Solution algorithms of an automated control system for a technological process of thermal vortex enrichment

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Abstract. As a part of the development of a comprehensive resource-saving technology and the organization of high-tech production of nanostructures based on carbon and silicon dioxide to improve the properties of building and structural materials, the algorithms for the software package Automated Control System for the Technological Process for Obtaining Concentrates of MD1 and MD2 Nanostructures are described in part providing thermal vortex enrichment. Algorithms have been developed for controlling an analog value according to the PID control law, stopping the production line in emergency mode, and regenerating bag filters as they become clogged. The purpose and characteristics of the processes, the information used, the results of the solution, the decision algorithms and the requirements for the test example are described.

1. Introduction

To create the ecological technologies [1–5] and software package “Automated control system for the technological process of obtaining concentrates of nanostructures MD1 and MD2” in terms of providing thermal vortex enrichment [6–10], a survey was carried out that revealed processes subject to control by an analogue value according to the PID control law such as control of frequency drives, thyristor converters, positioners, and other equipment controlled by an analogous unified signal, with the possibility of manual control and automatic regulation of various process parameters. For such processes, as well as processes in energetics [11–15], shutdown of the production line in emergency mode, regeneration of bag filters as they become clogged, algorithms of automated processes have been developed. The purpose and characteristics of the processes, the information used, the results of the solution, the decision algorithms, and the requirements for the test example are described.

2. PID controller

This algorithm is designed to control the analog value according to the PID control law.

It is used to control frequency drives, thyristor converters, positioners, and other equipment, which are controlled by a unified analog signal, with the possibility of manual control and automatic regulation of various process parameters.

The output is presented in table 1, the intermediate and temporary in table 2, the output in table 3.
Table 1. Input data for the PID controller.

| No | Name of the input information array | Description                                    | Data type | Value range          | Notes          |
|----|------------------------------------|-----------------------------------------------|-----------|----------------------|----------------|
| 1  | COM_RST                           | Resetting the controller (restart)            | Bool      |                      |                |
| 2  | MAN_ON                            | Manual control                                | Bool      |                      |                |
| 3  | P_SEL                             | Inclusion of the P-component of the law       | Bool      |                      |                |
| 4  | I_SEL                             | Inclusion of the I-component of the law       | Bool      |                      |                |
| 5  | D_SEL                             | Inclusion of the D-component of the law       | Bool      |                      |                |
| 6  | NEG                               | Inverting the operation of the controller     | Bool      |                      |                |
| 7  | CYCLE                             | Block call time                               | Time      | T#1ms .. T#9999s    |                |
| 8  | SP_INT                            | Regulation task                               | Real      |                      |                |
| 9  | PV_IN                             | Adjustable value                              | Real      |                      |                |
| 10 | MAN                               | Manual output value                           | Real      | 0 .. 99999           |                |
| 11 | GAIN                              | Gain                                           | Real      |                      |                |
| 12 | TI                                | Integration time                              | Time      | > = CYCLE            |                |
| 13 | TD                                | Differentiation time                          | Time      | > = CYCLE            |                |
| 14 | DEADB_W                           | Dead zone                                     | Real      | > = 0.0              |                |
| 15 | LMN_HLM                           | The upper limit of the output quantity        | Real      | LMN_LLM .. 100.0 ..  |
| 16 | LMN_LLM                           | Lower output limit                            | Real      | -100.0 .. LMN_HLM    |                |

Table 2. Temporary and intermediate data for the PID controller.

| No | Name of the input information array | Description                                    | Data type | Value range       | Notes     |
|----|------------------------------------|-----------------------------------------------|-----------|-------------------|-----------|
| 1  | LMN                                | Control quantity                              | Real      | LMN_LLM .. LMN_HLM|           |
| 2  | STD_PID                            | PID Continuous Controller                     | CONT_C    |                   |           |
| 3  | RETURN_VAL                         | Return value                                  | Word      |                   |           |
| 4  | NGAIN                              | Inverted Gain                                 | Real      |                   |           |

Table 3. Output data for the PID controller.

| No | Name of the input information array | Description                                    | Data type | Value range | Notes |
|----|------------------------------------|-----------------------------------------------|-----------|-------------|-------|
| 1  | PV                                 | Adjustable value                              | Real      |             |       |
| 2  | ER                                 | The amount of mismatch (error)                | ER        |             |       |
| 3  | LMN_VAL                            | DAC control value                             | Int       | 0 .. 27648  |       |
Figure 1 shows the solution algorithm.

![Solution algorithm for the PID controller](image)

**Figure 1.** Solution algorithm for the PID controller.
Test Case Requirements.
The input data is selected from valid ranges of values (table 4).

Table 4. Valid input data for the PID controller.

| No | Name of the input information array | Choice for testing                        |
|----|------------------------------------|--------------------------------------------|
| 1  | COM_RST                           | False                                      |
| 2  | MAN_ON                            | Check the operation with manual control - True, in automatic mode - False |
| 3  | P_SEL                             | True, False                                |
| 4  | I_SEL                             | True, False                                |
| 5  | D_SEL                             | True, False                                |
| 6  | NEG                               | True, False                                |
| 7  | CYCLE                             | T#100ms                                    |
| 8  | SP_INT                            | In the range of values, PV_IN ± 5%         |
| 9  | PV_IN                             | In the range of values                      |
| 10 | MAN                               | In the range of values                      |
| 11 | GAIN                              | In the range of values                      |
| 12 | TI                                | In the range of values                      |
| 13 | TD                                | In the range of values                      |
| 14 | DEADB_W                           | In the range of values                      |
| 15 | LMN_HLM                           | In the range of values                      |
| 16 | LMN_LLM                           | In the range of values                      |
The output is presented in table 5.

Table 5. Test results for the PID controller.

| No | Name of the input information array | Test results |
|----|------------------------------------|--------------|
| 1  | PV                                 | Value PV_IN  |
| 2  | ER                                 | Numeric value - difference between PV_IN - SP_INT |
| 3  | LMN_VAL                            | With MAN_ON = False, the numerical value of the calculated output value in the format for the DAC is according to the regulation law established by P_SEL, I_SEL, D_SEL and the parameters GAIN, TI, TD. When NEG = False, it works in reverse mode ("cooler"). With MAN_ON = True LMN_VAL = MAN |

3. Emergency stop
This algorithm is designed to stop the production line in emergency mode.

It is used to stop the line depending on the state of the process equipment, as well as the values of the process parameters.

The output is presented in table 6, the intermediate and temporary in table 7, the output in table 8.

Table 6. Input data for emergency stop.

| No | Name of the input information array | Description | Data type | Value range | Notes |
|----|------------------------------------|-------------|-----------|-------------|-------|
| 1  | P_out_topk                         | The pressure at the beginning of the swirl tube | Real |  |  |
| 2  | M1_1_on                            | Blower M1-1. Job. | Bool |  |  |
| 3  | M1_1_alarm                         | Blower M1-1. Frequency Drive Failure | Bool |  |  |
| 4  | M2_1_on                            | Smoke exhaust M2-1. Job. | Bool |  |  |
| 5  | M2_1_alarm                         | Smoke exhaust M2-1. Frequency Drive Failure | Bool |  |  |
| 6  | M3_1_on                            | Drive auger feed material M3-1. Job | Bool |  |  |
| 7  | M3_1_alarm                         | Drive auger feed material M3-1. Frequency Drive Failure | Bool |  |  |
| 8  | T_cool                             | Air flow temperature in the cooling duct | Real |  |  |
| 9  | T_vozd_out                         | Air temperature at the outlet of the combustion chamber | Real |  |  |
| 10 | Poloz_5_1                          | Gate 5-1c position | Real |  |  |
| 11 | FREQ_M1_1                          | Blower M1-1. Rotation frequency | Real |  |  |
| 12 | FREQ_M2_1                          | Smoke exhaust M2-1. Rotation frequency | Real |  |  |
Table 7. Temporary and intermediate data for emergency stop.

| No | Name of the input information array | Description                                                                 | Data type | Value range | Notes |
|----|-------------------------------------|-----------------------------------------------------------------------------|-----------|-------------|-------|
| 1  | P_out_topk_Low                       | Lower pressure value at the beginning of the vortex enrichment pipe         | Real      |             |       |
| 2  | T_cool_Hi                           | The upper value of the air flow temperature in the cooling duct             | Real      |             |       |
| 3  | T_vozd_out_Low                      | Lower air temperature at the outlet of the combustion chamber              | Real      |             |       |
| 4  | T_vozd_out_Hi                       | The upper value of the air temperature at the outlet of the combustion chamber | Real      |             |       |
| 5  | T_vozd_out_cool                     | The value of the air temperature at the outlet of the combustion chamber to turn off the M2-1 blower | Real      |             |       |

Table 8. Output for emergency stop.

| No | Name of the input information array | Description                                                                 | Data type | Value range | Notes |
|----|-------------------------------------|-----------------------------------------------------------------------------|-----------|-------------|-------|
| 1  | M1_1_toff                           | Blower M1-1. Switch off                                                    | Bool      |             |       |
| 2  | M2_1_toff                           | Smoke exhaust M2-1. Switch off                                              | Bool      |             |       |
| 3  | M3_1_toff                           | Drive auger feed material M3-1. Switch off                                  | Bool      |             |       |
| 4  | Burn_block                          | Burner. Lock                                                               | Bool      |             |       |

Solution Algorithm:
1. Start
2. Data entry (receiving information about the parameters):
   - P_out_topk
   - T_cool
   - T_vozd_out
   - M1_1_on
   - M1_1_alarm
   - M2_1_on
   - M2_1_alarm
   - M3_1_on
   - M3_1_alarm
3. Condition (emergency check)
   - (P_out_topk<P_out_topk_Low and FREQ_M2_1 = 100) or
   - (T_cool>T_cool_Hi and Poloz_5_1 = 100) or
   - T_vozd_out<T_vozd_out_Low or
   - (T_vozd_out>T_vozd_out_Hi and FREQ_M1_1) or
   - M1_1_on = false or
   - M1_1_alarm = true or
   - M2_1_on = false or
- M2_1_alarm = true or
- M3_1_on = false or
- M3_1_alarm = true

If any of the conditions is fulfilled, then the actions from paragraph 4 are performed.
If not, the survey again occurs.

4. Actions (actions to be taken in the presence of an emergency)
- Burn_block = true
- M1_1_toff = true
- M2_1_toff = true

After the action is completed, the condition from paragraph 5 is checked.

5. Condition (check whether the air from the combustion chamber has cooled down)
- T_vozd_out < T_vozd_out_cool

If the condition is met, then the action from paragraph 6 is performed, otherwise 7.

6. Action (completion of the emergency stop process)
- M3_1_toff = true

7. The end

Test Case Requirements
The input data is selected from the valid ranges of values (table 9).

| No | Name of the input information array | Choice for testing |
|----|------------------------------------|-------------------|
| 1  | P_out_topk                         | In the range of values |
| 2  | M1_1_on                            | False             |
| 3  | M1_1_alarm                         | True              |
| 4  | M2_1_on                            | True              |
| 5  | M2_1_alarm                         | True, False       |
| 6  | M3_1_on                            | True              |
| 7  | M3_1_alarm                         | True              |
| 8  | T_cool                             | In the range of values |
| 9  | T_vozd_out                         | In the range of values |
| 10 | Poloz_5_1                           | In the range of values |
| 11 | FREQ_M1_1                          | In the range of values |
| 12 | FREQ_M2_1                          | In the range of values |
| 13 | P_out_topk                         | In the range of values |

The output is presented in table 10.

| No | Name of the input information array | Test results |
|----|------------------------------------|--------------|
| 1  | M1_1_toff                          | True         |
| 2  | M2_1_toff                          | True         |
| 3  | M3_1_toff                          | True         |
| 4  | Burn_block                          | True         |

4. Bag filter regeneration
This algorithm is designed to regenerate bag filters as they become clogged.

Input data is represented in type REAL (table 11), INT; output data in REAL type (table 12).
### Table 11. Input data for the regeneration of bag filters.

| No | Name of the input information array | Description                                                                 | Data type | Value range | Notes |
|----|-------------------------------------|------------------------------------------------------------------------------|-----------|-------------|-------|
| 1  | P_filtr_razn                        | Pressure difference in clean and dirty bag filter chambers                   | Real      |             |       |
| 2  | N_open                              | Number of openings of the filter bag regeneration valves                     | Real      |             |       |
| 3  | T_open                              | Regeneration valve open time                                                | Real      |             |       |
| 4  | T_close                             | Regeneration Valve Closed Time                                              | Real      |             |       |
| 5  | P_filtr_max                         | The pressure difference in the filter chambers at which regeneration starts  | Real      |             |       |
| 6  | FREQ_M2_1_reg                       | The value of the rotation speed of the exhaust fan M2_1 during the regeneration of filters | Real      |             |       |

### Table 12. Output data for the regeneration of bag filters.

| No | Name of the input information array | Description                                                                 | Data type | Value range | Notes |
|----|-------------------------------------|------------------------------------------------------------------------------|-----------|-------------|-------|
| 1  | Air_filtr_reg                       | Bag Filter Regeneration Signal                                              | Bool      |             |       |
| 2  | M3_1_toff                           | Drive auger feed material M3-1. Switch off                                  | Bool      |             |       |
| 3  | C_FREQ_M2_1                          | Smoke exhaust M2-1. Speed control                                          | Real      |             |       |

Solution Algorithm:
1. Start
2. Data entry (receiving information about the parameters):
   - P_in_filtr
   - P_in_filtr
3. The calculation
   - P_filtr_razn = P_in_filtr - P_in_filtr
4. Condition (comparison of pressure difference with the maximum allowable)
   - P_filtr_razn > P_filtr_max
   When the condition is met, the action in paragraph 5 is performed.
5. Action (regeneration starts)
   - the output parameter Air_filtr_reg is set to true
   - M3_1_toff = true
   - C_FREQ_M2_1 = FREQ_M2_1_reg
   - Air_filtr_reg takes true for the time set by the T_open parameter, then there is a pause equal to the time set in the T_close parameter. The closing opening cycle is repeated the number of times set in the N_open parameter
6. Action (upon completion of regeneration)
   - M3_1_ton = true
7. The end
Test Case Requirements
Input data are selected from the valid ranges of values (table 13).

**Table 13.** Input Values for Bag Filter Regeneration.

| No | Name of the input information array | Choice for testing |
|----|------------------------------------|--------------------|
| 1  | P_in_filtr                         | 0.6                |
| 2  | P_out_filtr                        | 0.0                |
| 3  | P_filtr Razn                       | 0.6                |
| 4  | P_filtr_max                        | 0.5                |
| 5  | N_open                             | 9                  |
| 6  | T_open                             | 2.0                |
| 7  | T_close                            | 2.0                |
| 8  | FREQ_M2_1_reg                      | 50                 |

The output is presented in table 14.

**Table 14.** Test results for emergency stop.

| No | Name of the input information array | Test results |
|----|------------------------------------|--------------|
| 1  | Air_filtr_reg                      | True         |
| 2  | M3_1_toff                          | True         |
| 3  | C_FREQ_M2_1                         | 50           |
| 4  | Burn_block                         | True         |

5. Conclusion
The use of algorithms for controlling the analog value according to the PID law of regulation, stopping the production line in emergency mode, regeneration of bag filters as they become clogged up as part of the Automated Process Control System for the Preparation of MD1 and MD2 Nanostructure Concentrates program in terms of providing thermal vortex enrichment will provide:

- continuous technological control of equipment operation and parameters of the technological process of thermal vortex enrichment;
- process safety in the production of MD1;
- collection of data on technological processes and equipment operation, their processing, display and documentation;
- optimization of the technological process through the use of developed visualization tools, modern control algorithms and analysis of accumulated technological information;
- minimizing the influence of the human factor on the processes of collecting and processing information about the technological process;
- automatic prevention of emergency situations.

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