Implementation of a jig control system at BUDRYK Coal Mine

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Abstract. The article presents conceptual assumptions and achieved functional-utility effects concerning the implementation of control and visualization system of operation of pulsating jigs in the Coal Mechanical Processing Plant of BUDRYK Coal Mine. The system includes six OSM medium-grain and two OM fine jigs. The communication structure of the control system, including the connection with the master controller, is presented. The process of selecting the controller settings, to stabilize the quality parameters of the coal beneficiation, is discussed.

1. Introduction

Pulsating jigs are commonly used in processing plants of Polish mines. This popularity is related, among others, to their reliability and a wide range of grain classes of the feed sent for beneficiation [1]. Coal beneficiation in a jig, which consists in among others, material loosening and transporting, is a complex process, characterized by multidimensionality, non-linearity, fluctuation of parameters and nonstationary character of disturbances. Increasing level of requirements in relation to the quality of coal concentrate, obtained at the jig output, requires to use modern, safer and more reliable control systems. Solutions from the broadly understood field of industrial automation, using modern microprocessor systems, efficient and fast communication modules, come to support. Their implementation enables comprehensive control over the entire production process, its selected fragments or of a single machine.

As a part of development and modernization of the Mechanical Coal Processing Plant at BUDRYK Coal Mine, 8 new jigs, equipped with modern KOGASTER control systems, are implemented. At the time of writing this article, three jigs were put into operation, the remaining ones are under construction.

2. Structure of the jig beneficiation system in BUDRYK Coal Mine

The system installed in the BUDRYK Coal Mine includes 8 jigs, which form three beneficiation systems (Figure 1):

- beneficiation of coal type 34 - 3 OSM jigs,
- beneficiation of coal type 35 - 3 OSM jigs,
- beneficiation of secondary coal - 2 OM jigs.
Each jig is divided into three sections separating the beneficiation products. In the first and second sections the waste product is obtained, in the third section an intermediate product and a concentrate are received. The facility is supplied with coal 34 and 35 by 4 belt conveyors B-1200 (two from each buffer tank). The excess material from the OSM jigs is transported to the secondary beneficiation node. Heavy products from the jigs are received by the B-1000 bucket conveyors. These conveyors are equipped with frequency converters, which allow to adjust their efficiency to the current load [2].

3. **Characteristics of the jig control system**

A correct realization of beneficiation process, taking place in the jig, requires use of an appropriate control system for devices being a part of the node. In the process of hard coal beneficiation, taking place in pulsating jigs, a very important element influencing its proper progress, has an efficient and precise control over raw material feed and output of enriched product [3, 4]. It is related to the need of a complex node automation, which can provide proper interaction of jig with the feed system and bucket conveyors, receiving products from the jig. The combination of controllers of above mentioned machines, the use of distributed input-output modules to operate the executive elements and measuring devices, the use of operator panels and visualization-archiving systems and ensuring reliable data transmission among the automation elements, form an integrated system ensuring comprehensive control of the entire process.

The jigs control system at the BUDRYK Coal Mine is divided into 4 control cabinets. One cabinet supports 2 jigs. In each cabinet there is an independent PLC installed to supervise an operation of two machines. In each of the 3 sections of a jig the following parameters are measured (Figure 2):

- height of the separation layer,
- opening degree of the heavy product bleed gap,
- pressure in the air manifolds,
- pressure in the equalisation reservoirs,
- lower water flow rate.
In addition the following parameters are also measured:
- feed flow rate,
- control air pressure,
- pressure in the hydraulic system,
- load on bucket conveyor motors.

The following devices are also connected to the control cabinet of the jig control system:
- compressor for preparing control air,
- hydraulic aggregate supplying cylinders of heavy products reception systems,
- throttles of lower water supplied to jig,
- throttles of working air.

Controlled parameters are:
- draining flow rate of the heavy product,
- lower water flow rate,
- air pressure in the pulsating chambers,
- speed of the bucket conveyor.

The jig control system strictly cooperates with the master system of the processing plant, which manages the operation of machines supplying the feed to a jig, as well as realizing technological interlocks used to stop the whole or a part of node safely. Figure 3 shows the communication structure among the jigs control systems and the master system.
The communication was carried out using the Profinet network, a universal communication network based on the industrial Ethernet standard. The internal controller of the jigs control system is connected via ModbusTCP. In addition, using this communication standard, the embedded controller will be connected to an additional visualization system, which will be installed in the soundproof operator’s cabin enabling a supervision of the machinery operation.

The diagram showing the procedure of interaction between the master system and the jig control system is shown in Figure 4. A command to switch on the jig is sent from the master system to the jig controller, which first activates the pulsation valves, then it sets the throttle of working air, mounted at the jig input. After the above operations, the information is sent to the master system about the readiness of the jig to switch on the working air blower. After the blower is switched on, the air pressure is checked both in the equalisation tanks and in the pulsation chambers of the jig. At the same time, the lower water valve is opened and the water flow rate at the inlet to each compartment is checked. Correct values of water pressure and flow rate are the basis for the acceptance of the feed. During the jig operation, other parameters of the machine are checked, but the most important of them include correct functioning of the heavy product receiving systems. A detection of a malfunction results in immediate delete of the feed flow, and an activation of the light and sound signal. The feed can also be switched off at the request of the operator, which is done by using a dedicated button located on the control panel.

During the beneficiation process, the controller performs the following functions [5]:

- an operation of actuators, including:
  - switching of the hydraulic pump, supplying the circuits of hydraulic valves, with fault indication when there is no operating signal and pressure drop,
  - a control of float position, with indication of irregularities resulting from incorrect pulsation, or from float sinking, when movement does not take place despite correct pressure pulsation in the pulsating chamber,
  - a control of air pressure, including amplitudes of change, related to float movement and pressure values in the subsequent phases of the cycle, indicating the level of water in the chamber, with an appropriate alarm,
  - a control and signalling of parameters, including bottom water flow rate, oil pressure in hydraulic cylinders, valve control air pressure, feed rate and status of fuse and power supply units in the control cabinet,
- a pulsation control, which includes:

![Figure 4. Structure of data exchange.](image-url)
switching of inlet and outlet air valves to/from the pulse chambers, according to a pre-set time cycle with a specified cycle length, pause phases, emptying and filling,
- a stabilization of the average air pressure in the inlet manifold to the pulsation valves through the bypass valve, which improves the working conditions of the blower by reducing the flow oscillation and allows to switch off the pulsation in the case of a short-term supply failure (without switching off the blower),
- an automatic correction of the inlet and outlet phase and/or a correction of setpoint value of the stabilised air pressure in the inlet manifold, changing the amount of injected air and removed in a single pulsation cycle, performed in the case of an abnormal amplitude of float pulsation, with acceptable limits of changes,
- an automatic correction of the inlet/outlet phase length ratio in the event of an abnormal average water level in the pulsating chamber indicated by the pressure gauges in order to change the retention air volume in the chambers,
- a control of the bleed gap, which includes:
  - a control loop, step-by-step change of the position of the culvert in order to maintain a pre-set position of the float (the lowest or average position during the pulsation cycle), usually associated with the position of the trigger threshold,
  - an automatic correction of a pre-set float position as a function of simulated substitutional density changes introduced by the operator, which, to a limited extent, replace the current change in weights levelling the float,
  - an automatic correction of the measured position of the float, as a function of the measured degree of the culvert opening, flow of the lower water and the float depth in relation to the drain, taking into account the effects of hydrodynamic and inertial forces affecting the float movement,
  - an automatic correction of simulated float density in the event of a deviation between the set and measured ash content of the concentrate or its calorific value,
  - flushing, aimed at removing grains blocking the flow and making it impossible to close the culvert, performed in the case of closing faults, or involving multiple quick opening and closing of the culvert, with a repeated attempt at increased closing below the previous position and signalling of failure in the case of the test failure,
- a shutdown sequence of the installation, at the operator’s request,
- a sequence of switching on the installation, at the operator's request.

4. Adjustment of the heavy product collection system in the BUDRYK Mine conditions

Raw material (feed), delivered to the jig starts to pulsate. This movement is achieved by injecting and releasing air into the pulsation chambers. A separation of feed in a jig is a complex process. A segregation is associated not only with the difference in specific weights, but also with the size of grains, from which larger grains tend to fall down, an amplitude of movement and accelerations depending on the frequency or even the form of pulsation, the flow rate of lower water and the thickness of the material layer on the screen. In the end, the grains with the highest falling speed are located on the sieve deck (heavy product), while the grains with the lowest falling speed are carried to the surface of the material to be beneficiated (light product). One of the basic functions, performed by the machine control system, is a collection of heavy products. The effectiveness of the beneficiation process depends on the location of the separation layer. The separation layer is a layer from which half of the grains are transferred to the light product and half to the heavy product. In the jigs installed in the Budryk Mine, float sensors moving vertically in a mixture of water and grains, according to the frequency of pulsation, were used to measure the height of the grains forming the separation layer. These sensors are mounted directly to the heavy product collection system. A diagram of the bottom product collection system from the Budryk Mine jigs is shown in Figure 5.
A collection gap is located at the end of the chamber, before the overflow door. The float ends with a plate, which is a reflective element of the ultrasonic sensor, measuring the float position. On the basis of information from the sensor, the opening of the collection gap is increased/reduced and receiving intensity of heavy product is changed, which results in a change in location of the separation layer (density of separation). The aim is to maintain the separation layer at the level of the overflow door. Disturbances, in form of a change in the quantity and densiometric composition of the feed, cause fluctuations in the separation density. The task of control system is to minimize them. It should be noted that the dynamic parameters of collecting system change under influence of changes in the feed characteristics and are also different for changes in the flow rate of the heavy product. A block diagram of the automatic control system for heavy product collection from the jig is shown in Figure 6.

![Figure 5. Culvert system in KOMAG type jigs [6, 7].](image)

The controlled object is the collecting system, which is impacted by the disturbances $z(t)$. This system is equipped with a hydraulic cylinder, which makes it possible to change the opening of the
bleed gap, thus changing the intensity of the heavy product collection. The measuring device is a metal float, of a specific density, together with an ultrasonic sensor. The sensor sends a feedback signal v(t). This signal is compared with the set value of the separation layer w(t) height, corresponding to the set density of the separation. The e(t) signal received in the comparing system, called the deviation, is transmitted to the regulator, which converts it into a u(t) control signal, which is the basis for changing the opening of the bleed gap (the collection intensity of the heavy product).

The main objective of the regulation is to compensate the impact of disturbing parameters on the regulated ones by changing the setting values so that the adjusted values differ slightly from the required (preset) values.

The most popular PID type regulator is used for this task. In the case of controlling the collection of the heavy product it is essential to optimize the dynamics of the control system in order to eliminate the impact of disturbance and maintain zero error from the steady state extortion. Because of these interferences, which could lead to unpredictable operation of the differential part, from the group of PID regulators, the PI controller with the structure described by the equation was selected:

\[ G_{PI}(s) = K_p (1 + \frac{1}{T_i s}) \]  

(1)

where:

- \( K_p \) – proportional gain,
- \( T_i \) – integration time.

The first implementation stage of new jigs in the BUDRYK Mine involved the start-up of two OSM jigs, which are parts of the coal type 35 enrichment system and one secondary beneficiation jig. The OSM jigs are supplied with feed from one belt conveyor. During the commissioning activities, a test was conducted in which one OSM jig was tuned using the Zigler-Nichols method directly on the real object. The other jig was started at the control parameters obtained from simulation tests, using the Matlab/Simulink software.

For simulation tests it was assumed that the jig is characterized by dynamic properties of the first order inertial object, with a delay [8]. The transition function of such a system in the operator form can be written as:

\[ Y(s) = \frac{ke^{-\tau T}}{sT + 1} U(s) \]  

(2)

where:

- \( Y(s) \) – position of the float (density of separation),
- \( U(s) \) – opening of the bleeder flap (flow rate of the heavy product),
- \( k \) – amplification (0.005 for positive changes, 0.003 for negative changes was assumed),
- \( \tau \) – time delay (9 s for positive changes, 28 s for negative changes),
- \( T \) – time constant (18 s for positive changes, 36 s for negative changes).

The presented model is described with different parameters (k, T, \( \tau \)) because the dynamic characteristics of the receiving zone in the jig are different for positive and negative changes in the flow rate [8]. For the purpose of the simulation, the current parameters of the OSM jig implemented in the BUDRYK Mine, were assumed as follows:

- output: 250 Mg/h,
- active working surface: 24 m\(^2\),
- trough width: 3000 mm,
- trough length: 8000 mm,
- number of beneficiation sections: 3.

It was assumed that the bed had the shape of a cube with dimensions corresponding to the width of the jig and the length of a single section. The thickness of layers was determined from the volume balance of material flowing in and out of the jig.

For simulation tests, the feed characteristics presented in Table 1 was assumed.
Table 1. The feed characteristics used for the regulator initial settings.

| Fraction density, g/cm³ | Feed, % |
|-------------------------|---------|
| < 1.3                   | 23.78   |
| 1.3 ÷ 1.4               | 9.84    |
| 1.4 ÷ 1.5               | 6.38    |
| 1.5 ÷ 1.6               | 8.81    |
| 1.6 ÷ 1.7               | 7.13    |
| 1.7 ÷ 1.8               | 4.06    |
| 1.8 ÷ 2.0               | 4.29    |
| > 2.0                   | 35.71   |
| Sum                     | 100.00  |

In the first and second sections, the material of a density > 1.8 g/cm³ was separated, while in the third section the separation density was 1.5 g/cm³. It was also assumed that the movement velocity of individual layers in the horizontal layer changed linearly. The highest velocity was observed in the layer of the lowest density.

The basic task of the regulation system is to adjust the opening of the bleed gap (heavy material flow rate), to increase the opening when the float goes up and to reduce the opening when the float goes down. Tuning the regulator requires an implementation of such solutions that the regulation system acts in accordance with the requirements and meets the adopted criteria of regulation quality. In the real system, constantly exposed to disturbances, statistical parameters of the error signal are analyzed. The first accepted measure of the control quality was the absolute mean value of the error signal. It is required that in the steady-state of the system, this value shall be as low as possible:

\[
\min |\bar{e}| = \frac{1}{n-1} \sum_{i=0}^{n} e(i) \tag{3}
\]

where:
- \(\bar{e}\) – average value of the control error
- \(e(i)\) – discrete series of values representing an error in the control signal.

When tuning the controller, it is necessary to take into account the operation of the system in transition states. The ITSE (Integral Time Square Error) indicator is a good measure of the control quality used in fixed-value systems, where the transition process is to be discontinued as quickly as possible:

\[
\min \text{ITSE} = \min \sum_{i=0}^{n} e^2(i) \tag{4}
\]

where:
- \(e(i)\) – discrete series of values representing an error in the control signal.

The parameters, obtained in simulation tests, were introduced to the PLC controlling an operation of one of the machines. The parameters of the controller, used in the second jig, were determined by bringing the collection systems to the stability limit, to the moment when the constant oscillations begin to appear. This was achieved by increasing the \(K_p\) gain factor (in a closed system with a regulator) gradually. For such oscillations the critical vibration period \(T_{kr}\) was determined. The obtained coefficients were entered into the formulae from Table 2. In both cases the algorithm uses anti-windup system. It prevented an excessive signal increase in the integrator module of the regulator after exceeding the upper or lower limit of the control signal. When these limits are exceeded, an
integration stops and takes the last value that occurred before the control signal exceeded a predetermined level. The integrator only starts to sum up the successive error values when the signal returns to the set range [9]. Such a mechanism allows to limit over-regulations resulting from the saturation of the regulator output signal.

Table 2. Optimal controller settings according to the Zigler-Nichols method.

| Regulator | Optimal controller settings |
|-----------|----------------------------|
|           | $K_p$ | $T_i$ |
| PI        | $0.45K_{kr}$ | $0.85T_{kr}$ |

Table 3 compares the relative values of the assumed regulation quality standards in both cases.

Table 3. Values of relative quality metrics for the considered cases.

| Regulation quality ratio | $|e|$ | ITSE |
|--------------------------|------|------|
| Real object tuning       | 100.0% | 100.0% |
| Tuning based on computer simulation | 106.1% | 102.8% |

5. Summary and conclusions

Due to an efficient cooperation with the BUDRYK Mine employees, the start-up of new machines was carried out successfully. Introduced changes allowed to improve the functionality and adjust the control system to the user's needs. KOMAG researchers obtained important information on the specific requirements of the user concerning the mentioned system, as well as important measurement data, thanks to which the system will be further improved. It is planned to expand the system introducing additional control functions in the aspect of complex automation of the jig node operation. This applies, in particular, to the collector air supply system.

Basing on the industrial research carried out on the jig control system, it can be concluded that the KOGASTER SSWO control system enables an accurate separation of the processed material. The analysis of the obtained results showed that total losses of flammable material in the waste product were minimal.

The following conclusions can be drawn from the analysis of the jig heavy product collection system and the tests of the control system:

1. The product collection section of the jig is a non-linear object whose dynamic properties change depending on the direction of variation around the work point.
2. The value of the ITSE quality criterion does not change significantly in the analysed variants of regulator parameters selection, which probably proves the appropriate dynamics of the applied control system model.
3. The mathematical model of the collection system proposed in the paper allows for a certain analysis of the jig float collection system as an object of regulation, however, due to the influence of disturbances such as: change of the feed flow rate, its characteristics and change of particular grain classes shares, they cause that the settings are not sufficient for an effective operation of the system in industrial conditions.
4. A further analysis of the effects of using algorithms with different methods of compensation of unfavourable phenomena accompanying the regulation of non-linear processes is required.
5. In further research a more detailed analysis of the collection system is planned, taking into account such disturbances as: change of the feed flow rate, change of particular grain classes shares and change of the feed characteristics, in terms of the structure of the collection system mathematical model.
6. Although the feed for the jig was transported by one conveyor and despite the position of the separating flap (Figure 1) - the middle position, it cannot be stated that the material was evenly distributed between the two jigs, which could have an impact on the obtained results.

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