Speed Controlled Belt Conveyors: Drives and Mechanical Considerations

Milan Z. BEBIC, Leposava B. RISTIC
Faculty of Electrical Engineering, University of Belgrade, 11000 Belgrade, Serbia
bebic@etf.bg.ac.rs, leposava.ristic@etf.bg.ac.rs

***Abstract*—The paper presents variable speed belt conveyor system where the reference speed is changed in order to achieve improved energy efficiency of operation. The recorded measurements show that belt tension varies within the same limits as under constant speed operation. These results introduce a new insight of the present state of the art in variable speed belt conveyor drives. The system is realized with remote control from the control center on an open pit mine. The structure of the multi-motor drive system of a single conveyor, as well as of the network-based control system distributed among belt conveyor stations and the control center are shown. Speed control of a belt conveyor system is organized to provide better utilization of the available material cross section on the belt and reduced electrical energy consumption of the drive. The experimental results obtained on the system prove that, under existing constraints, the applied algorithm has not introduced additional stress to the belt or mechanical assemblies during acceleration and deceleration processes, while providing higher energy efficiency of operation.**

***Index Terms*—mining industry, variable speed drives, belts, algorithm, stress.**

I. Introduction

In different branches of industry where bulk materials are processed, different types of belt conveyors (BCs) are used for the transport. Continuous mining in large open pit mines (OPM), most often applied to excavate coal for utilization in thermal power plants, represents the main application for large scale BCs in transport of overburden or ore (coal). Recently, very long BCs have been built with lengths of several dozen kilometers. Systems comprising several BC stations are formed due to the length of the route as well as necessity to shift the route regularly as a consequence of technological demands. BC stations have been placed along the envisaged route so that material is transferred from BC to BC several times until it has reached the final destination. The installed power of these BCs is large and each rationalization of energy consumption can provide significant savings, which is naturally of significant interest for a user [1-5]. According to [6], in-mine overburden and coal transportation represent approximately half of the total production costs per one tone of extracted coal. Although energy efficiency improvement programs in mining are widespread and target all aspects of mining [7], the comminuting and material handling operations have been identified as having the highest potential for energy efficiency improvement.

Since the belt conveyor is a typical system that performs electromechanical energy conversion, the improvement of energy efficiency can be achieved at four levels: at the level of performance, operation, equipment and technology [8]. This paper focuses on reference speed control and its influence on belt tension. After applying efficiency improvements at aforementioned levels in each particular system, it is still probable to further receive energy savings, with the application of reference speed control [9], but it has real significance only if it does not introduce additional mechanical stress in the system. The results of measured belt tension force on the variable speed belt conveyors often lack in the present literature. Therefore, the paper will validate the applied concept of control of real system of BCs in an OPM through measurement results of speed, torque and belt tension.

Although energy efficiency depends on the equipment units and operating conditions (including those imposed by mine planning and design), it also depends on operator practices, which are affected by skill and training [7]. These inefficiencies can be due to the excavator operator, or the applied control algorithm of the main working axes of bucket wheel excavator [7, 10]. Application of the algorithm for bucket wheel excavator control according to the criterion of desired capacity, in which results of the measuring volume flow system are used as feedback information on the capacity [11], can reduce variation of incoming volume flow in the next cut. In fact, the instantaneous cross section of the incoming material is altered thereby reducing the gaps within the material on the belt. With more uniform longitudinal distribution of material on the belt, the change of reference speed will be lower.

Since belt conveyors generally operate with the average material cross-section less than 100% at constant rated speed, the standard DIN22101 [12] implies reduction of belt conveyor reference speed in order to maximize the material cross-section and decrease energy consumption. Therefore, if the speed is adjusted for the transport of a certain quantity of material according to algorithm presented in [4], or in [13], energy savings will be achieved based on the decreased power necessary for driving the belt [13]. The main prerequisites to realize any of the algorithms for operation with reduced speed is certainly the existence of variable geometry discharge chutes [14] i.e. transfer points between two belt conveyors with automatic adjustment of the position of the deflection plate to the actual belt speed and material flow.

On the other hand, it has been shown in [15] that, due to the complexity of the mechanics of driving a loaded belt, increased filling of the belt is expected to cause increase in friction coefficient, which can reduce the effect of decreased power with decreased speed.

The work is partially supported by Grant TR 33017 of the Serbian Ministry of Education, Science and Technological Development.

Digital Object Identifier 10.4316/AECE.2018.01007

In accordance with trends in modern industry, in [16], the authors propose the virtual prototype technology thereby providing a new way for the safety analysis and design of the belt conveyor. The authors believe that virtual prototyping enables dynamic analysis of belt conveyor and provides proper knowledge about the belt tension during acceleration and deceleration, thus preventing belt rupture, coal vibration, belt slip on the drive pulley, uncontrolled running of the belt conveyor, belt fire and other accidents due to ruined safety.

The authors of the recent literature [9, 17, 18], claim that current research activities on speed control for belt conveyors mainly focuses on the calculation and the prediction of possible energy savings. Additionally, they also consider that just a few studies focus on the dynamics of belt conveyors in transient operation. Hence, they propose a three-step method [17] that can be used to determine a proper way to accelerate a speed controlled belt conveyor during transient operation. The method should help to avoid following risks: the belt over-tensioning in the splicing area, slippage of the belt around the drive or brake pulley, motor overheating and material spillage. In the first step within this method called „initiation”, an initial estimation of acceleration time is calculated concerning belt tension rating, the conveyor tension ratio limitations around driven/braked pulleys and the motor torque rating. In the second step, called „calculation” the dynamic analysis of the conveyor is performed trough FEM simulations applying the results achieved in the first step. Searching for optimal acceleration time is performed during the third step called „optimization”.

While the authors of the previously presented literature mostly focus on the determination of acceleration time in order to avoid spillage of material over the belt, the deceleration is put aside. In addition to acceleration, an abrupt deceleration unfavorably affects all mechanical assemblies, couplings, bearings, the belt, etc. Creating an algorithm for generating the speed reference based on information of instantaneous value of incoming material cross section onto the belt, implies that the constant reference deceleration of the drive, must conform with the total inertia of the drive including the bulk material on the belt. Therefore, BC drives with a route not traversing incline use braking with a resistor and chopper in the DC circuit. An abrupt deceleration would lead to activating the electric braking system whereby the braking energy within the resistors would unnecessarily be transformed into heat.

Due to aforementioned reasons, variable deceleration coefficient $k(t)$ should provide deceleration with drive torque nearly zero (but not negative) and therefore operation with minimum energy consumption. It can be determined using the expression (1), derived from the Newton’s law,

$$k(t)_{oe} = \frac{T_l(t)}{J_\Sigma(t)}, \tag{1}$$

where $J_\Sigma(t)$ is the total inertia referred to motor shaft, including the effect of material mass. In accordance with DIN22101 standard, the load torque T_l can be expressed as

$$T_l(t) = T_{l0} + T_l(m_{bm}), \tag{2}$$

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

$$J_\Sigma(t) = J_{\Sigma 0} + J_\Sigma(m_{bm}), \tag{3}$$

where $J_{\Sigma 0}$ is a constant part of the total moment of inertia and $J_\Sigma(m_{bm})$ is proportional to mass of the material on the belt and is time dependant.

Both constant part of the load torque and constant part of the moment of inertia can be calculated with sufficient accuracy. The values can also be periodically updated to account for changes in the system of BCs, due to either changes of length or changes in condition of the equipment. However, variable components of load torque and moment of inertia remain unknown since they are functions of material mass on the belt and external conditions, such as roller bearing conditions or freezing.

Due to previously mentioned cases, it can be derived that the optimum value for $k(t)$ has to fulfill the following three criteria:

1) the absolute value of $k(t)$ must be less than absolute value of $\Delta A_{in}/\Delta t$ during deceleration, in order to avoid spillage of material over the belt, (ΔA_{in} is the change in instantaneous value of cross section of incoming material to the belt during the short period Δt).

2) the technical criteria, $|k(t)| \leq k_{max\ technical}$, 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 (1).

The value $k_{oe}(t)$ should not be applied during periods of deceleration when $|k_{oe}(t)| > k_{max\ technical}$. For this reason, motors of the multi-motor drive of BC have to develop torques in accordance with (4).

$$T_e \geq k_{max\ technical} \cdot J_\Sigma(t) - T_l(t) \tag{4}$$

In the previous expressions $k_{max\ technical}$ is maximum value of deceleration which should be determined, as well as maximum acceleration in accordance with the recommendations given in [3]. Based on available data and specified safety margin and taking into account the given criteria and constraints, a value for deceleration coefficient $k(t)$ is determined and applied in the algorithm for reference speed generation for each particular belt in the system of five belt conveyers in an open pit mine, which is displayed in [4]. The experimental results performed on the system will be presented in this paper and analyzed in view of mechanical stresses of the belt and mechanical assemblies influenced by BC’s variable speed operation. Such an analysis has not been presented in the literature so far and therefore represents the main contribution of the paper, along with the comprehensive description of the multi-motor drive system.

The paper is organized as follows: after the Introduction, Section II presents multi-motor BC drive and control system. Section III describes remote control operation of the system from the Control Center enabling implementation of reference speed control, improved safety, monitoring and diagnostics. Section IV briefly surveys the options for tensioning devices. Section V presents experimental results obtained on the realized system of belt conveyors in Drmno OPM in Serbia, shown in Fig. 1. The Conclusion is given in the last section, followed by technical data and the list of references.

Figure 1. ECS System in OPM Drmno, Serbia at the time of measurement

II. Multi-motor Belt Conveyor Drive

Analyses and research conducted in the field of belt conveyor drives have shown that there are multiple reasons to use variable speed drives (VSDs) for belt drives [14, 19-23] such as:

- VSDs enable starting and stopping with predefined acceleration and deceleration rate. This type of starting method is beneficial for the motor and mechanical parts of the drive, particularly for BC drives, given the fact that the belt of the BC is elastic. The belts endure significant axial strain for two main reasons, the first being their length and the second being the material they are made of. Starting a BC with the acceleration adapted to the BC characteristics provides a steady start without torque oscillations and unnecessary strain on all of the elements, especially the belt. The same applies for the process of deceleration and stopping.
- Adapting the speed of the BC to the quantity of material which is being transported enables utilization of full belt width and operation with improved energy efficiency.
- Decreasing dynamic tensioning when adjusting the speed and starting, as well as decreasing wear, contributes to a decreased number of malfunctions and increased exploitation period for the facility.
- Torque control of individual motors in a multi-motor BC drive allows the load torque to be distributed proportionally according to the rated data of the motors.
- Through speed control, meaning through a short-term decrease of speed, belt slippage on the driving pulley can be eliminated.

Due to the listed undoubted advantages, like many other today BCs of various sizes and purposes, the considered BC system on OPM is realized with controlled speed, consisting of multi-motor drives with induction motors supplied from frequency converters (FC). Due to the significance of these motors in the process, they are supplied with thermal probes for measuring the temperature of the bearings and stator windings. The motors also have possibilities for installing vibration sensors. All sensors can be connected to the FC control system or the PLC (programmable logic controller) based control system of the BC station.

The power module of the frequency converter comprises the rectifier, DC link circuit and inverter. Rectifiers within converters can be uncontrolled or controlled. Uncontrolled rectifiers or diode rectifiers are simple and reliable, and it is with these rectifiers that the input phase voltage and the first harmonic of input phase current are practically in phase. This significantly contributes to the total power factor of the converter being close to unity when the load of the drive is close to the rated value. Controlled rectifiers are thyristor-type, or more recently, transistor-type rectifiers. Controlled rectifiers enable the energy recuperation, i.e., the transfer of energy is possible in both directions, from the grid to the drive and from the drive back into the grid. This is particularly important in drives where there is a significant amount of potential or kinetic energy released under certain conditions. Also, the savings of energy can be achieved by means of returning it into the grid [24]. However, thyristor rectifiers have unfavorable characteristics in the sense of grid connection, poor power factor and the presence of higher order harmonics. Transistor-type, or active front end (AFE) rectifiers, which operate on the PWM principle, enable a bi-directional energy transfer with a power factor equal to unity and very low content of higher order harmonics in the grid current. Additionally, active rectifiers enable a constant voltage to be maintained within the DC circuit all the way up to 65% of the grid voltage and can be used as an active compensator for the reactive power on the bus bars from which they are supplied. With regard to price, the most favorable are diode rectifiers, then thyristor rectifiers and finally transistor, active rectifiers.

The basic role of the DC link circuit is to stabilize DC voltage at the input of the inverter. This circuit, in voltage source inverters, must contain capacitors which, aside from filtering, provide reactive energy for operation of the motor. Reactors for decreasing the content of higher order harmonics, which result from the commutation of inverter transistors, can be located in the DC link circuit or in front of the rectifier. When the reactors are in front of the rectifier, they reduce the distortion of line current which results from the operation of the rectifier. The connection location for reactors depends on the concept adopted by the manufacturer. When selecting a frequency converter, one must consider the necessary value of inductance and the way in which they are connected, as well as the characteristics of the grid to which the converters are being connected. In drives which require electrical braking, a braking system consisting of the braking module (the chopper) and a resistor for braking energy dissipation are optionally installed within the DC circuit. The described braking system is not indispensable if one of the aforementioned controlled AFE rectifiers is used.

The inverter is made up of six groups of fully controlled semiconductor switches (power transistors) in a three-phase bridge connection. In today's generation of convertors, the switches operate in pulse width modulation (PWM) mode at high switching frequencies of several kHz. As a result of this, the waveform of the motor current is practically sinusoidal. This last fact is a significant benefit for drives with frequency converters because practically no additional losses occur in the motor in comparison to operation when being supplied by the grid. Pulse width modulation is realized using modulation techniques based on some of the algorithms for controlling motors such as flux oriented control (FOC) [25] or direct torque control (DTC) [26-27]. The power module construction of an FC provides high efficiency in operation, usually between 0.95 and 0.99.

For FCs which are used for a BC drive, it is particularly important that they have a PID speed regulator with a window and an additional input for external reference torque. Fig. 2 shows a principle block diagram of the regulation module of this FC type. In the case of multi-motor BC drives, the same values for Ext. Ref. Speed and Ext. Ref Torque are forwarded to all FCs from the supervisory control system. The window block disables the speed regulator if the actual speed value is close to external reference speed, i.e. when the difference is less than Δω, internal reference torque is zero. Then all drives provide the same torque corresponding to the value of Ext. Ref. Torque.

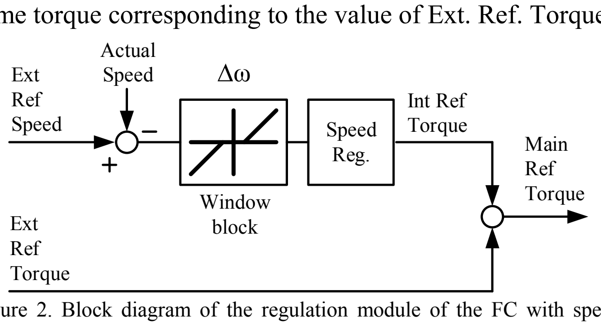

Figure 2. Block diagram of the regulation module of the FC with speed regulator with a window and an additional input for external reference torque

This way, equal load sharing has been achieved for all drives even if they do not rotate at the same speed, for example, due to varying diameters of driving pulleys as a result of worn rubber coating or stuck-on mud. In order to achieve more efficient integration of FCs in the entire drive system, simple monitoring, adjustment and control, FCs have been equipped with various capabilities for connecting with other components:

• Local communication serves for adjusting, controlling and monitoring the operation of the FC or the drive as a whole, locally, meaning at the converter itself.

• Digital inputs and outputs, with an operational DC voltage of 24 V enabling the exchange of logical commands with other components.

• Relay inputs and outputs enable the exchange of logical commands at voltage levels up to 220 V.

• Analog inputs and outputs, which are normally supplied with the control module of an FC enabling reference and providing feedback connections aimed at integrating the converter into the control system. Analog inputs and outputs can use DC voltage (0-10 V), current (0-20 mA) or impulse (0-5000 Hz) type signals.

• Modern FCs also feature the capability of connecting with other units in the system and supervisory control levels, SCADA, etc., through various standard communication protocols, RS232 and RS485, ProfiBus, Interbus, DeviceNet, Modbus, Ethernet, etc. The communication options for FCs offer extensive capabilities for control and monitoring the FC and drive, both locally and remotely.

Belt conveyors use two configurations of frequency convertors: single- and multi-drives. Frequency converters for single drives are commonly manufactured with diode rectifiers and transistor inverters. Short belt conveyors with an incline usually do not incorporate a braking system consisting of the braking module (the chopper) and a resistor. If an electrical braking is required due to the shortening of the ramp-down time, and/or speed control, braking chopper and resistor is installed within the DC link circuit. This is technically and economically acceptable if a braking power is not greater than approximately 20% of the drive power and if braking is rarely used. If greater braking power is needed, two options exist: to use AFE in parallel with diode rectifier or to use only AFE.

FCs in single drive configuration can be used in multi-motor drives, but in that case the coordination of the drive functions is achieved through higher level control system. Multi drive configuration FCs consists of a separate rectifier and inverter modules. Fig. 3 presents FC in the single drive configuration, used in multi-motor drive of BCs within Overburden ECS (excavator-conveyor-spreader) system in Drmno OPM in Serbia.

If multi-motor drives use multi drive FCs, they are configured from a separate rectifier and inverter modules. One diode rectifier module and one AFE rectifier module supply power to the shared DC link circuit powering the necessary number of inverters and motors. The total installed power of the rectifiers is equal to the total installed power of the inverters. The power of an AFE rectifier can be less than the power of a diode rectifier, considering that with a BC the necessary braking power is normally less than the drive power. An advantage of this configuration type is that the load sharing between drives can be conducted in the DC circuit. However, in multi-motor BC drives this advantage is not required because all drives always operate in the same mode. Two rectifier modules can be utilized for decreasing the distortion of current in the supply line, but this requires utilizing a three-winding transformer, with secondary windings connected to achieve a phase angle displacement of secondary voltages by 30°.

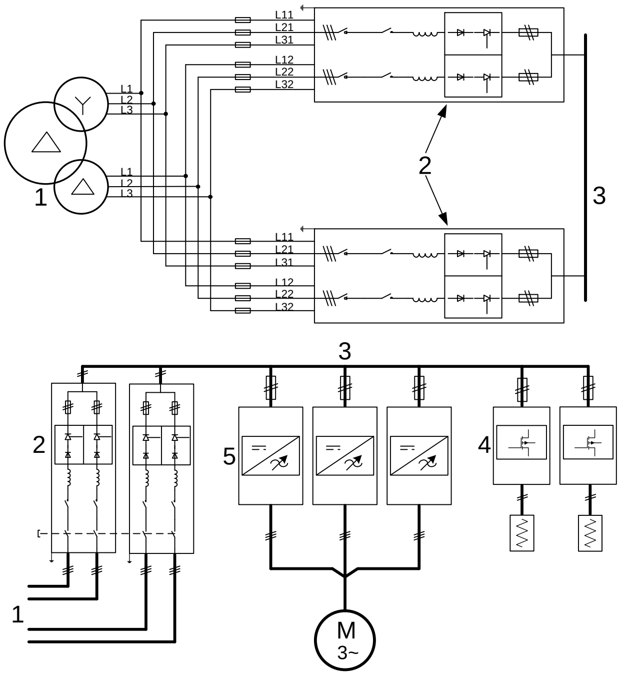

Figure 3. The single drive configuration of frequency converter in four quadrant operation of multi-motor drive of BC at the ECS system: 1: three-winding transformer; 2: rectifier modules; 3: DC link circuit; 4: braking modules (choppers with braking resistors); 5: inverter modules

Using a three-winding transformer increases the total price of the drive as a system. The division of rectifiers into two rectifier modules is advantageous since modules with lower power ratings can be used, whereby the necessary number of reserve parts is decreased. In the case of malfunction of one of the rectifier modules, operation can continue with just one unit, but with limited conveying capacity, which entails the limited drive power. Just like rectifiers, inverters can be configured with multiple parallel connected lower-power modules whereby benefits are achieved through the simple replacement, reserve parts' quantity and operational reliability.

With multi-motor BC drives, along with variable speed, the FCs must also provide equal sharing of load. Transport systems which use BCs with multiple motors are normally complex and require the proper control system, not just because of the drive, but rather because of other technological functions. For these purposes, PLCs are used. PLCs which are used in these types of cases are able to perform a portion of the control functions with all drives, as well as with the belt drive. Fig. 4 shows a principle block diagram of control of a belt drive with four motors. A speed regulator function is implemented into the PLC where the reference speed is generated according to the algorithm for improved BC energy efficiency. The speed regulator can be PI or PID. Strong differential action should be avoided due to the elasticity of the belt. All of the aforementioned functions in the PLC must be realized with a constant sample rate. A sampling time of 100-150 ms is sufficient and corresponds to the speed change. The output signal of the speed regulator, as the reference torque, is forwarded to all FCs. In the given example, there is an FC using a DTC algorithm. The individual drive speeds are estimated values, which are obtained from the FC. The accuracy of this information is more than sufficient for this drive type. The processor that processes signals within the FC is much faster than the processor in the PLC because it must process the fast changing variables - current and torque. Communication between the PLC and FCs must be achieved through adequately fast standard protocols such as ModBus+, ProfiBus, Ethernet or DeviceNet, the speed of communication would be no less than 1.5 Mb/s to facilitate the rapid exchange of information such as Control Word, Status Word and Fault Word.

The distribution of load between drives can be achieved using the master-follower option, which is a feature of nearly all standard FCs. In that case, one of the drives is the master and its internal speed regulator regulates the belt speed while the remaining drives receive the reference torque from the master. This solution is not suitable in cases when some of the drives need to be put out-of-use. In such cases, it is necessary to change the role of individual FCs, which is not often simple, and may require production interruption. BCs with multi-motor drives can operate even when all drives are not active due to reserves in power, decreased load as a result of decreased capacity or the shortened length of the BC, which is a common case in open pit mines.

In connection with the algorithm for reference speed generation that is applied at the considered system of BCs, the reference speed during variable speed mode of BC operation can also be applied to single motor BCs with VSD, as well as to BCs with greater capacities having multiple drive motors. With multi-motor BC drives, along with variable speed, the drives must also provide equal load sharing. In the observed BC system, all advantages of applied VSDs are used. Regarding the issue raised in this paper, the main two are speed adjustment when starting and stopping with a predefined acceleration and deceleration rate and elimination of belt slippage on the driving pulley through speed control, i.e. through a short-term decrease of speed.

III. CONTROL CENTER

The operation of conveyor at lower than rated speed would lead to a decrease in the amount of energy needed to conduct transport, as stated before [13]. Different algorithms are developed for generating the reference speed of the system of belt conveyors as a function of instantaneous cross section of material on the belt, in order to achieve reduced electrical energy consumption but to avoid potential spillage of material, slippage of the belt, activation of electrical braking and unnecessary stress of belts and mechanical assemblies. The validation of the proposed idea is achieved through experimental results recorded on an existing system of belt conveyors in an open pit mine and presented in [4] and [13]. It has been proved that with reference speed determined according to both approaches (constant [4], and variable (based on fuzzy logic control) acceleration and deceleration rate [13]), reduced electrical energy consumption is gained under given constraints of the considered system of belt conveyors.

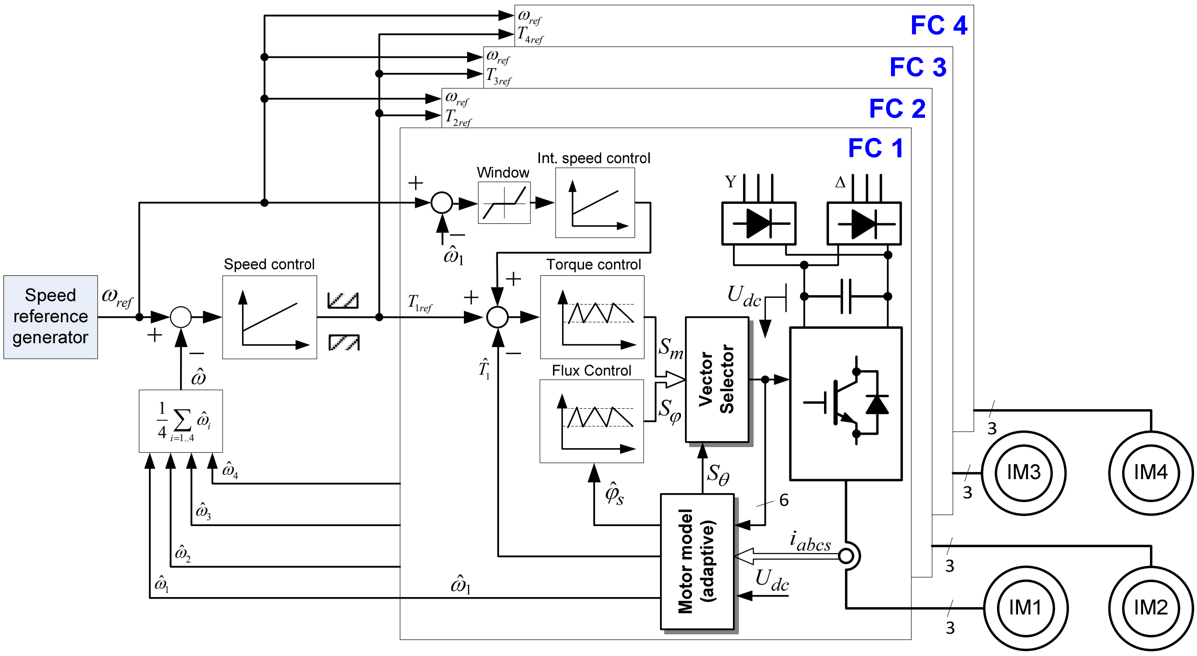

Figure 4. Block Diagram for Control of a Multi-motor BC Drive

In accordance with [4], additional measurements of belt tension during the operation of belt conveyor with controlled reference speed will prove that belt tension remain within the same limits as is in the case of the operation with constant speed. Fig. 5 shows a simplified diagram of a BC system with five BC stations, an excavator and a spreader. During the operation, the excavator can deposit material on either BC 1 or BC 2. The material is conveyed over BC 3 and BC 4 to BC 5, from where the material is then transferred to the spreader.

In a BC system like the one shown in Fig. 5 (BC1 and BC2 are bench conveyors, BC3 and BC4 are connecting conveyors and BC5 is dump-side conveyor), if belt speed regulation is used, a larger amount of information needs to be exchanged and this requires using fast communication protocols as well as the appropriate methods of data transfer. Due to the length of the route, fiber optic cables are used or, if the conditions and configuration of the terrain allow, wireless communication is utilized. A simplified communication network configuration of the BC system is shown in Fig. 6. The supervisory control system is located within the control center (CC) alongside the PC with monitors in which SCADA is implemented. Within the control center is also the PLC, which controls the operation of the BC system (as a whole), and the remaining necessary equipment. The PLC and PC are connected via Ethernet to the PLCs on the BC stations. On each BC station, there are four FCs, which are connected to the PLC through a ProfiBus network. An algorithm for controlling belt speed has been implemented into the PLC on the BC stations and an algorithm for calculating the reference speeds of a speed controlled BCs as the function of instantaneous capacity, has been implemented into the PLC within the CC.

The operation of modern BC systems is controlled from one location, namely from the control center, which is housed in a location easily accessible to people, e.g., in an administrative building. Fig. 6 shows the principle of organization of a control center. By using modern communication technologies, all information on the status of each BC is available in the control center. Using a SCADA system, a complete overview of all important elements for the functioning of the facility can be obtained.

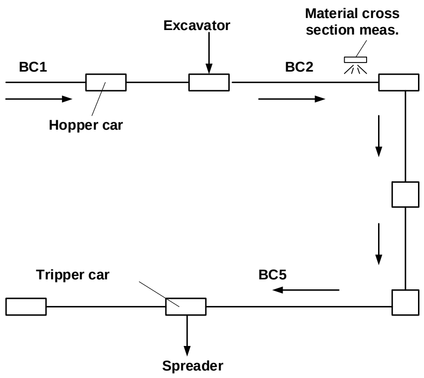

Figure 5. BC System with five BC stations

Additionally, it is possible to execute all control functions, from powering up and belt tensioning, to putting the system into operation and stopping it. A SCADA system offers extensive capabilities and advantages:

- Display of the status and control of the switchgear; using the available commands, individual switches can be toggled on and off, and the entire facility can be automatically turned on according to a defined procedure, whereby the process for preparing the facility for operation is accelerated.

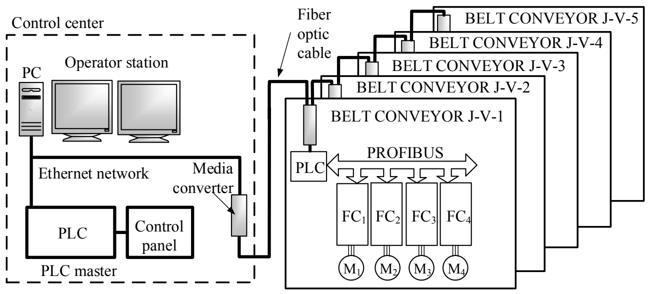

Figure 6. Communication Network of a BC System

- Display of peripheral limit switches on a BC station; reaction of any limit switch registers as a change of color of the corresponding symbol.

- Display of temperatures for the bearings of the motor and gearbox.

- Along with the visual display, in the case when the permitted values are exceeded, or during other irregular states, corresponding audio and light signals are emitted. Additionally, such events are logged and the sequence of their occurrence can be analyzed when needed.

Controlling a system from one location significantly increases its utilization time. Since 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 work has been shortened. A full display of the system status facilitates preventive maintenance and in the case of malfunction the maintenance service has information on the necessary repair before arriving on location.

For the complete and proper functioning of a system controlled from a CC, aside from the communication system, monitoring network and control network, video and audio communication with the system structures must also exist. Video monitoring enables the operator to monitor the status at characteristic locations and audio allows him/her to have communication with the repair teams or with the on-site service personnel. The aforementioned devices can be connected by Ethernet protocol using IP technology so that a separate plant network is created. The control and plant network should be hardware independent, meaning that they are realized with completely separate devices, antennae and cables. On the one hand, the information transferred through the control network has a high priority and delays in the transfer of information are not allowed to occur. Then again, video and audio signals do not have a high priority, but rather the amount of transferred data is quite large. It is particularly important to highlight that every time communication is interrupted in the control network, the system must be stopped as if the EMERGENCY STOP command has been issued.

Fig. 7 shows the control and plant network for the BC system considered in the paper, comprising five BC stations controlled from the control center.

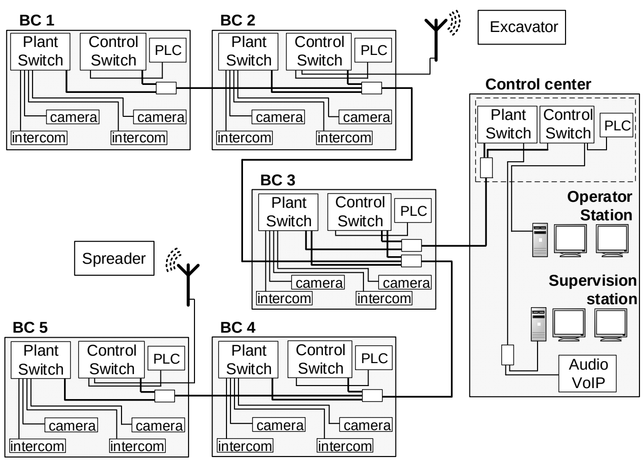

Figure 7. Control and plant networks

IV. Belt Tensioning Devices

Designing a system of belt conveyors of high capacity, speed and therefore large installed power to transport overburden in open pit lignite mines, is a very complex engineering task. Besides selecting and configuring drive systems for conveyors with significant lengths, the author of [28] emphasizes that a major challenge is to correctly design an effective and reliable belt tensioning system. With such tensioning systems, the failure rate of the conveyor will be reduced and belt durability increased. This is of significant interest, since the belt length makes its investment and operating costs greater than those of all other conveyor sub-assemblies [28]. Additionally, the authors of [9] believe that there is a lack of knowledge how to determine values for the permitted acceleration and the demanded acceleration in transient operation, what may lead to amplification of two major risks: belt breaking at the belt splicing area and slipping between the belt and the drive pulley. Although standards DIN 22101 and similar, or CEMA Belt books [29] determine the framework within which the design procedure of belt conveyor system must be conducted, the authors of listed literature agree that the design, selection and analysis of the operation of modern belt conveyors with different tensioning devices require complex computational procedures and simulation studies. They suggest applying the method in which estimation based on calculations is initially performed, followed by corrections based on simulations, in order to achieve proper steady-state and transient operation of the considered belt conveyor.

Two main groups of take-up devices for belt conveyors exist according to [28]:

1. fixed take-up devices, those with fixed position of the tensioning pulley during conveyor operation and

2. those with changing position of the tensioning pulley during conveyor operation, which can be further grouped into following categories:

a) weight (gravity);

b) constant tension – equipped with a hydraulic or pneumatic system driving the tensioning pulley;

c) automatic – equipped with automation systems;

d) follow-up – the required changes of the tensioning force follow changes of the driving torque on the pulley.

Take-up systems contain tensioning carts performing different travel lengths, determined as the distance between their extreme positions during start up, steady state operation, deceleration and stoppage of the conveyor, influenced by the change of the loading state of the belt and its flexibility characteristics [28], in order to maintain belt tension within required limits. Many factors have an effect on the forces in the belt such as conveyor's resistance to motion, the type of tensioning device and the method of controlling the start up and deceleration of the drive system. Also, the elasticity modulus of the belt is the parameter which is used in the design phase to determine the length of the tensioning cart travel, but the exploitation has shown that this parameter is changing during the operating life of belt conveyor due to two main reasons: different rheological characteristics of the belt comparing to samples studied at the laboratory and wearing of the belt influenced by changes on the terrain which are not adequately accompanied by the necessary changes in mode of belt conveyor operation regarding design phase. Therefore, the author of [30] suggests using follow-up belt tensioners instead of devices with a stationary tensioning pulley: for a comparable load of transported material, belt conveyors with a follow-up tensioning station have the force in the belt between 40% and 80% of the value of the force in the belt of a conveyor with a winch tensioner. This is due to their mode of operation, meaning that they adjust the level of tension force to be proportional to the changing of driving force thereby providing minimal belt tension throughout the period of the conveyor work.

V. Experimental Results

The belt conveyors within the system considered in the paper are designed with the fixed take-up devices, i.e. with a constant position of the tensioning pulley during conveyor operation. The operators in the control center can occasionally change the position of the tensioning pulley (while the belt is stopped) in order to compensate for changes in condition and extension of the belt length. Belt tension is measured at the take-up pulley, indicated as position 3 in Fig. 8, which represents the belt conveyor structure. All results presented in the paper are measured at the first connecting belt conveyor, BC3 as shown in Fig. 5. In the following time diagrams, speed (v_3) and torque (T_3) are average values for the multi-motor drive of BC, A_{3in} is the cross section of incoming material on the belt, all presented as percentages of their rated values. The cross section A_{3in} is measured just before the transfer point on BC2, so the data can be considered as the instantaneous volume of incoming material.

For each belt conveyor, the belt tension rating is a given and thus a constant value, and consequently, the belt tension force is presented as a percentage of that value.

Fig. 9 presents characteristic values during the start up period of loaded BC. It can be seen that variable acceleration profile is applied with the aim to reduce the mechanical jerk and to realize soft start. The acceleration time, as well as belt tension force, is within the safety limits recommended in the references [9, 17, 18]. The torque has a small value due to short length of the belt, and operation with smaller than rated capacity at the time of the recording. Moreover, motors are selected with extended power margin for variable speed operation with self-cooling.

Two hours of constant speed operation of loaded belt conveyor are displayed in Fig. 10. The congruence of the belt tension force time diagram with torque diagram is mainly because the period between gaps in incoming material, caused by the excavator, agrees with transport time of the material over the actual length of the belt. The value of tension force varies between 68 and 84% of belt tension rating.

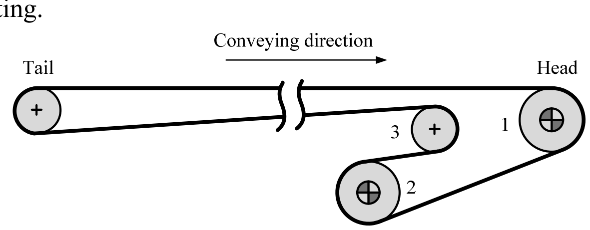

Figure 8. Belt conveyor with two driving pulleys. 1 and 2 – driving pulleys, 3 – tensioning (take-up) pulley

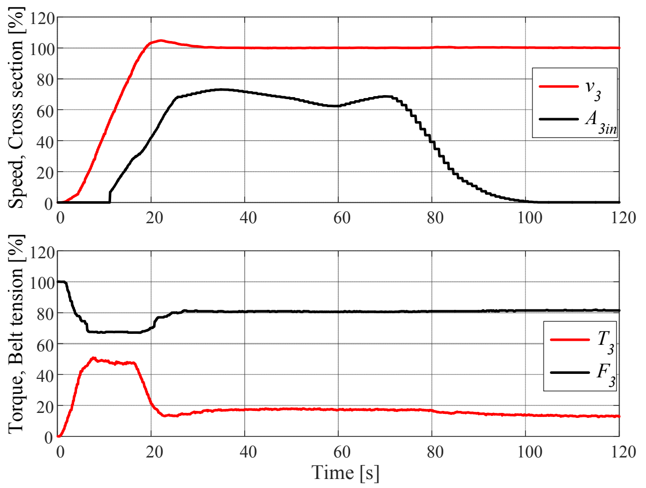

Figure 9. Start up process of the BC 3. – lightly loaded belt on the start (v3ref - reference speed, v3 - actual speed, A3in - incoming material cross section, T3ref - average value of reference torque, T3 - average value of actual torque, F3 - belt tension force)

In accordance with incoming cross section of bulk material, two hours of belt conveyor operation with speed controlled are presented in Fig. 11. The algorithm with constant deceleration, shown in Introduction is applied. Since comparative analysis between belt conveyor operation with constant and variable speed is planned to be conducted, measurements have to be recorded under similar conditions. Therefore, the average incoming cross section value was about 80% and consequently the variations of speed were within restricted range. It is obvious, as in the case of constant speed operation that time function of belt tension force is in line with torque, which follows existing load on the belt. Since the control algorithm attempts to gain more uniform material cross section distribution on the belt, it must reduce the gaps within the time diagram of material cross section on the belt, which appear as a negative consequence of excavator’s way of operation. This causes the alternation of periods of deceleration and acceleration, within which dynamic torque components appear, followed by the expected variations of belt tension force. As the acceleration constant is greater than deceleration constant, owing to the primary goal of applied algorithm to avoid spillage of material over the belt, an equivalent dynamic torque component is also greater. But, even with it, as it can be seen from the results presented in Fig. 11 and in Fig. 12, which is the zoomed part with the greatest range of speed change from record presented in Fig. 11, the value of tension force varies between 68 and 84% of the belt tension rating. This is the same range as in the case of constant speed operation, with frequency of changes determined by incoming material cross section.

Experimental results present strengths and weaknesses of the applied algorithm for reference speed generating, but also it can be concluded that application of the algorithm provides reduction of energy consumption and it does not introduce additional increase of belt tension force. Moreover, in the case of modern BC system with remote control, all unwanted increase of belt tensioning force can be avoided with the use of additional control of tensioning carts from control center, or by replacing devices with a stationary tensioning pulley with follow-up belt tensioners.

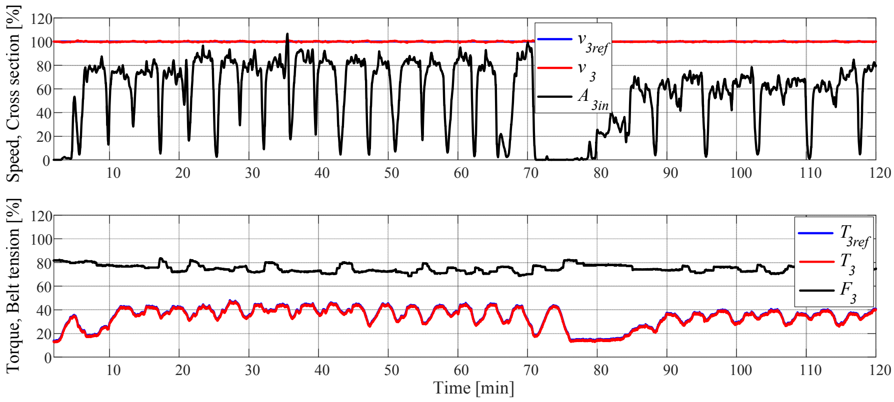

Figure 10. Constant speed operation of BC 3: v_{3ref} - reference speed, v_3 - actual speed, A_{3in} - incoming material cross section, T_{3ref} - average value of reference torque, T_3 - average value of actual torque, F_3 - belt tension force

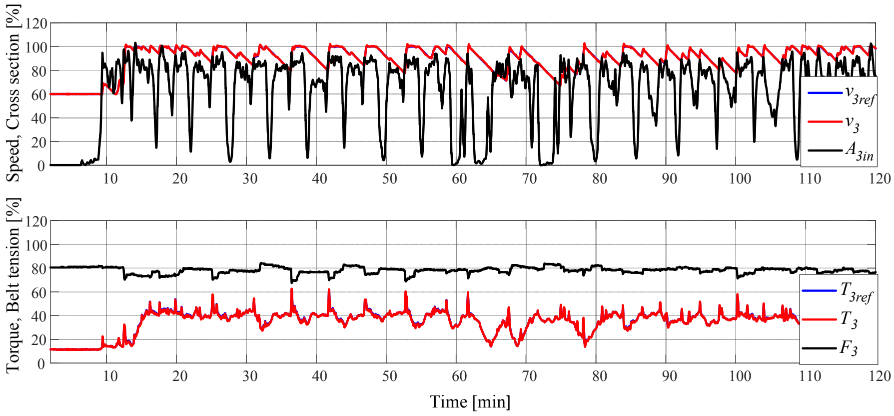

Figure 11. Speed controlled operation of BC 3: v_{3ref} - reference speed, v_3 - actual speed, A_{3in} - incoming material cross section, T_{3ref} - average value of reference torque, T_3 - average value of actual torque, F_3 - belt tension force

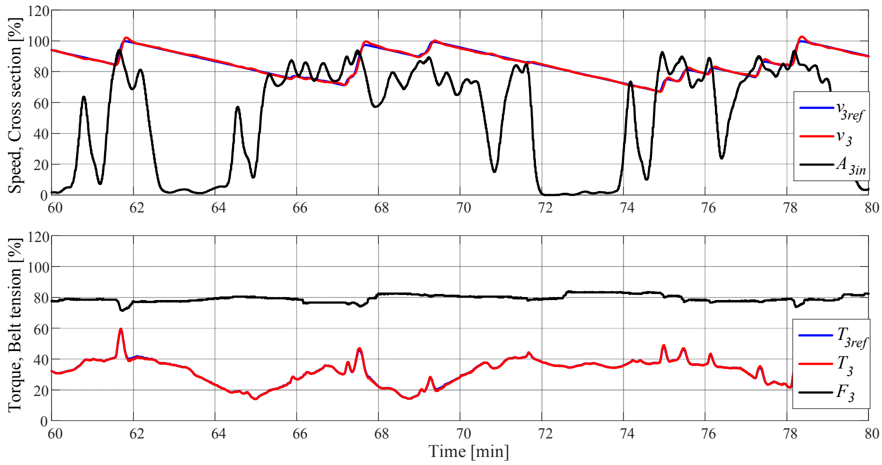

Figure 12. The zoomed part of the Fig. 11: v_{3ref} - reference speed, v_3 - actual speed, A_{3in} - incoming material cross section, T_{3ref} - average value of reference torque, T_3 - average value of actual torque, F_3 - belt tension force

VI. Conclusion

The paper experimentally verifies the finding that, under existing constraints of the system, the applied algorithm for variable speed control introduces neither additional stress to the belt nor the mechanical assemblies during the process of acceleration and deceleration. Unlike constant speed belt conveyor systems, the algorithm for variable speed control provides better utilization of the available material cross section on the belt and reduced electrical energy consumption of the drive. According to data presented in [13] obtained on the same BCS, variable speed operation provides the reduction of both average power [MW] and average value of specific energy [kWh/m^3], in the range from 3% to 19%, compared to constant speed operation, while variations of belt tension stay within the same limits as in the constant speed operation. The measured results of the belt tension force, shown in the paper, introduce a new insight into the variable speed belt conveyors.

Obviously, space is left to further improve the presented algorithm for reference speed generation, especially aimed at finding optimum value for acceleration under numerous constraints that exist in such a BC system. Finally, the authors of the paper must agree with [31], that although there have been several milestone improvements in energy management in the mining sector, it appears that there has not yet been widespread adoption of best practice measures. This is the case owing to a lack of initiatives that can be categorized as behavioral, financial and organizational. Performance with respect to energy management and conservation must be constantly improved, removing different kinds of barriers throughout extensive research work.

APPENDIX A

TABLE I. THE BASIC BC SYSTEM DATA

System of BCs data: Number of belt conveyors: 5; Total installed power:20 MW; Current length: 7.7 km.	**BC data:** Belt width 2000mm; Number of drives 4; Maximum length 3.25km; Rated speed 4.65 m/s; Rated capacity; 6600m^3/h
Frequency converters: Input voltage: 3×690V + 3×690V (12 pulse supply) Rated power (heavy duty): 1250kW Control method DTC Shaft sensorless operating mode	**Motor data (rated):** Voltage:3×690 V; Winding connection: Δ; Power: 1000kW Speed: 995rpm; Duty: S1, ED 100%; Efficiency: 96.50%; Power factor: 0.837; Current: 1036 A; Torque: 9600Nm

ACKNOWLEDGMENT

The authors wish to express their gratitude to the members of the Laboratory for Electrical Drives at the University of Belgrade, School of Electrical Engineering for their help and support in preparation of the paper.

REFERENCES

[1] W. Daus, S. Körber, and N. Becker, “Raw Coal Loading and Belt Conveyer System at the Nochten Opencast Mine,” Braunkohle Surface Mining, vol. 50, issue 2, p. 12, March/April 1998.

[2] S. Zhang and X. Xia, “Modeling and energy efficiency optimization of belt conveyors,” Applied Energy, vol. 88, issue 9, pp. 3061-3071, Sep. 2011, doi:10.1016/j.apenergy.2011.03.015

[3] Y. Pang and G. Lodewijks, “Improving energy efficiency in material transport systems by fuzzy speed control,” in Proc. 3rd IEEE International Symposium on Logistics and Industrial Informatics, Aug. 2011, pp. 159-164, doi:10.1109/LINDI.2011.6031139

[4] B. Jeftenić, I. Mihailović, M. Bebić, L. Ristić, D. Jevtić, N. Rašić, Saša Štatkić, “Energy efficiency in transportation of bulk material with frequency controlled drives,” in Proc. 14th International Power Electronics and Motion Control Conference EPE-PEMC 2010, Ohrid, Macedonia, Sept. 2010, pp. T5 105-113. doi:10.1109/EPEPEMC. 2010.5606597

[5] J. Schützhold, K. Benath, V. Müller, and W. Hofmann, “Design criteria for energy efficient belt conveyor drives,” in Proc. 2014 International Symposium on Power Electronics, Electrical Drives, Automation and Motion, June 2014, pp. 1256-1263. doi:10.1109/SPEEDAM.2014.6871921

[6] F. D. Popescu, “Controls ways of the transportation capacity variation for the canvas conveyer,” WSEAS Transactions on System and Control, vol. 3, pp. 393-402, 2008. ISSN: 1991-8763

[7] K. Awuah-Offei, “Energy efficiency in mining: a review with emphasis on the role of operators in loading and hauling operations,” Journal of Cleaner Production, vol. 117, pp. 89-97, March 2016. doi:10.1016/j.jclepro.2016.01.035

[8] X. Xia and J. Zhang, “Control systems and energy efficiency from the POET perspective,” in Proc. IFAC Conference on Control Methodologies and Technology for Energy Efficiency, Vilamoura, Portugal, 2010, pp. 1-6, doi:10.3182/20100329-3-PT-3006.00047

[9] Daijie He, Yusong Pang and Gabriel Lodewijks, “Determination of Acceleration for Belt Conveyor Speed Control in Transient Operation,” IJET International Journal of Engineering and Technology, vol. 8, issue 3, pp. 206-211, June 2016, doi:10.7763/IJET.2016.V8.886

[10] M. Dolipski, P. Cheluszka, and P. Sobota, “Investigating the simulated control of the rotational speed of roadheader cutting heads, relating to the reduction of energy consumption during the cutting process,” Journal of Mining Science, vol. 51, issue 2, pp. 298-308, March 2015, doi:10.1134/S106273911502012X

[11] N. Rašić, M. Bebić, L. Ristić, I. Mihailović, D. Jevtić, and S. Štatkić, “Improved efficiency of bucket wheel excavator operation with advances in the control algorithm,” in Proc. 4th International Symposium on Environmental Friendly Energies and Applications (EFEA), Sept. 2016, pp. 1-6. doi:10.1109/EFEA.2016.7748809

[12] STANDARD DIN 22101 Continuous conveyors - Belt conveyors for loose bulk materials - Basis for calculation and dimensioning, pp. 1-55, edition 2011-12.

[13] L. B. Ristic and B. I. Jeftenic, “Implementation of Fuzzy Control to Improve Energy Efficiency of Variable Speed Bulk Material Transportation,” IEEE Transactions on Industrial Electronics, vol. 59, issue 7, pp. 2959-2969, July 2012. doi:10.1109/TIE.2011.2169639

[14] J. Hiltermann, G. Lodewijks, D. L. Schott, J. C. Rijsenbrij, J. A. J. M. Dekkers, and Y. Pang, “A Methodology to Predict Power Savings of Troughed Belt Conveyors by Speed Control,” Particulate Science and Technology, vol. 29, issue 1, pp. 14-27, Jan. 2011. doi:10.1080/ 02726351.2010.491105

[15] H. Lauhoff, “Speed Control on Belt Conveyors - Does it Really Save Energy?,” Bulk solids handling, vol. 25, p. 10, 2005.

[16] C. Yan and X. He, “Model and Dynamic Simulation of Belt Conveyor,” in Proc. 2010 International Conference on Intelligent System Design and Engineering Application, Oct. 2010, pp. 949-951. doi:10.1109/ISDEA.2010.331

[17] D. He, Y. Pang, and G. Lodewijks, “Speed control of belt conveyors during transient operation,” Powder Technology, vol. 301, pp. 622-631, Nov. 2016, doi:10.1016/j.powtec.2016.07.004

[18] D. He, Y. Pang, and G. Lodewijks, “Green operations of belt conveyors by means of speed control,” Applied Energy, vol. 188, pp. 330-341, Nov. 2017, doi:10.1016/j.apenergy.2016.12.017

[19] Z. Kasztelewicz and J. Szymański, “Energy Saving Control Method of Electrical Drives in Coveyor Belts with Regulated Speed in Surface Brown Coal Mine,” Archives of Mining Sciences, vol. 53 (2), pp. 319-329, 2008.

[20] J. Kwaśniewski, “The use of monitoring to improve the reliability and endurance of continuous coal handling systems,” Archives of Mining Sciences, vol. 56, pp. 651–664, 2011.

[21] M. Dolipski, E. Remiorz, and P. Sobota, “Dynamics of non-uniformity loads of AFC drives,” Archives of Mining Sciences, vol. Vol. 59, No 1, pp. 155-168, Jan. 2014, doi:10.2478/amsc-2014-0011

[22] A. V. Rocha, H. d. Paula, M. E. d. Santos, and B. J. C. Filho, “Increasing long belt-conveyors availability by using fault-resilient medium voltage AC drives: Part II - Reliability and maintenance assessment,” in Proc. 2012 IEEE Industry Applications Society Annual Meeting, 2012, pp. 1-8. doi:10.1109/IAS.2012.6374079

[23] B. Jeftenić, M. Bebić, L. Ristić, and S. Štatkić, “Design and Selection of Belt Conveying Equipment & Systems,” in Design and Selection of Bulk Material Handling Equipment and Systems : Mining, Mineral Processing, Port, Plant and Excavation Engineering, , J. Bhattacharya, Ed., Kolkata: Wide Publishing, 2012, p. 254. ISBN 9788190904377

[24] N. Mitrovic, V. Kostic, M. Petronijevic, and B. Jeftenic, “Multi-Motor Drives for Crane Application,” Advances in Electrical and Computer Engineering, vol.9, no.3, pp. 57-62, 2009, doi:10.4316/AECE.2009.03011

[25] I. Birou, V. Maier, S. Pavel, and C. Rusu, “Indirect Vector Control of an Induction Motor with Fuzzy-Logic based Speed Controller,” Advances in Electrical and Computer Engineering, vol.10, no.1, pp. 116-120, 2010. doi:10.4316/AECE.2010.01021

[26] Marko M. Rosic and M. Z. Bebic, “Analysis of Torque Ripple Reduction in Induction Motor DTC Drive with Multiple Voltage Vectors,” Advances in Electrical and Computer Engineering, vol. Vol. 15, No. 1, pp. 105-114, 2015, doi:10.4316/AECE.2015.01015

[27] Petar Matić and S. N. Vukosavić, “Speed Regulated Continuous DTC Induction Motor Drive in Field Weakening,” Advances in Electrical and Computer Engineering, Vol. 11, No. 1, pp. 97-102, 2011. doi:10.4316/AECE.2011.01016

[28] P. Kulinowski, “Analytical Method of Designing and Selecting Take-up Systems for Mining Belt Conveyors,” Archives of Mining Sciences, vol. 58 (4), pp. 1301-1315, Jan. 2013, doi:10.2478/amsc-2013-0090

[29] CEMA, Belt conveyors for bulk materials, 6th ed.: Conveyor Equipment Manufacturers Association, Florida, USA, 2007.

[30] P. Kulinowski, “Simulation Method of Designing and Selecting Tensioning Systems for Mining Belt Conveyors,” Archives of Mining Sciences, vol. 59 (1), pp. 123-138, Jan. 2014, doi:10.2478/amsc-2014-0009

[31] M. Levesque, D. Millar, and J. Paraszczak, “Energy and mining – the home truths,” Journal of Cleaner Production, vol. 84, pp. 233-255, Dec. 2014, doi:10.1016/j.jclepro.2013.12.088