Controlled multi motor drives of high power belt conveyors: Practical experiences during the exploitation of the system on open pit mine

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Abstract: - The paper presents practical experiences in the three years period of exploitation of the Fifth Excavator-Conveyor-Spreader system on the Open pit mine „Drmno” in Kostolac. The algorithm for generating the speed reference under the criteria of maximum material loading rate of belt conveyor is realized on the system of five belt conveyors, which is remotely controlled from the Control center. Hence, the energy efficient transport of material is achieved. The positive effects of the remote control concept, which consequently has better time utilization of the system, are discussed in the paper. Also, problems that are noticed in the considered period of exploitation are analyzed and principles for their solutions are proposed.

Key-Words: - Variable speed belt conveyors, Control center, SCADA (system control and data acquisition), remote control, energy efficiency, fuzzy logic control, transfer point, belt misalignment

1 Introduction

One of the key elements in energy policy of all developed countries in the world is energy efficiency, because it contributes to the improvement of economy and extends the lifetime of conventional energy sources. The greatest part of total electrical energy is still generated by fossil fuels. In many countries, most electrical energy comes from coal. In the following decades, the focus will be on thermal power plants to further increase electrical energy capacities, requiring the rise of coal production.

In various branches of industry where bulk materials are produced or used, various types of belt conveyors (BCs) are used for the transport of materials. Two excavation methods are used in open pit mines (OPM): discontinuous mining, which is characteristic for smaller-capacity mines and for mines where the excavated material is of a greater hardness (uses shovel excavators and draglines, while the transport of materials is conducted by trucks) and continuous mining, which is used in large OPMs where coal is excavated for use in thermal power plants and which is considered in the paper. The mechanization in these types of mines is organized into systems, such as an ECS (excavator-belt conveyor-spooler) for excavating overburden, or an ECSY (excavator-belt conveyor-stock yard) for excavating coal. Requirement for continuous operation and large installed power are common characteristics for these systems.

Three years ago, a new ECS system on OPM „Drmno”, which is presented in Fig. 1, has been built and put into operation. It consists of the excavator SRs 2000, system of five BCs (maximum length 3.25km per transporter, rated conveying capacity 6600 m³/h and controlled multi motor drives with installed power of 4x1MW per transporter) and spreader ARs 2000. Due to the length of the route and the necessity to shift the route regularly as a result of the technological demands a system of several BCs, i.e. BC stations, is formed. BC stations are placed along the envisaged route so that material is transferred from BC to BC several times until it reaches the final destination (Fig. 1). The authors of the paper have been deeply involved in the realization of the system of BCs from its beginning. The idea of energy efficient transport of overburden based on speed control has been applied. Hence, a new way of operation of such systems is realized.
Conventional systems of conveyors transport bulk material at the constant, rated speed. When the system is at rated capacity, the cross section of material on the belt is at the maximum value, i.e. the belt is fully loaded. However, investigations and statistical analyses show that systems like this, due to technology of excavation very often work at reduced capacity. Most often the instantaneous cross section area of material on the belt is less than the rated value, and even no-load operation makes up a significant part of the system’s operational time. The necessary power for driving the system of belt conveyors depends on the quantity of transported material, as well as on the speed of the belts. Considering the aforementioned facts, the following conclusion can be made: since the belt conveyor often operates at a decreased capacity, the same quantity of material can be transferred at a lower than rated speed, leading to instantaneous power reduction, along with significant energy savings [1].

2 Control of multi-motor drive of belt conveyor

BCs with greater capacities have multiple drive motors. Fig 2 shows control block diagram of a belt drive with multiple motors. A speed regulator function is implemented in the PLC on the BC station, while the reference speed is generated in the master PLC in the control center (CC), as a result of applied algorithm.

The speed regulator on the BC station can be PI or PID. Strong differential action should be avoided due to the elasticity of the belt. Special attention is given to uniform load distribution among individual drives on a conveyor. The PLC software has one speed regulator which controls the average speed of drives.
that each belt in the system of BCs will be constantly and optimally loaded. The instantaneous capacity changes quite frequently and sporadically, meaning that the speed should be increased and decreased in the same manner as the instantaneous capacity changes, but these dynamic processes would be unfavorable for BC. With the application of different control strategies, the acceleration and deceleration of a belt can be controlled in order to ensure minimum energy consumption under the existing technical constraints of the system.

With the goal of developing an algorithm to improve the energy efficiency of the system, capacitive utilization of the system, system reliability, extension of the service life of the equipment and reduction of costs for system maintenance, theoretical, simulation and experimental methods are combined. Two different algorithms are developed and applied:

- with the constant and previously defined deceleration and variable acceleration,
- with variable acceleration and deceleration, on the base of fuzzy logic control (FLC).

2.1 Algorithm with constant deceleration

The algorithm for generating the reference speed of the belt drive with constant deceleration is defined as follows:

1. If BC in the system of BCs is considered the theoretical belt speed can be expressed as:

\[ v_{i}(t) = \frac{A_{in}(t)}{A_{r}} v_{in}(t) \]  \hspace{1cm} (1)

In (1) \( A_{in}(t) \), \( v_{in}(t) \) and \( A_{r} \) are the instantaneous value of cross section of incoming material, the instantaneous speed of the previous belt and the rated value of cross section, respectively. The actual reference speed of the belt drive \( v_{ref}(t) \) is calculated according to (3) under the conditions defined by (2):

\[ \frac{dv_{i}(t)}{dt} \geq 0 \text{ and } v_{i}(t) - v_{ref}(t) \geq \varepsilon \]  \hspace{1cm} (2)

\[ v_{ref}(t) = c \cdot \int (v_{i}(t) - v_{ref}(t))dt + v_{ref}(t_{1}) \]  \hspace{1cm} (3)

where \( t_{i} \) is the moment when both conditions defined by (2) are acquired, \( c \) and \( \varepsilon \) are constants with dimensions \([s^{-1}]\) and \([\%]\) respectively, while \( dv_{i}/dt \) is time derivative of theoretical belt speed with the dimension of \([s^{-1} \%]v_{i} \), where \( v_{i} \) \([m/s]\) is rated speed.

2. When the conditions from (2) are not fulfilled, i.e. \( \frac{dv_{i}(t)}{dt} < 0 \text{ and } v_{i}(t) - v_{ref}(t) < -\varepsilon \), the actual reference speed is determined on the basis of (5),

\[ v_{ref}(t) = v_{ref}(t_{2}) - k \cdot (t - t_{2}), \]  \hspace{1cm} (5)

where \( t_{2} \) is the moment when at least one of the conditions from (4) ceases to be valid and \( k \) is deceleration. During the period when the quantity of material coming onto the conveyor increases, the reference speed of the drive is determined according to (3), and at that time the drive accelerates. The constant \( c \) determines the dynamic of reference speed. In this manner the cross section of the material on the speed controlled belt increases, meaning it gravitates towards \( A_{r} \). When the quantity of incoming material decreases, the reference speed is calculated based on (5), i.e. the speed decreases with a deceleration \( k \).

The constant \( k \) determines the deceleration of the drive which must confirm with the dynamic characteristics of the drive. An abrupt deceleration unfavorably affects all mechanical assemblies, couplings, bearings, the belt, etc. BC drives with a route which does not traverse an incline use braking with a resistor and chopper in the DC circuit. An abrupt deceleration would lead to the activation of the electric braking system whereby the braking energy would unnecessarily transform into heat within the resistors. Regarding these conditions and constraints a value for constant \( k \) is empirically determined and applied in the algorithm for generating the reference speed of the belt on the of V ECS system. The results of measurements performed on the system are given in [2]. These results show that the maximum value of the material cross section on the belt is not achieved due to two reasons: the minimum speed is limited to 50% of the rated speed and the speed does not exactly follow the reduction of the instantaneous material cross section on the belt due to constant value of deceleration. As the absolute value of constant \( k \) decreases, the deviation from the maximum material cross section increases, but the activation of the electric braking system is avoided in all modes of operation, except in the case of emergency stop. Therefore, the system of BCs does not operate with maximum efficiency.

2.2 Algorithm based on fuzzy logic control

Due to aforementioned reasons, \( k \) should be variable to provide deceleration with drive torque nearly zero (but not negative) and therefore operation with minimum energy consumption. It can be determined using the expression (6), derived from the Newtons law,

\[ k(t)_{oe} = \frac{T_{l}(t)}{J_{Σ}(t)} \]  \hspace{1cm} (6)
where $J_S(t)$ is the total inertia referred to motor shaft, including the effect of material mass. In accordance with DIN22101 standard, $T_l$ can be expressed as

$$T_l(t) = T_{l0} + T_l(m_{bm})$$  \hspace{1cm} (7)

where $T_{l0}$ is constant part of the total load torque and $T_l(m_{bm})$ is a part which is a function of mass of the material on the belt and consequently time dependant. Similar can be derived for the total moment of inertia of the loaded belt conveyor,

$$J_S(t) = J_{S0} + J_S(m_{bm}),$$  \hspace{1cm} (8)

where $J_{S0}$ is a constant part of the total moment of inertia and $J_S(m_{bm})$ is a part proportional to mass of the material on the belt and is also time dependant.

The constant part of the load torque, as well as the constant part of the moment of inertia, can be calculated with sufficient accuracy. The values can also be updated from time to time to account for changes in the system of BCs, due to changes of length or changes in condition of the equipment. However, components of load torque and moment of inertia remain unknown since they are functions of mass of material on the belt and external conditions. This leads to inaccurate calculation of $k$ and inappropriate deceleration of a BC.

Due to aforementioned facts, it can be derived that the optimum value for $k(t)$ has to fulfill following three criteria: 1) the absolute value of $k(t)$ must be less than absolute value of $\Delta A_{in}/\Delta t$ in the period of deceleration, in order to avoid spillage of material over the belt, 2) technical criteria, $k(t) \leq k_{max\_tech} = 3.5 \text{ [s}^{-1}\text{]} \cdot \nu_r$, in order to keep stress of belts and mechanical assemblies during the deceleration within tolerance and 3) the criteria for optimum energy consumption under given constraints of the system, defined with (6).

The value $k_{max\_tech}(t)$ must not be applied during periods of deceleration when $k_{max\_tech}(t) > k_{max\_tech}$. For this reason, motors of the multi motor drive of BC have to develop torques in accordance with (9).

$$T_e \geq k_{max\_tech} \cdot J_S(t) - T_l(t)$$  \hspace{1cm} (9)

The expression (9) leads to the conclusion that measured value of the drive torque has to be incorporated in the algorithm for generating reference speed, in order to provide operation of the system with optimum $k(t)$, within existing operating conditions. This value is achieved with SCADA system, meaning that it is always available.

Fuzzy control was found to calculate acceleration and deceleration, based on measuring three values: speed of previous BC, cross section of incoming material, and the drive torque. The block diagram of the algorithm for generating the reference speed of BC with FLC is shown in Fig. 3. A sampling time $T_s = 50 \text{ ms}$ is adequate for dynamics of the system. As it can be seen from Fig. 3, FLC has two inputs: $DW_{ref}$ according to (10),

$$DW_{ref}(n) = v_r(t) - v_{ref}(n-1),$$  \hspace{1cm} (10)

and the drive torque $T_e$. The task of maintaining the torque of the motor at a zero value during periods of deceleration is now provided by the FLC. Therefore, the deceleration is achieved while avoiding all the problems caused with the parameters variation due to external conditions. The FLC is with single output, the increment of the reference speed $N(DW_{ref})$. It is based on Mamdani’s reasoning methods, developed using Fuzzy Logic Toolbox and integrated into Matlab Simulink dynamic model of BC. Membership functions, fuzzy rules, results of simulations and measurements of characteristic values on the system with applied algorithm with FLC are given in [3].

![Fig. 3 Algorithm for generating the reference speed of the belt with FLC](image)

The measurements taken over a period of eight months on the V ECS system on OPM „Drmno” confirmed the expected savings in electrical energy consumption. Twenty series of measurements were generated in various exploitation conditions: the system was operated with constant speed, with variable speed and constant deceleration and with FLC, each for several hours. Fig. 4 provides data on consumption of electrical energy per cubic meter of transferred overburden.

**Fig. 4 Specific energy consumption [kWh/m³]:** 3rd, 4th and 5th BC station: red bars - constant speed operation, blue bars - algorithm with constant deceleration, green bars - algorithm with FLC.
with FLC - the reduction of average value of specific energy \([\text{kWh/m}^3]\), in the range from 3% to 19%, comparing to constant speed operation.

3 Practical experiences

Realization of the system for supervision and control [2] (SCADA) in the CC enables visualization of all relevant parameters of the control system with the use of graphical presentations. Controlling a system from one location significantly increases its utilization time. Because the system is managed by just one operator and individual procedures have been automated, many subjective weaknesses have been eliminated and the time needed to conduct necessary works has been shortened. A full display of the system status facilitates preventative maintenance and in the case of malfunctions, the maintenance service has information on the necessary repair before arriving on location. The necessary time to start the whole ECS system with five conventional conveyors with operators on each BC station is between 5 and 10 min when there is no material at the first (bench) conveyor. During that time, motors with high rated power are starting to operate mining that up to 20 MW of installed power is engaged from 5 to 10 minutes in no load operation during the only one putting system into operation. In the case of BCs with ASDs, the starting time of each BC can be adjusted depending on parameters of the conveyor and material which is transported and it varies within the interval of 30 to 90 seconds. Fig. 5 presents time diagram of belt speeds during the starting up period of the system when each drive of five BC drives accelerates following the „S“ shaped rump of the reference speed to the rated speed. Also, the time necessary to stop the whole system is reduced to approximately 15 s.

Belt drive speed controls offer the capability of automatic compensation for belt slippage on the driving pulleys. Slippage can be detected by measuring the speed of the free-moving take up pulley and comparing it with the speed of the driving pulley. Upon the occurrence of slippage, the speed is gradually decreased until slippage stops and then the drive is accelerated again at the assigned rate of acceleration up until the necessary speed is reached. If slippage does not stop by decreasing the speed to the defined minimum value, the drive must be stopped.

During exploitation of the BC system, it was noticed that the bearings of the gearbox and motor heat up less when speed regulation is used, meaning operation at an average lower than rated speed, compared to the operation of a BC system at constant rated speed. The measurements which were taken over a longer period of time showed that the total power factor for the entire system was greater than 0.95, which is yet another benefit.

![Fig. 5 Starting up period of the BC system](image)

However, control of the reference speed of the system causes certain problems on the transfer point between two BCs. When a BC changes its speed, it causes the material which is transitioning from the head of the conveyor onto the next conveyor, or being loaded into a carriage or bunker, to possess varying kinetic energy which results in its movement having a variable trajectory, as it is presented in Fig. 6.

![Fig. 6 Schematic presentation of the transfer point](image)

An operator from CC, based on experience and the actual situation on the transfer point, acts though spindle drive of baffle plates and changes the geometry of transfer point. As the material trajectory depends on variable capacity and adhesion between material and the surface of the rubber belt, it is required to have a transfer point between two BCs with variable geometry in the case of BCs with constant speed. Many factors have the influence on the shape of material trajectory, which are differently treated and presented in the literature [4]. After a longer period of operation, especially in the case of BCs with variable speed, these factors...
may cause non symmetrical distribution of material across the profile of the rubber belt, resulting in the misalignment of the belt along the route, as it is presented in Fig.7.

Fig.7 Distribution of material cross section across the belt profile

At first, placement of baffle plates in the proper position must be automated as the function of speed to insure complete functionality of the system. Secondarily, if we assume that the cross section area of material at the transfer point is nearly constant thanks to the regulation of speed, the trajectory of material at the transfer point will depend on other factors, such as the type of material and moisture, i.e., the specific weight.

As the dependency of the necessary position of the baffle plate is a function of speed and the characteristics of the material, a possible solution could be the application of a non-linear regulator using a two-dimensional lookup table in which the positions of the baffle plate would be entered as the function of speed and status of the material. The range of speed regulation should be divided into the necessary number of values in order to obtain sufficiently precise regulation of the position. The number of various statuses of the material would depend on the composition of the material which is being transported. The selection of the status of the material would need to be entered manually by the operator. That should not be a problem because the status of the material is not commonly a variable value like belt speed is. The described regulation process can be implemented in the PLC. Of course, for all of this it is necessary to have a sufficiently accurate measurement of the baffle plate position and the capability of effectively repositioning it into the desired position.

4 Conclusion

The paper presents potentials and experiences in the application of a novel control strategy for the reference speed control in the system of BCs, as a new, energy efficient way of bulk material transport on OPMs. Based on the presented mode of operation, savings in the electrical energy consumption are gained in the system of BCs which are the greatest energy consumers on OPMs. The authors have previously implemented algorithm with constant deceleration improved with the application of advanced control techniques. As a result, a new algorithm for generating reference speed based on fuzzy logic with variable deceleration has been developed and applied, providing additional energy savings in the BC system. Furthermore, diagnostics of all elements from the CC enables fast detection and elimination of failures caused by malfunctions of the equipment. Automated and centralized starting of the system provides reduced time required to prepare system after fault elimination compared to the case with operators on BCs. The possibility to monitor and archive a great number of signals from the system of BCs on the operator station in the CC and to analyze them enables the prevention of problems from the mechanical maintenance domain. Additional regulation of the baffle plate position as a function of speed and material specific weight will be the topic of authors' future work, to insure complete functionality of the system.

References: