RHE2X/4X
Desktop Reference PID Controller

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Rheonik Messtechnik GmbH
Rudolf-Diesel-Straße 5
D-85235 Odelzhausen
Germany

Tel + 49 (0)8134 9341-0
info@rheonik.com

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RHE2X/4X Transmitter

Addendum Desktop Reference PID Controller

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Baseline reference:
Version 0.10 of this document reflects the properties of the RHE2X and RHE4X firmware version 2.07 and later. The corresponding version of the RHEComPro program is 3.1.3 or later.

1 Introduction

Starting with the Release 2.07 of the RHE2X and RHE4X Firmware a PID Controller feature has been added to be configured for the 4-20mA Analog Outputs when the RHE transmitter is ordered with an option which includes the Assurance Factor feature (e.g. option codes AF, OG, CT, and FF). The PID Controller feature allows the generation of a constant mass or volume flow when the output is attached to a pump or a valve which allows the modulation of the mass or volume flow through the respective RHM sensor.

This document describes the theoretic operation in the next section, followed by the parameterization, and some practical parameter sets. Since there are at least two methods to describe parameterize PID Controls please familiarize yourself with the meaning of the parameters described in the next section. Should you want to apply known PID parameters this sections either explains whether your parameters can be used as they are or how they are to be converted.

2 Theory of Operation for the Rheonik PID Controller

2.1 Input Signal Conditioning

In order to determine the parameters of the PID controller it is important to know the time delay implied by the data flow through the RHE transmitter. The following diagram shows the data flow of the Mass and Volume Flow data inside the RHE transmitter from the phase measurement to the 4-20mA Analog Output drivers.

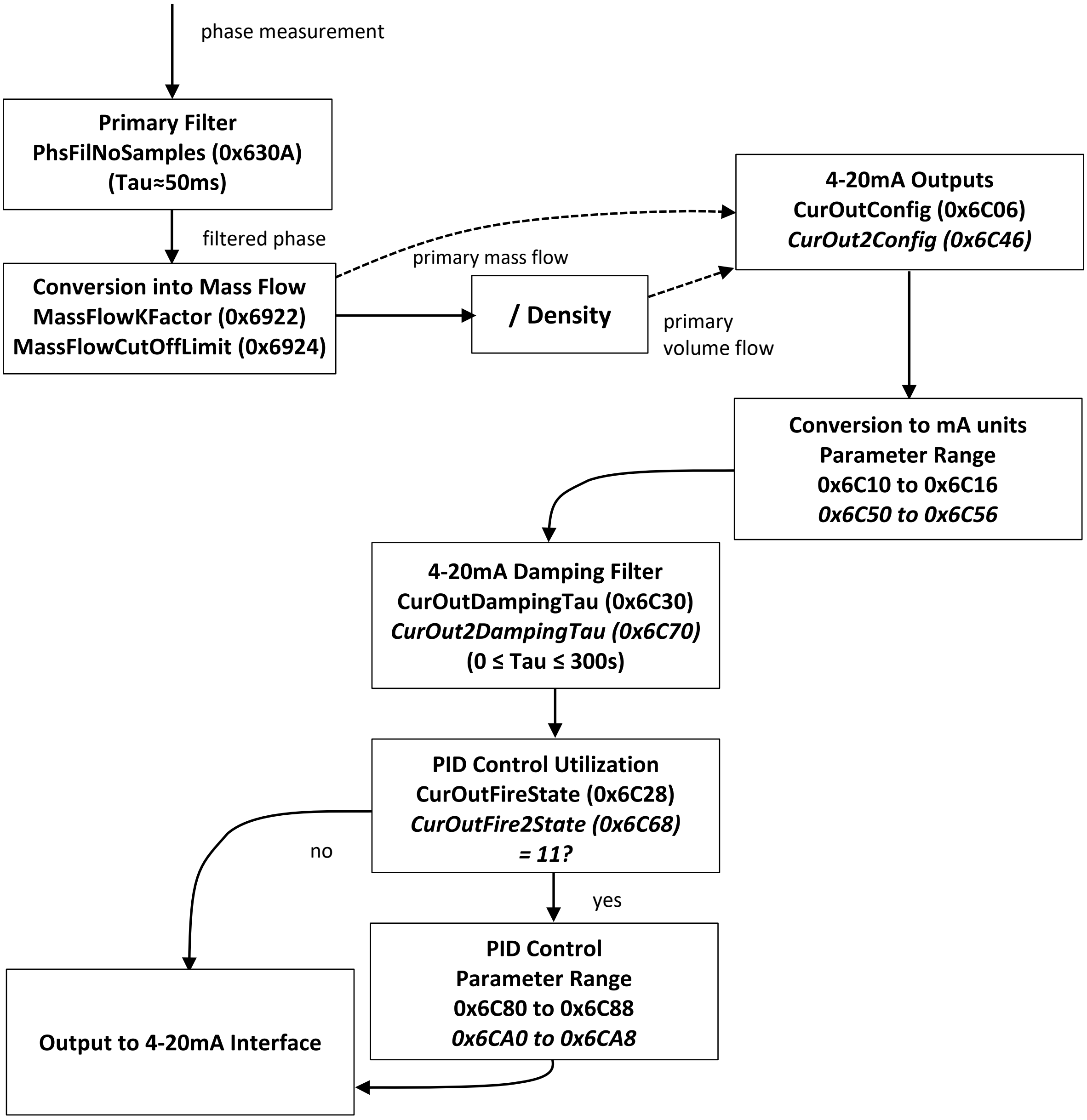

Figure 1: Filtering of the Mass or Volume Flow as Input of the PID Control

In general it is recommended to set the size of the primary filter (PhsFilNoSamples [0x630A]) to 5 (around 50ms depending on the RHM frequency) for precise measurements of a non-uniform mass flow. For a uniform mass flow the 4-20mA Damping Filter can be disabled (CurOutDampingTau=0). This results in a signal delay time due to the primary filter of around 50ms to which a time span of 70ms for RHE-internal data processing has to be added, resulting in a total delay for the input signal of about 120ms.

When a RHE4X with “Fast Filling” option is configured for a fast response time the total signal delay may be reduced to 20ms or less. Currently, such configurations are determined solely by Rheonik for special applications, but are expected to become available to customers for self-configuration rather soon.

For unsteady mass flows, e.g. caused by piston pumps, the input signal of the PID controller must be filtered in a manner that the signal gets steady enough to allow a non-oscillating control loop. In this case the 4-20mA Damping Filter must be configured with a time constant of sufficient size. The effect of the Damping Filter may be tested by outputting the dampened signal directly to the 4-20mA interface, e.g. by setting CurOutFireState temporarily to 0. It should be evident, that a heavily dampened signal also will add significantly to the time delay of the input signal. The selected Tau value should be added to the mentioned signal delay of 120ms in order to obtain the total signal delay.

In order to smoothen possible interferences of the 10ms calculation cycle and the RHM sensor cycle the time constant Tau 4-20mA Damping Filter should be set to at least 0,1s when the differential portion of the PID controller is used ($K_D \neq 0$).

To the total signal delay additional delays caused by the final control element such as a valve or a pump must be added to determine a total loop delay. This total loop delay is important when the stability of the control loop and possible range of the “K” parameters is considered.

The mass or volume flow is converted to mA units before the resulting (virtual) mA signal is filtered by the Damping Filter. The result of the conversion will not necessarily lie in the range of 4 to 20mA and even may be negative. It is important that the signal around the target value lies in the range of 4 to 20mA.

A simple input parameterization will map the nominal range of the RHM sensor to the 4-20mA output range and then calculate the target value respectively. For example, assuming an RHM20 in parallel configuration the maximum mass flow parameter CurOutCompMsFlwRtMax (0x6C10) is set to 300kg/min and the minimum mass flow parameter CurOutCompMsFlwRtMin (0x6C12) is set to 0kg/min. A target mass flow of 150kg/min is converted to the respective mA range with the help of the following formula:

$$target\ [mA] = target\ \left[\frac{kg}{min}\right] * \left(\frac{CurOutCurMax - CurOutCurMin}{CurOutCompMsFlwRtMax - CurOutCompMsFlwRtMin}\right) + CurOutCurMin$$

Since CurOutCurMax is recommended to remain at 20mA and CurOutCurMin at 4mA this can be simplified to

$$target\ [mA] = target\ \left[\frac{kg}{min}\right] * \left(\frac{16\ [mA]}{CurOutCompMsFlwRtMax - CurOutCompMsFlwRtMin}\right) + 4\ [mA]$$

and applied to the example

$$target\ [mA] = 12\ [mA] = \ 150\ \left[\frac{kg}{min}\right] * \left(\frac{16\ [mA]}{300\ \left[\frac{kg}{min}\right]}\right) + 4\ [mA]$$

In the example above we also could set CurOutCompMsFlwRtMax to 180kg/min and CurOutCompMsFlwRtMin to 120kg/min which also would result in a target current of 12mA. However, this would cause an implicit amplification of the input signal (by 5) which has to be considered when determining the “K” parameters of the control loop, see section 2.2.

Therefore, it is recommended to keep the defined mass or volume flow input range constant when adapting the “K” parameters in order to optimize the behavior of the control loop. In order to keep the calculation simple the specified minimum flow should be zero. Since the internal calculation is done with the help of IEEE floating point numbers the “K” parameters of the PID Controller may be defined in a wide range and there is no need to shift the input range to achieve a higher resolution or pre-amplification in the input signal path.

2.2 PID Controller Type

The PID Controller is implemented in a “parallel” fashion which has the form

$$u(t) = K_P * e(t) + K_I * \int e(t)dt + K_D * \frac{de(t)}{dt}$$

where *e(t)* is the tracking error, the difference of the desired output *r(t)* and the measured output *y(t)*

$$e(t) = r(t) - y(t)$$

and *u(t)* is the control output. The following table shows the assignment of the terms above to their Modbus registers. For a complete set of Modbus parameters related to the PID control see section 3.

Term	**Modbus Address**	**Register Name**	**Unit**
$y(t)$	0x4900 0x4A00	MassFlowRate or VolumetricFlowRate converted to mA and filtered, see section 2.1.	mA
Initial $r(t)$	0x6C80 *0x6CA0*	CurOutPIDInitTarget *CurOut2PIDInitTarget*	mA
$r(t)$	0x6C82 *0x6CA2*	CurOutPIDCurrTarget *CurOut2PIDCurrTarget*	mA
K_P	0x6C84 *0x6CA4*	CurOutPIDPropFactor *CurOut2PIDPropFactor*	Unit-less.
K_I	0x6C86 *0x6CA6*	CurOutPIDIntFactor *CurOut2PIDIntFactor*	1/s does not depend on dt.
K_D	0x6C88 *0x6CA8*	CurOutPIDDiffFactor *CurOut2PIDDiffFactor*	s does not depend on dt.
$u(t)$	0x4000 *0x4002*	CurrOut *CurrOut2*	mA
dt		10ms fixed. The PID control calculations are done cyclic in 10ms intervals (100Hz).	

The desired target value will be set to the initial target, e.g. CurOutPIDInitTarget, and may be modified by writing to the current target register, e.g. CurOutPIDCurrTarget. A write to this register has an immediate effect. Thus, a desired target value may be changed without resetting the RHE transmitter. This is also useful to check the response of the entire control loop to a step in the target value.

Currently, the PID Controller does not implement an automatic determination of the “K” parameters. In order to determine meaningful parameter set please refer to

https://en.wikipedia.org/wiki/PID_controller

and its “Manual tuning” or “Ziegler–Nichols method” sections.

The PID Control also may be specified slightly different in a (ISO) standard fashion which has the form

$$u(t) = K_P * \left(e(t) + \frac{1}{T_N} * \int e(t)dt + T_V * \frac{de(t)}{dt} \right)$$

Should you already have a working control loop in the standard fashion with known K_P, T_N and T_V parameters the constants of the “parallel” form may be calculated as

$$K_I = \frac{K_P}{T_N}$$

and

$$K_D = K_P * T_V$$

The reason to implement the parallel form is that the manual tuning process appears to be easier in this form where all three parameters are independent from each other.

3 PID Parameterization in the RHE Transmitter

Each of the possible two optional 4-20mA Analog Output interfaces of an RHE transmitter features a separate PID controller together with separate parameter sets. The table below shows the relevant parameters for the first Analog Output interface in normal typeface and for the second Analog Output Interface in italics.

Modbus Address	Register Name	Description
0x6C06 *0x6C46*	CurOutConfig *CurOut2Config*	**Current Output 1 Configuration:** Assigns an output channel to the current output 1 (*2*): 0 – Analog output is off. 1 – Analog output is configured for Mass Flow (default). 2 – Analog output is configured for Volumetric Flow. 3 – Analog output is configured for Density. 4 – Analog output is configured for Tube Temperature. 5 – Analog output is configured for Torsion Bar Temperature. 6 – Drive Gain 7 – Assurance Factor (since release 2.07)
0x6C10 *0x6C50*	CurOutCompMsFlwRtMax *CurOut2CompMsFlwRtMax*	**Current Output 1 (*2*) Compensated Mass Flow Rate Maximum:** Upper scale value used when CurOutConfig is set to 1. The mass flow value in this register corresponds to the CurOutCurMax value (i.e. it is the maximum output range). This value is based on the unit specified in the MassFlowUnit holding register (0x6106).
0x6C12 *0x6C52*	CurOutCompMsFlwRtMin *CurOut2CompMsFlwRtMin*	**Current Output 1 (*2*) Compensated Mass Flow Rate Minimum:** Lower scale value used when CurOutConfig is set to 1. The mass flow value in this register corresponds to the CurOutCurMin value (i.e. it is the minimum output range). This value is based on the unit specified in the MassFlowUnit holding register (0x6106).
0x6C14 *0x6C54*	CurOutCompVolMax *CurOut2CompVolMax*	**Current Output 1 (*2*) Compensated Volume Maximum:** Upper scale value used when CurOutConfig is set to 2. The volumetric flow value in this register corresponds to the CurOutCurMax value (i.e. it is the maximum output range). This value is based on the unit specified in the VolumeFlowUnit holding register (0x610A).
0x6C16 0*x6C56*	CurOutCompVolMin *CurOut2CompVolMin*	**Current Output 1 (*2*) Compensated Volume Minimum:** Lower scale value used when CurOutConfig is set to 2. The volumetric flow value in this register corresponds to the CurOutCurMin value (i.e. it is the minimum output range). This value is converted from (write) or to (read) the unit specified in the VolumeFlowUnit holding register (0x610A).

Modbus Address	Register Name	Description
0x6C28 *0x6C68*	CurOutFireState *CurOut2FireState*	**Current Output 1 (*2*) Fire State:** Determines the behavior ("fail high" or "fail low") and value of the analog output when analog range is exceeded (values 1 to 5), i.e. the output is above the upper (CurOutCurMax) or is below the lower (CurOutCurMin) limits, or an error condition exists in the SoftError (0x401C) or ErrorStatus (0x401A) fields (values 6 to 10). 0 – Output tracks the signal and clamps at the CurOutMaxCur and CurOutMinCur values when its range is exceeded (default). 1 – 22 mA : range exceeded only 2 – 0 mA : range exceeded only (not for RHE4X, has 3.2mA minimum) 3 – 2 mA : range exceeded only (not for RHE4X, has 3.2mA minimum) 4 – 3.2 mA : range exceeded only 5 – 3.6 mA : range exceeded only 6– 22 mA : error condition exists only 7– 0 mA : error condition exists only (not for RHE4X, has 3.2mA minimum) 8– 2 mA : error condition exists only (not for RHE4X, has 3.2mA minimum) 9 – 3.2 mA : error condition exists only 10 – 3.6 mA : error condition exists only 11 – Engage PID Control For the PID Control the measurement selection in CurOutConfig (0x6C06) must be less than 5.
0x6C30 *0x6C70*	CurOutDampingTau *CurOut2DampingTau*	**Current Output 1 (*2*) Damping Tau:** Time constant (Tau) of the current output damping in seconds. An exponential damping mechanism is used within a defined band, see CurOutDampingBand (0x6C32). When the output values leave the defined band the damping is disabled. A value of 0.0 disables the damping.
0x6C32 *0x6C72*	CurOutDampingBand *CurOut2DampingBand*	**Current Output 1 (*2*) Damping Band:** Defines the band range for the damping of the current output in percent of the range between CurOutCurMin (0x6C0A) and CurOutCurMax (0x6C08) 20mA. A value of 100 makes sure that the values never leave the band and that the damping always is active.
0x6C80 *0x6CA0*	CurOutPIDInitTarget *CurOut2PIDInitTarget*	**Current Output PID Initial Target:** Initial target value for the PID controller of the first (*second*) current output interface. This value must be in the range of CurOutCurMin (0x6C0A) to CurOutCurMax (0x6C08), otherwise a configuration error is signaled. This value and the registers in the range of 0x6C80 to 0x6C88 are used only when CurOutFireState (0x6C28) is set to 11.
0x6C82 *0x6CA2*	CurOutPIDCurrTarget *CurOut2PIDCurrTarget*	**Current Output PID Current Target:** Current target value for the PID controller of the first (*second*) current output interface. This register is initialized to the value in CurOutPIDInitTarget (0x6C80) and may be overwritten any time. A new value will have an immediate effect.
0x6C84 *0x6CA4*	CurOutPIDPropFactor *CurOut2PIDPropFactor*	**Current Output PID Proportional Factor:** Proportional factor for the PID controller of the first (*second*) current output interface. This value may be negative for inverted controls loops.
0x6C86 *0x6CA6*	CurOutPIDIntFactor *CurOut2PIDIntFactor*	**Current Output PID Integral Factor:** Integral factor for the PID controller of the first (*second*) current output interface. This value may be negative for inverted controls loops.

Modbus Address	Register Name	Description
0x6C88 *0x6CA8*	CurOutPIDDiffFactor *CurOut2PIDDiffFactor*	**Current Output PID Differential Factor:** Differential factor for the PID controller of the first (*second*) current output interface. This value may be negative for inverted controls loops.

The descriptions should make the functionality of each parameter clear. The target value in CurOutPIDCurrTarget is set to CurOutPIDInitTarget during the initialization of the RHE. Thereafter, it may be modified by Modbus accesses and any new value will have an immediate effect. Thus, the initial target may be set to zero and the flow may be started by a supervisory system by writing a non-zero target value into CurOutPIDCurrTarget. Furthermore, this feature can be used to study the step response of the entire control loop by modifying this parameter with the help of the RHEComPro program.

4 Some PID Parameter Examples

The following table shows the PID control parameters for a turbine-type pump with 1000kg/min capacity.

Modbus Address	Register Name	Value
0x6C06 *0x6C46*	CurOutConfig *CurOut2Config*	1 – Analog output is configured for Mass Flow (default).
0x6C10 *0x6C50*	CurOutCompMsFlwRtMax *CurOut2CompMsFlwRtMax*	1000 [kg/min}
0x6C12 *0x6C52*	CurOutCompMsFlwRtMin *CurOut2CompMsFlwRtMin*	0 [kg/min]
0x6C28 *0x6C68*	CurOutFireState *CurOut2FireState*	11 – Engage PID Control
0x6C30 *0x6C70*	CurOutDampingTau *CurOut2DampingTau*	3 [s] (see section 2.1)
0x6C32 *0x6C72*	CurOutDampingBand *CurOut2DampingBand*	100 [%]
0x6C80 *0x6CA0*	CurOutPIDInitTarget *CurOut2PIDInitTarget*	0 [kg/min] For a start without mass flow.
0x6C82 *0x6CA2*	CurOutPIDCurrTarget *CurOut2PIDCurrTarget*	12 [mA] (≈500 [kg/min]) Or similar value set when the mass flow is to be started.
0x6C84 *0x6CA4*	CurOutPIDPropFactor *CurOut2PIDPropFactor*	0,6
0x6C86 *0x6CA6*	CurOutPIDIntFactor *CurOut2PIDIntFactor*	0,24 [1/s]
0x6C88 *0x6CA8*	CurOutPIDDiffFactor *CurOut2PIDDiffFactor*	0,38 [s]

Due to some shortcomings of the pump-internal control unit the resulting flow was smooth in the range of 30% to 100% of the capacity, but showed some severe instabilities below 30% which could not be compensated to obtain a smooth flow pattern.

The next table shows the PID control parameters for a pneumatic valve with 1000kg/min capacity. This valve featured a slow response to its control inputs and it therefore was difficult to achieve a stable mass flow.

Modbus Address	Register Name	Value
0x6C06 *0x6C46*	CurOutConfig *CurOut2Config*	1 – Analog output is configured for Mass Flow (default).
0x6C10 *0x6C50*	CurOutCompMsFlwRtMax *CurOut2CompMsFlwRtMax*	1000 [kg/min}
0x6C12 *0x6C52*	CurOutCompMsFlwRtMin *CurOut2CompMsFlwRtMin*	0 [kg/min]
0x6C28 *0x6C68*	CurOutFireState *CurOut2FireState*	11 – Engage PID Control
0x6C30 *0x6C70*	CurOutDampingTau *CurOut2DampingTau*	3 [s] (see section 2.1)
0x6C32 *0x6C72*	CurOutDampingBand *CurOut2DampingBand*	100 [%]
0x6C80 *0x6CA0*	CurOutPIDInitTarget *CurOut2PIDInitTarget*	0 [kg/min] For a start without mass flow.

Modbus Address	**Register Name**	**Value**
0x6C82 *0x6CA2*	CurOutPIDCurrTarget *CurOut2PIDCurrTarget*	8 [mA] (≈250 [kg/min]) Or similar value set when the mass flow is to be started.
0x6C84 *0x6CA4*	CurOutPIDPropFactor *CurOut2PIDPropFactor*	0,6
0x6C86 *0x6CA6*	CurOutPIDIntFactor *CurOut2PIDIntFactor*	0,2 [1/s]
0x6C88 *0x6CA8*	CurOutPIDDiffFactor *CurOut2PIDDiffFactor*	1 [s]

Due to the non-linearity of the valve characteristics above 50% of its capacity and its slow response time this configuration could be used only be below this limit. In principle it could be possible to govern both items, pump and valve, with both analog output interfaces when they are parameterized in a manner that there is a defined mass flow, e.g. 50% of the total capacity, at which a takeover from one item to the other occurs.

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Rheonik Messtechnik GmbH
Rudolf-Diesel-Straße 5
D-85235 Odelzhausen
Germany

Tel + 49 (0)8134 9341-0
info@rheonik.com