75 A
on lamp load, max.	5 W
Output voltage	
for signal "1", min.	20 V DC
Output current	
for signal "1" rated value	750 mA
for signal "0" residual current, max.	10 µA
Output delay with resistive load	
"0" to "1", max.	15 µs ; of the standard outputs, max. (Q0.2 to Q1.1) 2 µs; of the pulse outputs, max. (Q0.0 to Q0.1) 2 µs
"1" to "0", max.	130 µs ; of the standard outputs, max. (Q0.2 to Q1.1) 10 µs; of the pulse outputs, max. (Q0.0 to Q0.1) 10 µs
Parallel switching of 2 outputs	
for increased power	Yes
Switching frequency	
of the pulse outputs, with resistive load, max.	20 kHz ; Q0.0 to Q0.1
Aggregate current of outputs (per group)	
all mounting positions	
up to 40 °C, max.	6 A
horizontal installation	
up to 55 °C, max.	6 A
Relay outputs	
Max. number of relay outputs, integrated	0
Cable length	
Cable length, shielded, max.	500 m
Cable length unshielded, max.	150 m
Analog inputs	
Number of analog potentiometers	2 ; Analog potentiometer; resolution 8 bit
Encoder	
Connectable encoders	
2-wire sensor	Yes
Permissible quiescent current (2-wire sensor), max.	1 mA
1st interface	
Type of interface	Integrated RS 485 interface
Physics	RS 485
Functionality	
MPI	Yes ; As MPI slave for data exchange with MPI masters (S7-300/S7-400 CPUs, OPs, TDs, Push Button Panels); S7-200-internal CPU/CPU communication is possible in the MPI network with restrictions; transmission rates: 19.2/187.5 kbit/s

PPI	Yes ; with PPI protocol for program functions, HMI functions (TD 200, OP), S7-200-internal CPU/CPU communication ; transmission rates 9.6/19.2/187.5 kbit/s
Serial data exchange	Yes ; As freely programmable interface with interrupt facility for serial data exchange with third-party devices with ASCII protocol transfer rates: 1.2 / 2.4 / 4.8 / 9.6 / 19.2 / 38.4 / 57.6 / 115.2 kbit/s; the PC/PPI cable can also be used as RS232/RS485 converter
MPI	
Transmission rate, min.	19.2 kbit/s
Transmission rate, max.	187.5 kbit/s
Integrated Functions	
Number of counters	6 ; High-speed counters (30 kHz each), 32 bits (incl. sign), can be used as up/down counters or for connecting 2 incremental encoders with 2 pulse trains offset by 90° (max. 20 kHz (A/B counters)); parameterizable enable and reset input; interrupt facilities (incl. call of subroutine with any content) when the setpoint is reached; reversal in counting direction, etc.
Counter frequency (counter) max.	30 kHz
Number of alarm inputs	4 ; 4 rising edges and/or 4 falling edges
Number of pulse outputs	2 ; High-speed outputs, 20 kHz, with interrupt option; pulse-width and frequency modulation option
Limit frequency (pulse)	20 kHz
Galvanic isolation	
Galvanic isolation digital inputs	
between the channels	Yes
between the channels, in groups of	6 and 8
Galvanic isolation digital outputs	
between the channels	Yes ; Optocoupler
between the channels, in groups of	5
Permissible potential difference	
between different circuits	500 V DC between 24 V DC and 5 V DC
Degree and class of protection	
IP20	Yes
Ambient conditions	
Environmental conditions	For further environmental conditions, see "Automation System S7-200, System Manual"
Operating temperature	
horizontal installation, min.	0 °C
horizontal installation, max.	55 °C
vertical installation, min.	0 °C
vertical installation, max.	45 °C
Air pressure	
permissible range, min.	860 hPa

permissible range, max.	1080 hPa
Relative humidity	
Operation, min.	5 %
Operation, max.	95 % ; RH class 2 in accordance with IEC 1131-2
Configuration	
programming	
Command set	Bit logic instructions, compare instructions, timer instructions, counter instructions, clock instructions, transmissions instructions, table instructions, logic instructions, shift and rotate instructions, conversion instructions, program control instructions, interrupt and communications instructions, logic stack instructions, integer maths, floating-point math instructions, numerical functions
Program processing	free cycle (OB 1), interrupt-controller, time-controlled (1 to 255 ms)
Program organization	1 OB, 1 DB, 1 SDB subroutines with/without parameter transfer
Number of subroutines, max.	64
Programming language	
LAD	Yes
FBD	Yes
STL	Yes
Know-how protection	
User program protection/password protection	Yes ; 3-stage password protection
Connection method	
Plug-in I/O terminals	Yes
Dimensions	
Width	120.5 mm
Height	80 mm
Depth	62 mm
Weights	
Weight, approx.	360 g
Status	Jan 23, 2014

C.8 Siemens S7-200 EM 235

SIEMENS

Product data sheet 6ES7235-0KD22-0XA0

-	SIMATIC S7-200, ANALOG I/O EM 235, FOR S7-22X CPU ONLY, 4 AI, DC +/-10V; 1AQ, DC +/-10V 12 BIT CONVERTER
Input current	
from backplane bus 5 V DC, max.	30 mA
from sensor current supply or external current supply (24 V DC), max.	60 mA
Power losses	
Power loss, typ.	2 W
Analog inputs	
Number of analog inputs	4 ; Difference
permissible input voltage for voltage input (destruction limit), max.	30 V
permissible input current for current input (destruction limit), max.	32 mA
Input ranges	
Voltage	Yes
Current	Yes
Input ranges (rated values), voltages	
0 to +50 mV	Yes
0 to +100 mV	Yes
0 to +500 mV	Yes
0 to +1 V	Yes
0 to +5 V	Yes
0 to +10 V	Yes
-1 V to +1 V	Yes
-10 V to +10 V	Yes
-100 mV to +100 mV	Yes
-2.5 V to +2.5 V	Yes
-25 mV to +25 mV	Yes
-250 mV to +250 mV	Yes
-5 V to +5 V	Yes
-50 mV to +50 mV	Yes
-500 mV to +500 mV	Yes
Input ranges (rated values), currents	
0 to 20 mA	Yes
Thermocouple (TC)	

Temperature compensation	
Parameterizable	No
Analog outputs	
Number of analog outputs	1
Output ranges, voltage	
-10 to +10 V	Yes
Output ranges, current	
0 to 20 mA	Yes
Load impedance (in rated range of output)	
with voltage outputs, min.	5 kΩ
with current outputs, max.	0.5 kΩ
Analog value creation	
Integrations and conversion time/ resolution per channel	
Resolution with overrange (bit including sign), max.	12 bit ; 11 bits for current output
Basic conversion time, ms	< 0.25 ms
Interference voltage suppression for interference frequency f1 in Hz	40 dB, DC to 60 Hz
Settling time	
for voltage output	100 µs
for current output	2 ms
Displayable conversion value range	
bipolar signals	-32000 to +32000
unipolar signals	0 to 32000
Errors/accuracies	
Operational limit in overall temperature range	
Voltage, relative to output area	+/- 2 %
Current, relative to output area	+/- 2 %
Basic error limit (operational limit at 25 °C)	
Voltage, relative to output area	+/- 0,5 %
Current, relative to output area	+/- 0,5 %
Interference voltage suppression for f = n x (f1 +/- 1 %), f1 = interference frequency	
common mode voltage, max.	12 V
Interrupts/diagnostics/status information	
Diagnostics indication LED	
External fault EXTF (red)	Yes
Galvanic isolation	
Galvanic isolation analog inputs	
Galvanic isolation analog inputs	No

Galvanic isolation analog outputs	
Galvanic isolation analog outputs	No
Connection method	
Plug-in I/O terminals	No
Dimensions	
Width	71.2 mm
Height	80 mm
Depth	62 mm
Weights	
Weight, approx.	186 g
Status	Dec 30, 2013

C.9 Siemens S7-200 EM 232

SIEMENS

SIMATIC S7-200, ANALOG OUTPUT EM 232,
FOR S7-22X CPU ONLY, 4 AQ, +/- 10V DC,
0..20MA 12/11 BIT CONVERTER

-

Input current	
from backplane bus 5 V DC, max.	20 mA
from sensor current supply or external current supply (24 V DC), max.	70 mA
Power losses	
Power loss, typ.	2 W
Analog outputs	
Number of analog outputs	4
Output ranges, voltage	
-10 to +10 V	Yes
Output ranges, current	
4 to 20 mA	Yes
Load impedance (in rated range of output)	
with voltage outputs, min.	5 kΩ
with current outputs, max.	0.5 kΩ
Analog value creation	
Integrations and conversion time/ resolution per channel	
Resolution (incl. overrange)	V/12 bits, I/11 bits
Settling time	

for voltage output	100 µs
for current output	2 ms
Displayable conversion value range	
bipolar signals	-32000 to +32000
unipolar signals	0 to 32000
Errors/accuracies	
Operational limit in overall temperature range	
Voltage, relative to output area	+/- 2 %
Current, relative to output area	+/- 2 %
Basic error limit (operational limit at 25 °C)	
Voltage, relative to output area	+/- 0,5 %
Current, relative to output area	+/- 0,5 %
Galvanic isolation	
Galvanic isolation analog outputs	
Galvanic isolation analog outputs	No
Connection method	
Plug-in I/O terminals	No
Dimensions	
Width	71.2 mm
Height	80 mm
Depth	62 mm
Weight	
Weight, approx.	190 g
Status	Feb 25, 2013

C.10 Siemens S7-200 CP 243-1

SIEMENS

Product data sheet 6GK7243-1EX01-0XE0

Product-type designation	CP 243-1
	COMMUNICATIONSPROCESSOR CP243-1 FOR CONNECTING OF SIMATIC S7-22X TO INDUSTRIAL ETHERNET; FTP CLIENT COMMUNICATION; HTTP SERVER; FTP SERVER; E-MAIL CLIENT
Transmission rate	
Transfer rate / at the interface 1	10 … 100 Mbit/s
Interfaces	
Number of electrical connections	
• at interface 1 / in accordance with Industrial Ethernet	1
• for power supply	1
Design of the electrical connection	
• at interface 1 / in accordance with Industrial Ethernet	RJ45 port
Supply voltage, current consumption, power loss	
Type of voltage / of supply voltage	DC
Supply voltage	
• 1 / from backplane bus	5 V
• external	24 V
Consumed current / from external supply voltage / at 24 V / with DC	
• typical	0.053 A
• maximum	0.06 A
Resistive loss	1.5 W
Permitted ambient conditions	
Ambient temperature	
• for vertical installation	

• during operating phase	0 … 45 °C
• for horizontal installation	
• during operating phase	0 … 55 °C
• during storage	-40 … +70 °C
• during transport	-40 … +70 °C
Relative humidity / at 25 °C / without condensation / during operating / maximum	95 %
Protection class IP	IP20
Design, dimensions and weight	
Width	71.2 mm
Height	80 mm
Depth	62 mm
Net weight	0.15 kg
Product properties, functions, components / general	
Number of units	
• per CPU / maximum	1
• note	-
Performance data / S7 communication	
Number of possible connections / for S7 communication	
• maximum	8
• with PG connections / maximum	1
• with PG/OP connections / maximum	8
Performance data / IT functions	
Number of possible connections	
• as client / by means of FTP / maximum	1
• as server / by means of HTTP / maximum	4
• as e-mail client / maximum	1
Number of e-mails with 1024 characters / of e-mail client / maximum	32
Number of access rights / access protections	8
Storage capacity / of user memory / as flash memory file system	8 Mibyte
Number of possible write cycles / flash memory cells	100000
Product functions / management, configuration	
Product function / MIB support	No
Protocol / is supported / SNMP v1	No
Product functions / Diagnosis	
Product function / Web-based diagnostics	Yes

letzte Änderung: Feb 13, 2013

C.11 Siemens S7-200 PROFIBUS DP SLAVE MODULE

SIEMENS

Data sheet 6ES7277-0AA22-0XA0

SIMATIC S7-200, PROFIBUS DP SLAVE MODULE, 9.6KB TO 12MB, 1 PORT, PROFIBUS DP/MPI

Supply voltage	
Load voltage L+	
• Rated value (DC)	24 V
• permissible range, lower limit (DC)	20.4 V
• permissible range, upper limit (DC)	28.8 V
Input current	
from backplane bus 5 V DC, max.	150 mA
from sensor current supply or external current supply (24 V DC), max.	180 mA; 30 to 180 mA
Output voltage	
Rated value (DC)	
• 5 V DC	Yes
• 24 V DC	Yes; 20.4 to 28.8V
Output current	
For interface (5 V DC), max.	90 mA
For interface (24 V DC), max.	120 mA
• Current limitation	0.7 to 2.4 A

Power loss	
Power loss, typ.	2.5 W

Hardware configuration	
connectable nodes	TD 200 as of V2.0, OP, TP, PG/PC, S7-300/400, PROFIBUS DP master

Interfaces	
Number of RS 485 interfaces	1
MPI	
• Number of connections, max.	6
PROFIBUS DP	
• Node addresses	0 to 99, adjustable
• Number of stations per segment, max.	32
• Number of stations in network, max.	126; of which max. 99 EM 277
• automatic detection of transmission rate	Yes
• Transmission rate, max.	12 Mbit/s; 9,6 / 19,2 / 45,45 / 93,75 / 187,5 / 500 kbit/s; 1 / 1,5 / 3 / 6 / 12 Mbit/s
Cable length	
— Cable length, max.	1 200 m; 100 to 1200 m, depending on transmission speed

Protocols	
Bus protocol/transmission protocol	PROFIBUS DP (slave), MPI (slave)

Communication functions	
Number of connections	
• usable for PG communication	
— reserved for PG communication	1
• usable for OP communication	
— reserved for OP communication	1

Interrupts/diagnostics/status information	
Diagnostics indication LED	
• Bus fault BF (red)	Yes
• CPU error (red)	Yes
• DX mode (red)	Yes
• Power supply (red)	Yes

Isolation	
Isolation tested with	between external signal and control logic: 500 V AC (galvanic); 5 V DC interface: Isolation between output and module as well as 24 V DC supply voltage: 500 V AC (max. 1 min.); 24 V DC interface: Isolation no; same circuit as 24 V DC supply voltage

Connection method	
Plug-in I/O terminals	No

Dimensions	

Width	71.2 mm
Height	80 mm
Depth	62 mm

Weights	
Weight, approx.	175 g

last modified: 07/31/2017

C.12 Siemens S7-200 Programmable Controller System Manual, Proportional/Integral/Derivative (PID) Loop Instruction

SIEMENS

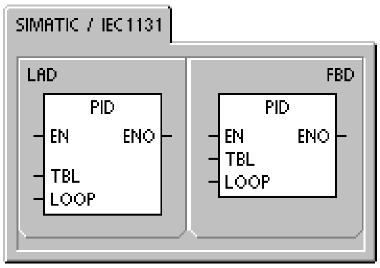
SIMATIC

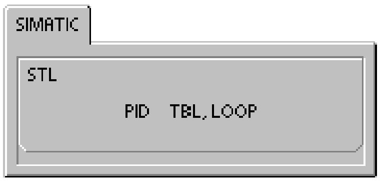
S7-200 Programmable Controller System Manual

This manual has the order number:
6ES7298-8FA24–8BH0

Edition 08/2008
A5E00307987-04

Proportional/Integral/Derivative (PID) Loop Instruction





The PID Loop instruction (PID) executes a PID loop calculation on the referenced LOOP based on the input and configuration information in Table (TBL).

Error conditions that set ENO = 0:

- SM1.1 (overflow)
- 0006 (indirect address)

Special Memory bits affected:

- SM1.1 (overflow)

The PID loop instruction (Proportional, Integral, Derivative Loop) is provided to perform the PID calculation. The top of the logic stack (TOS) must be ON (power flow) to enable the PID calculation. The instruction has two operands: a TABLE address which is the starting address of the loop table and a LOOP number which is a constant from 0 to 7.

Eight PID instructions can be used in a program. If two or more PID instructions are used with the same loop number (even if they have different table addresses), the PID calculations will interfere with one another and the output will be unpredictable.

The loop table stores nine parameters used for controlling and monitoring the loop operation and includes the current and previous value of the process variable, the setpoint, output, gain, sample time, integral time (reset), derivative time (rate), and the integral sum (bias).

To perform the PID calculation at the desired sample rate, the PID instruction must be executed either from within a timed interrupt routine or from within the main program at a rate controlled by a timer. The sample time must be supplied as an input to the PID instruction via the loop table.

Auto-Tune capability has been incorporated into the PID instruction. Refer to Chapter 15 for a detailed description of auto-tuning. The PID Tuning Control Panel only works with PID loops created by the PID wizard..

Table 6-43 Valid Operands for the PID Loop Instruction

Inputs/Outputs	Data Types	Operands
TBL	BYTE	VB
LOOP	BYTE	Constant (0 to 7)

Instruction Wizard

STEP 7-Micro/WIN offers the PID Wizard to guide you in defining a PID algorithm for a closed-loop control process. Select the **Tools > Instruction Wizard** menu command and then select **PID** from the Instruction Wizard window.

Tip

The setpoint of the low range and the setpoint of the high range should correspond to the process variable low range and high range.

Understanding the PID Algorithm

In steady state operation, a PID controller regulates the value of the output so as to drive the error (e) to zero. A measure of the error is given by the difference between the setpoint (SP) (the desired operating point) and the process variable (PV) (the actual operating point). The principle of PID control is based upon the following equation that expresses the output, M(t), as a function of a proportional term, an integral term, and a differential term:

Output	=	Proportional term	+	Integral term	+	Differential term
M(t)	=	$K_C * e$	+	$K_C \int_0^t e\,dt + M_{initial}$	+	$K_C * de/dt$

where:
- $M_{(t)}$ is the loop output as a function of time
- K_C is the loop gain
- e is the loop error (the difference between setpoint and process variable)
- $M_{initial}$ is the initial value of the loop output

In order to implement this control function in a digital computer, the continuous function must be quantized into periodic samples of the error value with subsequent calculation of the output. The corresponding equation that is the basis for the digital computer solution is:

M_n	=	$K_c * e_n$	+	$K_I * \sum_1^n e_x + M_{initial}$	+	$K_D * (e_n - e_{n-1})$
output	=	proportional term	+	integral term	+	differential term

where:
- M_n is the calculated value of the loop output at sample time n
- K_C is the loop gain
- e_n is the value of the loop error at sample time n
- e_{n-1} is the previous value of the loop error (at sample time n – 1)
- e_x is the value of the loop error at sample time x
- K_I is the proportional constant of the integral term
- $M_{initial}$ is the initial value of the loop output
- K_D is the proportional constant of the differential term

From this equation, the integral term is shown to be a function of all the error terms from the first sample to the current sample. The differential term is a function of the current sample and the previous sample, while the proportional term is only a function of the current sample. In a digital computer, it is not practical to store all samples of the error term, nor is it necessary.

Since the digital computer must calculate the output value each time the error is sampled beginning with the first sample, it is only necessary to store the previous value of the error and the previous value of the integral term. As a result of the repetitive nature of the digital computer solution, a simplification in the equation that must be solved at any sample time can be made. The simplified equation is:

M_n	=	$K_c * e_n$	+	$K_I * e_n + MX$	+	$K_D * (e_n - e_{n-1})$
output	=	proportional term	+	integral term	+	differential term

where:
- M_n is the calculated value of the loop output at sample time n
- K_C is the loop gain
- e_n is the value of the loop error at sample time n
- e_{n-1} is the previous value of the loop error (at sample time n – 1)
- K_I is the proportional constant of the integral term
- MX is the previous value of the integral term (at sample time n – 1)
- K_D is the proportional constant of the differential term

The S7-200 uses a modified form of the above simplified equation when calculating the loop output value. This modified equation is:

$\mathbf{M_n}$	=	$\mathbf{MP_n}$	+	$\mathbf{MI_n}$	+	$\mathbf{MD_n}$
output	=	proportional term	+	integral term	+	differential term

where:
- Mn is the calculated value of the loop output at sample time n
- MP_n is the value of the proportional term of the loop output at sample time n
- MI_n is the value of the integral term of the loop output at sample time n
- MDn is the value of the differential term of the loop output at sample time n

Understanding the Proportional Term of the PID Equation

The proportional term MP is the product of the gain (K_C), which controls the sensitivity of the output calculation, and the error (e), which is the difference between the setpoint (SP) and the process variable (PV) at a given sample time. The equation for the proportional term as solved by the S7-200 is:

$$MP_n = K_C * (SP_n - PV_n)$$

where:
- MPn is the value of the proportional term of the loop output at sample time n
- K_C is the loop gain
- SP_n is the value of the setpoint at sample time n
- PV_n is the value of the process variable at sample time n

Understanding the Integral Term of the PID Equation

The integral term MI is proportional to the sum of the error over time. The equation for the integral term as solved by the S7-200 is:

$$MI_n = K_C * T_S / T_I * (SP_n - PV_n) + MX$$

where:
- MI_n is the value of the integral term of the loop output at sample time n
- K_C is the loop gain
- T_S is the loop sample time
- T_I is the integration period of the loop (also called the integral time or reset)
- SP_n is the value of the setpoint at sample time n
- PV_n is the value of the process variable at sample time n
- MX is the value of the integral term at sample time n – 1 (also called the integral sum or the bias)

The integral sum or bias (MX) is the running sum of all previous values of the integral term. After each calculation of MI_n, the bias is updated with the value of MI_n which might be adjusted or clamped (see the section “Variables and Ranges” for details). The initial value of the bias is typically set to the output value ($M_{initial}$) just prior to the first loop output calculation. Several constants are also part of the integral term, the gain (K_C), the sample time (T_S), which is the cycle time at which the PID loop recalculates the output value, and the integral time or reset (T_I), which is a time used to control the influence of the integral term in the output calculation.

Understanding the Differential Term of the PID Equation

The differential term MD is proportional to the change in the error. The S7-200 uses the following equation for the differential term:

$$MD_n = K_C * T_D / T_S * ((SP_n - PV_n) - (SP_{n-1} - PV_{n-1}))$$

To avoid step changes or bumps in the output due to derivative action on setpoint changes, this equation is modified to assume that the setpoint is a constant ($SP_n = SP_{n-1}$). This results in the calculation of the change in the process variable instead of the change in the error as shown:

$$MD_n = K_C * T_D / T_S * (SP_n - PV_n - SP_n + PV_{n-1})$$

or just:

$$MD_n = K_C * T_D / T_S * (PV_{n-1} - PV_n)$$

where:

MD_n	is the value of the differential term of the loop output at sample time n
K_C	is the loop gain
T_S	is the loop sample time
T_D	is the differentiation period of the loop (also called the derivative time or rate)
SP_n	is the value of the setpoint at sample time n
SP_{n-1}	is the value of the setpoint at sample time n–1
PV_n	is the value of the process variable at sample time n
PV_{n-1}	is the value of the process variable at sample time n–1

The process variable rather than the error must be saved for use in the next calculation of the differential term. At the time of the first sample, the value of PV_{n-1} is initialized to be equal to PV_n.

Selecting the Type of Loop Control

In many control systems, it might be necessary to employ only one or two methods of loop control. For example, only proportional control or proportional and integral control might be required. The selection of the type of loop control desired is made by setting the value of the constant parameters.

If you do not want integral action (no “I” in the PID calculation), then a value of infinity “INF”, should be specified for the integral time (reset). Even with no integral action, the value of the integral term might not be zero, due to the initial value of the integral sum MX.

If you do not want derivative action (no “D” in the PID calculation), then a value of 0.0 should be specified for the derivative time (rate).

If you do not want proportional action (no “P” in the PID calculation) and you want I or ID control, then a value of 0.0 should be specified for the gain. Since the loop gain is a factor in the equations for calculating the integral and differential terms, setting a value of 0.0 for the loop gain will result in a value of 1.0 being used for the loop gain in the calculation of the integral and differential terms.

Converting and Normalizing the Loop Inputs

A loop has two input variables, the setpoint and the process variable. The setpoint is generally a fixed value such as the speed setting on the cruise control in your automobile. The process variable is a value that is related to loop output and therefore measures the effect that the loop output has on the controlled system. In the example of the cruise control, the process variable would be a tachometer input that measures the rotational speed of the tires.

Both the setpoint and the process variable are real world values whose magnitude, range, and engineering units could be different. Before these real world values can be operated upon by the PID instruction, the values must be converted to normalized, floating-point representations.

The first step is to convert the real world value from a 16-bit integer value to a floating-point or real number value. The following instruction sequence is provided to show how to convert from an integer value to a real number.

```
ITD     AIW0, AC0        //Convert an input value to a double word
DTR     AC0,  AC0        //Convert the 32-bit integer to a real number
```

The next step is to convert the real number value representation of the real world value to a normalized value between 0.0 and 1.0. The following equation is used to normalize either the setpoint or process variable value:

$$R_{Norm} = ((R_{Raw} / Span) + Offset)$$

where: R_{Norm} is the normalized, real number value representation of the real world value
R_{Raw} is the un-normalized or raw, real number value representation of the real world value
Offset is 0.0 for unipolar values
is 0.5 for bipolar values
Span is the maximum possible value minus the minimum possible value:
= 32,000 for unipolar values (typical)
= 64,000 for bipolar values (typical)

The following instruction sequence shows how to normalize the bipolar value in AC0 (whose span is 64,000) as a continuation of the previous instruction sequence:

```
/R      64000.0,  AC0    //Normalize the value in the accumulator
+R      0.5,  AC0        //Offset the value to the range from 0.0 to 1.0
MOVR    AC0,  VD100      //Store the normalized value in the loop TABLE
```

Converting the Loop Output to a Scaled Integer Value

The loop output is the control variable, such as the throttle setting of the cruise control on an automobile. The loop output is a normalized, real number value between 0.0 and 1.0. Before the loop output can be used to drive an analog output, the loop output must be converted to a 16-bit, scaled integer value. This process is the reverse of converting the PV and SP to a normalized value. The first step is to convert the loop output to a scaled, real number value using the formula given below:

$$R_{Scal} = (M_n - Offset) * Span$$

where: R_{Scal} is the scaled, real number value of the loop output
M_n is the normalized, real number value of the loop output
Offset is 0.0 for unipolar values
is 0.5 for bipolar values
Span is the maximum possible value minus the minimum possible value
= 32,000 for unipolar values (typical)
= 64,000 for bipolar values (typical)

The following instruction sequence shows how to scale the loop output:

```
MOVR    VD108,  AC0       //Moves the loop output to the accumulator
-R      0.5,  AC0         //Include this statement only if the value is bipolar
*R      64000.0,  AC0     //Scales the value in the accumulator
```

Next, the scaled, real number value representing the loop output must be converted to a 16-bit integer. The following instruction sequence shows how to do this conversion:

```
ROUND   AC0, AC0          //Converts the real number to a 32-bit integer
DTI     AC0,  LW0         //Converts the value to a 16-bit integer
MOVW    LW0, AQW0         //Writes the value to the analog output
```

Forward- or Reverse-Acting Loops

The loop is forward-acting if the gain is positive and reverse-acting if the gain is negative. (For I or ID control, where the gain value is 0.0, specifying positive values for integral and derivative time will result in a forward-acting loop, and specifying negative values will result in a reverse-acting loop.)

Variables and Ranges

The process variable and setpoint are inputs to the PID calculation. Therefore the loop table fields for these variables are read but not altered by the PID instruction.

The output value is generated by the PID calculation, so the output value field in the loop table is updated at the completion of each PID calculation. The output value is clamped between 0.0 and 1.0. The output value field can be used as an input by the user to specify an initial output value when making the transition from manual control to PID instruction (auto) control of the output. (See the discussion in the “Modes” section below).

If integral control is being used, then the bias value is updated by the PID calculation and the updated value is used as an input in the next PID calculation. When the calculated output value goes out of range (output would be less than 0.0 or greater than 1.0), the bias is adjusted according to the following formulas:

$$MX = 1.0 - (MP_n + MD_n) \quad \textit{when the calculated output } M_n > 1.0$$

or

$$MX = -(MP_n + MD_n) \quad \textit{when the calculated output } M_n < 0.0$$

where:
- MX is the value of the adjusted bias
- MP_n is the value of the proportional term of the loop output at sample time n
- MD_n is the value of the differential term of the loop output at sample time n
- M_n is the value of the loop output at sample time n

By adjusting the bias as described, an improvement in system responsiveness is achieved once the calculated output comes back into the proper range. The calculated bias is also clamped between 0.0 and 1.0 and then is written to the bias field of the loop table at the completion of each PID calculation. The value stored in the loop table is used in the next PID calculation.

The bias value in the loop table can be modified by the user prior to execution of the PID instruction in order to address bias value problems in certain application situations. Care must be taken when manually adjusting the bias, and any bias value written into the loop table must be a real number between 0.0 and 1.0.

A comparison value of the process variable is maintained in the loop table for use in the derivative action part of the PID calculation. You should not modify this value.

Modes

There is no built-in mode control for S7-200 PID loops. The PID calculation is performed only when power flows to the PID box. Therefore, “automatic” or “auto” mode exists when the PID calculation is performed cyclically. “Manual” mode exists when the PID calculation is not performed.

The PID instruction has a power-flow history bit, similar to a counter instruction. The instruction uses this history bit to detect a 0-to-1 power-flow transition. When the power-flow transition is detected, it will cause the instruction to perform a series of actions to provide a bumpless change from manual control to auto control. In order for change to auto mode control to be bumpless, the value of the output as set by the manual control must be supplied as an input to the PID instruction (written to the loop table entry for M_n) before switching to auto control. The PID instruction performs the following actions to values in the loop table to ensure a bumpless change from manual to auto control when a 0-to-1 power-flow transition is detected:

- Sets setpoint (SP_n) = process variable (PV_n)
- Sets old process variable (PV_{n-1}) = process variable (PV_n)
- Sets bias (MX) = output value (M_n)

The default state of the PID history bits is “set” and that state is established at startup and on every STOP-to-RUN mode transition of the controller. If power flows to the PID box the first time that it is executed after entering RUN mode, then no power-flow transition is detected and the bumpless mode change actions are not performed.

Alarm Checking and Special Operations

The PID instruction is a simple but powerful instruction that performs the PID calculation. If other processing is required such as alarm checking or special calculations on loop variables, these must be implemented using the basic instructions supported by the S7-200.

Error Conditions

When it is time to compile, the CPU will generate a compile error (range error) and the compilation will fail if the loop table start address or PID loop number operands specified in the instruction are out of range.

Certain loop table input values are not range checked by the PID instruction. You must take care to ensure that the process variable and setpoint (as well as the bias and previous process variable if used as inputs) are real numbers between 0.0 and 1.0.

If any error is encountered while performing the mathematical operations of the PID calculation, then SM1.1 (overflow or illegal value) is set and execution of the PID instruction is terminated. (Update of the output values in the loop table could be incomplete, so you should disregard these values and correct the input value causing the mathematical error before the next execution of the loop’s PID instruction.)

Loop Table

The loop table is 80 bytes long and has the format shown in Table 6-44.

Table 6-44 Loop Table

Offset	Field	Format	Type	Description
0	Process variable (PV_n)	REAL	In	Contains the process variable, which must be scaled between 0.0 and 1.0.
4	Setpoint (SP_n)	REAL	In	Contains the setpoint, which must be scaled between 0.0 and 1.0.
8	Output (M_n)	REAL	In/Out	Contains the calculated output, scaled between 0.0 and 1.0.
12	Gain (K_C)	REAL	In	Contains the gain, which is a proportional constant. Can be a positive or negative number.
16	Sample time (T_S)	REAL	In	Contains the sample time, in seconds. Must be a positive number.
20	Integral time or reset (T_I)	REAL	In	Contains the integral time or reset, in minutes. Must be a positive number.
24	Derivative time or rate (T_D)	REAL	In	Contains the derivative time or rate, in minutes. Must be a positive number.
28	Bias (MX)	REAL	In/Out	Contains the bias or integral sum value between 0.0 and 1.0.
32	Previous process variable (PV_{n-1})	REAL	In/Out	Contains the value of the process variable stored from the last execution of the PID instruction.
36 to 79	Reserved for auto-tuning variables. Refer to Table 15-1 for details.			