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Analysis of load unevenness of chain conveyor's driving motors on the basis of numerical simulations

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ABSTRACT

Purpose: Analysis of impact of extension degree of a telescopic trough installed on a drive end of a chain conveyor as well as time of conveyor start up on load unevenness of electric motors of conveyor's drives.

Design/methodology/approach: Analysis of load unevenness of electric motors of a chain conveyor was made basing on the current mean values of electric motors and mean driving torques of driving drums. Time curves were obtained from numerical simulation of operation of the 100 meters long chain conveyor of E260 trough profile and equipped with two 34x126 chains.

Findings: The analysis has shown purposefulness of development of the algorithm to control the conveyor operation improving its drives cooperation.

Research limitations/implications: Due to impossibility of carrying out tests in real conditions, a model of the conveyor was used for numerical simulations of the selected criteria operational states. The model was verified by comparison of the numerical simulation results with the results obtained on the testing facility located in Kopex Machinery in Tarnowskie Góry, Poland. The developed model will be used to verify the conveyor's control algorithm.

Originality/value: Numerical simulations of the conveyor operation were made in co-simulation technique integrating the software environment used in analysis of multi-body systems with MatLab Simulink software. Development of such integration will enable testing the functionality of the conveyor's control algorithm at changeable initial conditions and different states of conveyor operation.

Keywords: Mining industry; Chain conveyor; Numerical simulations

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ANALYSIS AND MODELLING

1. Introduction

Increase of length of longwall panels and increase of power of drives used in longwall mining systems force development and modernization of machines in the longwall system. AFC, used in transportation of run-of-mine from the longwall area to BSL, is one of the basic machines in a mine longwall system. Generally, AFCs are equipped with two drives: a discharge drive and a reversible drive, which cooperate with one or two electric motors. A torque generated by motors, multiplied by a gear, is transmitted to the driving drum, which cooperates with a scrapper chain, transforming the torque into the pulling force actuating the scrapper chain, scrappers and transported run-of-mine. Increase of conveyors length as well as uneven load to the conveyor with run-of-mine result in dynamic changes in motors load. In addition, elongation of scrapper chains causes their elastic deformations, what results in periodical or continuous loosening of the chain at the points where it leaves the driving drums. Chain loosening negatively affects the conveyor operation, causing increase of unevenness of load to drives and a risk of breaking the chain. AFCs can be equipped with a telescopic trough enabling control of the length of the scrapper chain outline as well as adjusts the chain tension [1, 6]. Elongation of the chain outline enables limiting or eliminating the chain loosening. However, it can cause excessive chain tension resulting in increase of chain resistance to motion and speeding up the wear of chain sub-systems. Use of frequency converters is another solutions aiming at control of chain conveyor operation to ensure proper chain tension [4, 5, 7]. Frequency converters and the telescopic trough on the reversible drive enable controlling the conveyor operation, minimizing the risk of failure at the same time. Thus, they enable extension of machine life and better use of the drives power. The computational model of the chain conveyor and the results of numerical simulations, which aim at determination of impact of telescopic trough extension on load of conveyor driving motors, are presented.

Impact of increase of voltage frequency of the current supplying the driving motors on the load to motors at conveyor start-up is presented on the basis analyses. Analysis of impact of changes of load to conveyor driving motors, occurring in a result of extension of the telescopic trough, or change of settings of frequency converters, enables determining the impact of these changes on load to the conveyor drives, what is required to develop the algorithm for the conveyor control.

2. Model of a chain conveyor

Model of AFC consists of its physical module and a module of electric motors. The module of the physical model was created in the software environment for the analysis of rigid body kinematics and dynamics. The module of electric motors was created in MatLAB/Simulink software programme. Numerical simulations of the conveyor operation were made in co-simulation technique [2, 3, 8].

The module of the physical model of the chain conveyor consists of rigid bodies connected by geometrical constraints and of elastic-and-damping elements. Force and the torque vectors as well as parameters of contacts between the selected bodies were defined in the model. Bodies of the physical module are the following simplified geometrical models: driving drums, the conveyor trough that makes the chain track, the scraper chain with scrapers, the telescopic trough of the reversible drive and the transducers recording tension of the chain on the discharge drive and the reversible drive. The model recreates the conveyor of 100 meters length, E260 trough profile and two 34 x 126 chains, (Fig. 1).

The module of electric motors consists of the model of 315kW asynchronous motors together with the power supply system with the frequency converter. In the calculation model, the following two motors were used: one on the conveyor discharge drive and one on the reversible drive. Each motor was equipped with the frequency converter.

Use of co-simulation technique required defining the rate of signal transmission between the modules of the physical model and the model of electric motors. Flow of the signals is shown in Fig. 2.

In the physical model, rotational speed of driving drums was recorded and the signal was sent to the model of the respective electric motor. The motor's driving torque was calculated from rotational speed and voltage frequency. Information about the torque was sent to the conveyor's physical model, considering the gear ration of the reducer. Mean value of the current recorded on each motor was the output signal from the motors' model. In the physical model, the input signal defining the extension of the telescopic trough on the reversible drive as well as the vector of the external load pressing the scrapers in the upper branch of the conveyor to the conveyor trough was determined.

Data recorded by the converters identifying chain tension were also the input data. Collected information will be entered to the control algorithm, which will be implemented in the currently developed calculation model.

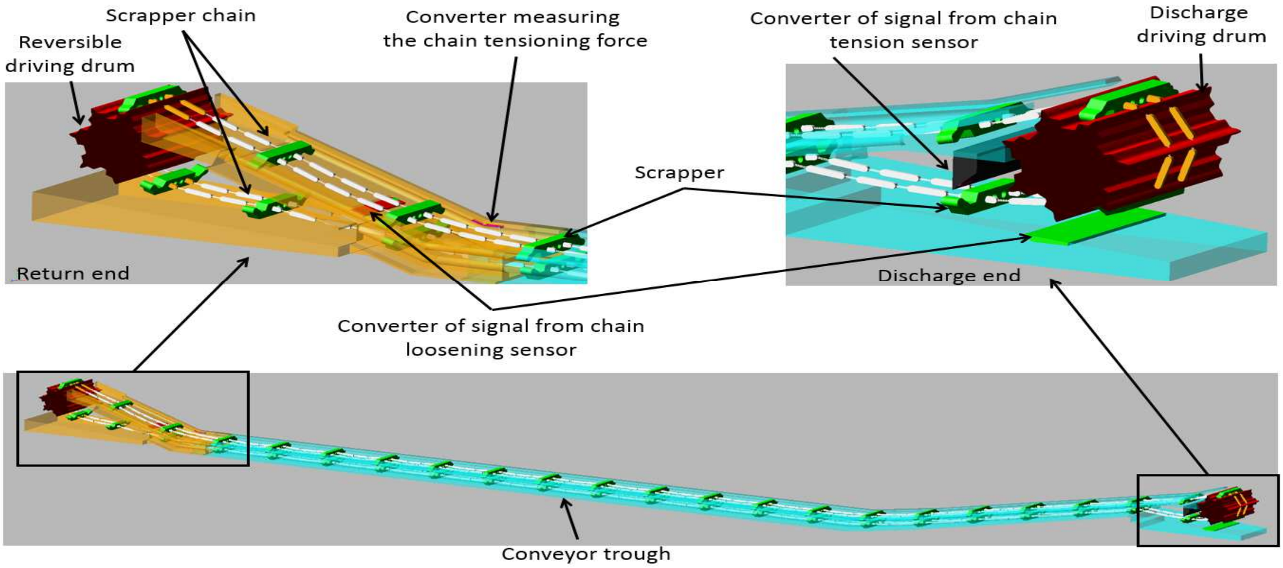

Fig. 1. Physical model of AFC

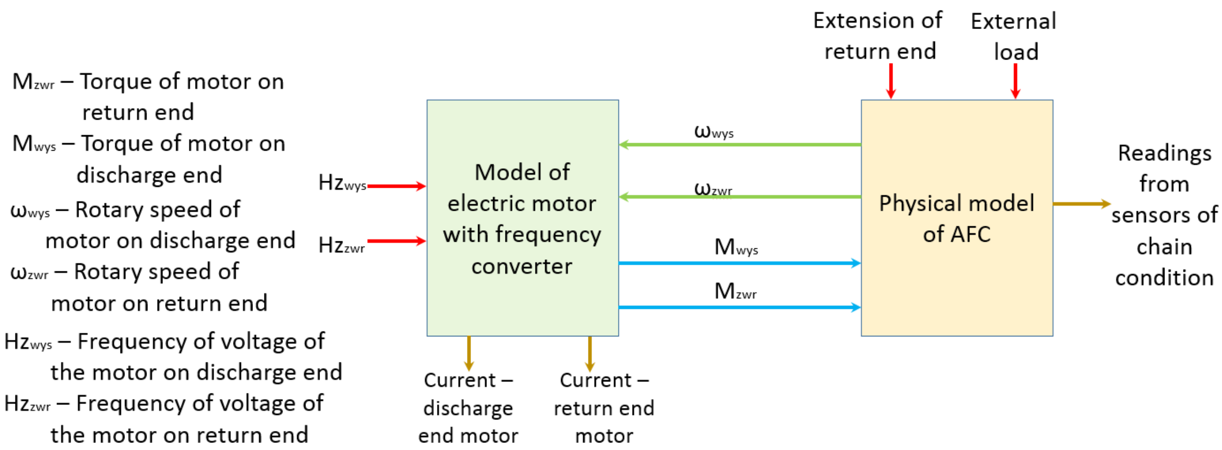

Fig. 2. Flow of signals in the calculation model of chain conveyor

3. Numerical simulation of the conveyor's load

Operation of the chain conveyor without load was numerically simulated on the computational model. Voltage frequency of the motor increased from 0 to 50 Hz in 1 s. Obtained time curves of the current in motors were compared with time curves of the current recorded at the test stand at Kopex Machinery in Tarnowskie Góry for the conveyor of the same length, size of trough outline and size of the chain. Time curves of the current measured in electric motors during start-up and travel without external load compared with those obtained for the conveyor at the test stand and with the results of numerical simulation are presented in Fig. 3.

Then the movement of the conveyor with the load was simulated. The load was reached in 12th second of the simulation in a form of vectors of forces pressing the selected scrappers in the upper branch of the chain to the conveyor trough. This load was maintained during stable operation. The conveyor was unloaded by removing the set loading vectors in the 30th second of the simulation. Time curves of the current in electric motors and time curves of the torque on driving drums are presented in Fig. 4.

Analyzing the curves presented in Fig. 4, the following stages of conveyor operation can be distinguished:

- Stage 1-conveyor start-up. At this stage, there is a rapid increase of the current in motors and the torque on driving drums. After reaching the maximum current in motors and the torque on driving drums, they decrease in a result of gaining speed by the conveyor until the moment of stabilization of the current and the torque on both drives.
- Stage 2-stable operation of the conveyor without the load. At this stage the current in electric motors and the torque on driving drums are constant at the level indispensable to overcome resistance to motion of the unloaded conveyor.
- Stage 3-uneven load of electric motors resulting from simulation of loading the run-of-mine on the conveyor. Applying the load results in significant increase of the current in the electric motor installed on a discharge end. the torque on the discharge drum (Fig. 4-place marked with 1) also dynamically increases with increase of the current. Smooth increase of the torque is observed with momentary decrease of rotary speed of the electric motor. In the second half of stage 3, the electric motor on the reversible drive supports operation of the electric motor installed on the discharge drive. Smooth increase of the current in the electric motor installed on the reversible drive and the torque on the reversible driving drum is noticeable. the torque on driving drums and the current in both motors reach the level of stable operation; stage 4 of conveyor operation starts.
- Stage 4-stabilized operation of the conveyor with the load. At this stage both the torque on driving drums and the current in electric motors oscillate around the value, which enables overcoming the resistance to motion of conveyor with transported run-of-mine (load). At this stage of operation, cyclic changes of the torque on driving drum and cyclic changes of the current in motors are observed. These changes result from distributing the load to discharge drive and reversible drive (at the beginning discharge drive is more loaded and after a while reversible drive is more loaded).
- Stage 5-removal of load. It can be interpreted as discharge of conveyor. The first reaction to removal of load is observed in time curve of the torque on discharge drum and in the current in electric motor installed on a discharge end. There is a rapid drop of both these parameters (Fig. 4-place marked with 2). In the case of removal of load, the torque on discharge driving drum drops to zero. Then it increases to the level, which enables overcoming the conveyor resistance to motion. The current in the electric motor installed on the return end and the torque on reversible drum also rapidly decreases. The load of both drives in the case of removal of external load is equalized in a significantly shorter time than it is, when the load is applied.

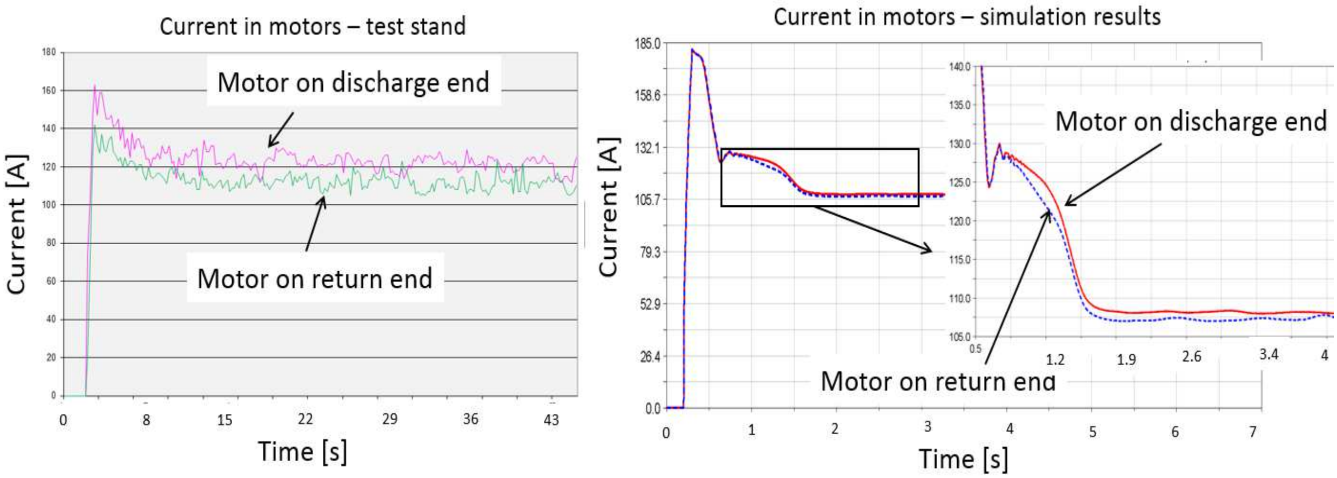

Fig. 3. Current recorded in electric motors on a testing stand and during numerical simulations

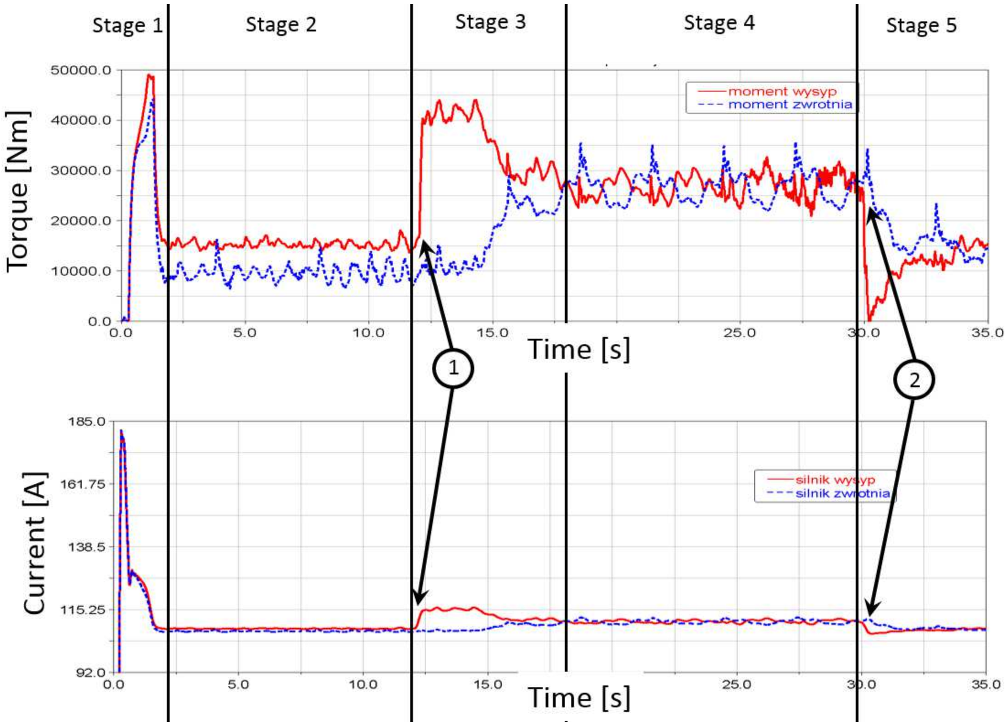

Fig. 4. Torque of driving drums and current values in motors during numerical simulation of conveyor operating with force vector equal to run-of-mine load of 12 000 kg

4. Numerical simulations determining the impact of extension of the telescopic trough on the load of conveyor's drives

Simulations of the impact of extension of the telescopic trough on conveyor's drives load were carried out for the following boundary conditions:

- length of the conveyor 100 m, middle position of the rod in a cylinder of the telescopic trough ("0") was assumed as the starting position (during simulation, extension of the cylinder was increased or decreased by 0.015, 0.04, 0.06, 0.08 and 0.1m),
- conveyor start-up was realized by increasing the frequency of voltage from 0 to 50Hz, in 1s,
- after starting up the frequency of voltage in conveyor motors was constant and equal to 50 Hz,
- conveyor's load, referring 12 000 kg of run-of-mine occurred in 12th s of simulation.

In Figure 5 torque curves on the discharge drive drum, in relation to the described variants of simulation, during which the telescopic trough on reversible drive was extended, what elongated the conveyor, were presented. Extension of the telescopic trough during the first simulation was assumed as the initial position (the rod in the middle of the cylinder's scope of operation). The curve of the torque on the driving drum in this simulation variant was marked on the diagrams by symbol "0". Next simulations were carried out with increased extension of the telescopic trough by +0.015, +0.04, +0.06, +0.08 and +0.1 m.

The simulations covered the following stages of operation: start up, stable operation without load, differentiated load of drives, and stable conveyor operation during transportation of run-of-mine. In Fig. 6, torques on the reversible driving drum, recorded during six described simulations, are given. The simulations also enabled determining the curves of the current recorded in electric motors. In Fig. 7, curves of the current recorded in the electric motor on discharge end during elongation of the telescopic trough on the reversible drive, are shown.

During analysis of simulation of stable operation of the conveyor without load, it was observed that the torque on the discharge driving drum at extension of the telescopic trough in the range 0-0.04 m is constant (at such extension of telescopic trough there are no significant dynamic loads). At extension of the telescopic trough greater than 0.04 m it was observed that load to the drives increases with increase of the conveyor's length. Increase of telescopic trough extension results in occurrence of cyclic dynamic loads. Cyclic increase and drop of the torque on the diagram is the evidence. The greater is difference between the minimal and the maximal torque in one cycle, the greater is dynamic load. Torque changeability on the reversible drum, resulting from elongation of the conveyor, is analogues to changeability of the torque recorded on the discharge drum. Applying the load cause uneven load to the conveyor drives. At this stage of the conveyor operation, the torque on the discharge drum rapidly increases reaching the highest values during simulation without the conveyor elongation (in the starting position) and at extension of telescopic trough by 0.015 m. The torque at telescopic trough extension equal to 0.04 m was lower than in the case of smaller extension. Further extension of the telescopic trough resulted in decrease of the torque on the discharge drum. It can also be noticed that torques on the discharge drum at conveyor elongation by 0.06, 0.08 and 0.1 m at this stage of operation are similar. The lowest torques on the reversible drum were recorded at extension of telescopic trough from 0 to 0.015 m. Then, the torque on the reversible drum increased with increase of extension of the telescopic trough. The highest torque was recorded at extension equal to 0.1 m.

From the simulations it results that extension of the conveyor's telescopic trough in the range 0.04-0.06m is most advantageous at the stage of uneven load to the drives.

At the stage of stable operation of the conveyor with load (during run-of-mine transportation), there was no significant change of the torque on discharge drum during elongation of the conveyor in the range 0-0.06m. Increase of extension of the telescopic trough above 0.06m resulted in increase of the torque and dynamic loads on the discharge drive. Impact of conveyor elongation on the torque on the reversible drum at stable operation, during run-of-mine transportation, is the same as in the case of the discharge driving drum.

Retraction of the telescopic trough was also simulated. Analysis of the results enable concluding that shortening the telescopic trough at assumed boundary condition does not cause significant changes in drives load. However, shortening the telescopic trough can cause chain loosening at places where it leaves the driving drum and wedging of chain link or the scraper. Such a situation can result in sudden dynamic overload in the driving system, and it can even cause the chain break and failure of the conveyor. The simulations enabled determining the curves of the current recorded in electric motors. In Fig. 7 time curves of the current recorded in the electric motor on discharge end during elongation the telescopic trough on the reversible drum are shown.

Fig. 8 shows curves of the current in the reversible drum motor, recorded during simulation.

Character and trend of the current recorded in motors placed on return end and discharge end regarding each stage of conveyor operation is conform to the previously described torque curves. In table 1 the list of the maximal current (P_z, P_w) in motors and torques (M_z, M_w) on driving drums in relation to analyzed extensions of the telescopic trough on the conveyor's reversible drive is given.

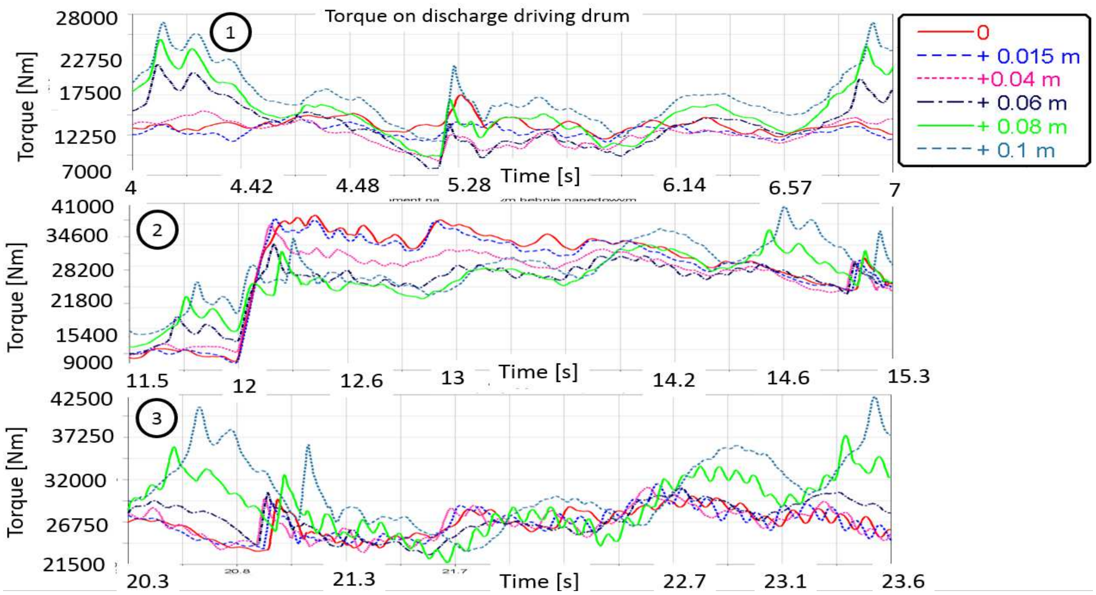

Fig. 5. Torques recorded on discharge driving drum at different extension of telescopic trough, 1-stage 2 of conveyor operation, 2-stage 3 of conveyor operation, 3-stage 4 of conveyor operation

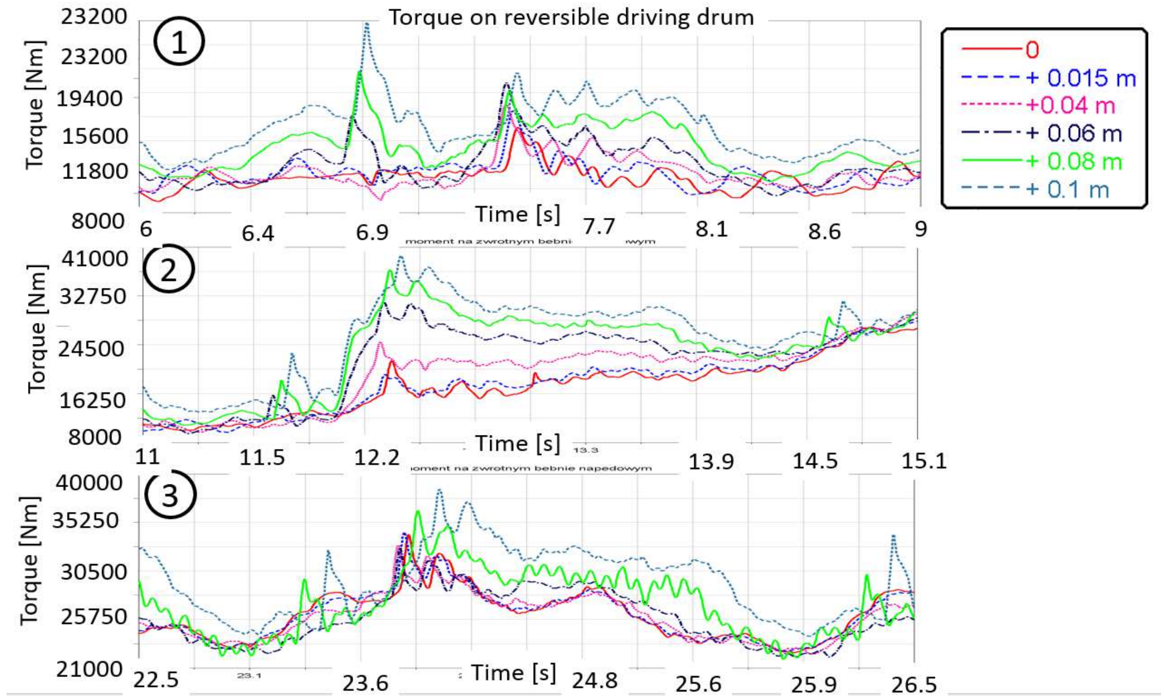

Fig. 6. Torques recorded on the reversible driving drum at different extension of the telescopic trough, 1-stage 2 of conveyor operation, 2-stage 3 of conveyor operation, 3-stage 4 of conveyor operation

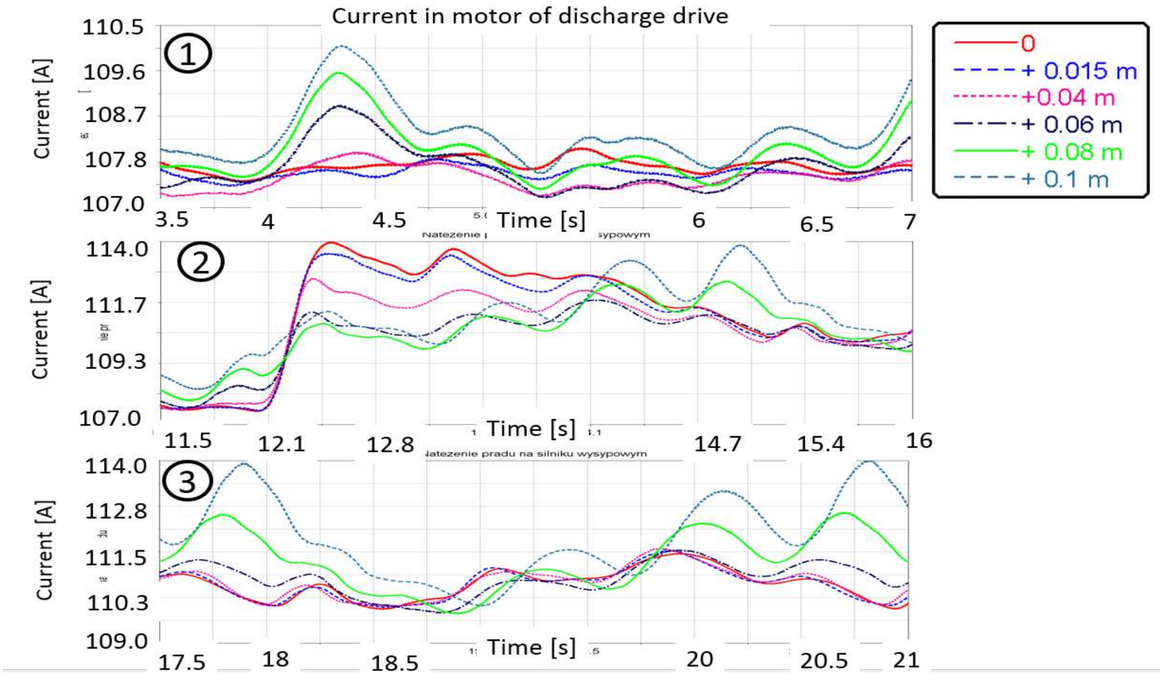

Fig. 7. Curves of the current recorded in the motor placed at discharge end at different extension of telescopic trough, 1-stage 2 of conveyor operation, 2-stage 3 of conveyor operation, 3-stage 4 of conveyor operation

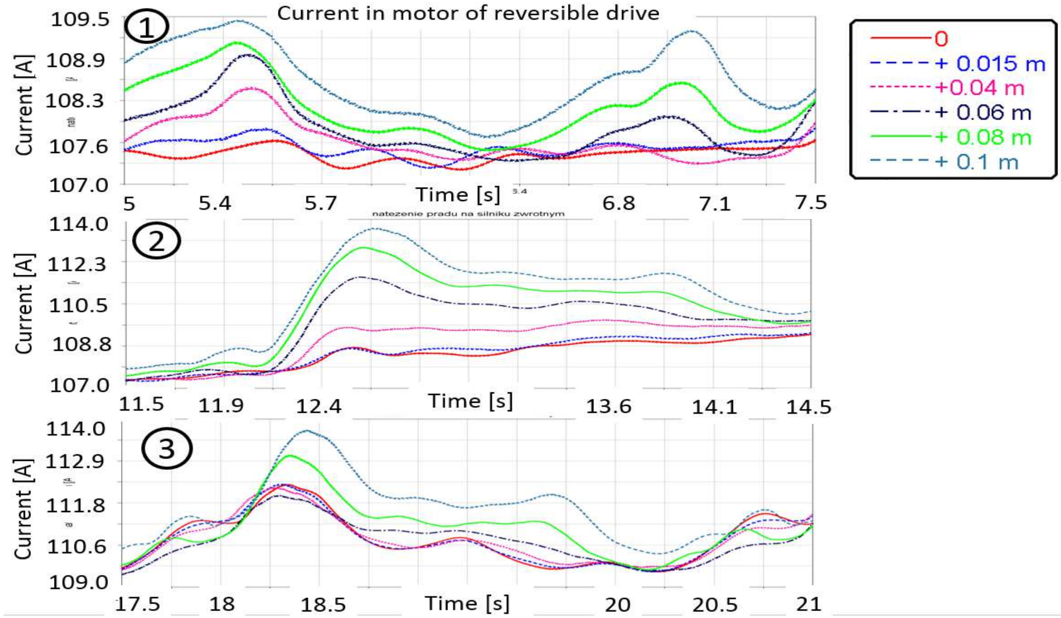

Fig. 8. Curves of the current recorded in the motor placed at return end at different extension of the telescopic trough, 1-stage 2 of conveyor operation, 2-stage 3 of conveyor operation, 3-stage 4 of conveyor operation

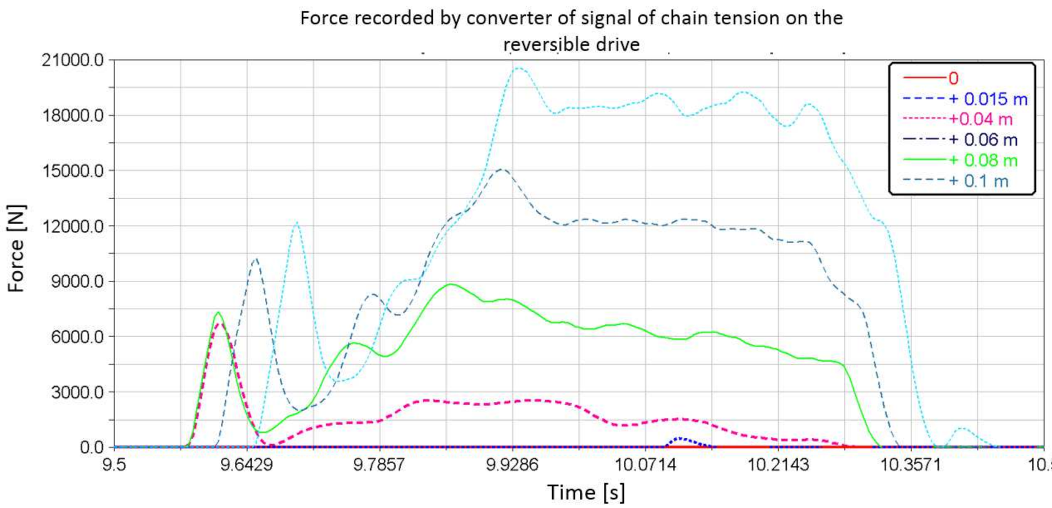

Fig. 9. Curves of forces recorded by the chain tension converter on the reversible drive for different extension of the telescopic trough

The model of converter of the signal from detector of chain tension on reversible drive was included in the calculation model. The converter measures the pressing force exerted by the scraper passing underneath on the measuring component. By measuring the force pressing the converter by the scraper and knowing the chain angle we can calculate tension of the scraper chain. In Fig. 9 the curve of the force read out form the chain tension converter on the conveyor's reversible drive, recorded during simulation at different extension of the telescopic trough is shown. We can observe periodicity of the force in the converter associated with movement of scrapers pressing it. At extension of the telescopic trough in the range 0-0.015 m chain tension on the return end was equal to zero. It means that scrapers moving under the converter did not exert any force. Increase of extension of the telescopic trough up to 0.04 [m] resulted in appearance of the small force on the chain tension converter. It means that chain tension increased and scrapers passing under the converter pressed it with the small force. Further extension of the telescopic trough caused significant increase of the pressing force of scrapers, what meant increase of chain tension. Monitoring the chain tension is important for proper operation of the conveyor as too high chain tension can speed up wear of conveyor components and too low tension can cause conveyor failure due to wedging the chain link or the scraper.

Table 1.
List of the maximal currents in motors and torques on driving drums (index z-return end, index w-discharge end)

Criterial state	Stage of conveyor operation		
	Stage 2	Stage 3	Stage 4
	P_z, P_w [A], M_z, M_w [Nm]		
Extension 0 [m]	P_z=108 P_w=108.3	P_z=111.9 P_w=113.9	P_z=111.9 P_w=111.9
	M_z=16 400 M_w=15 750	M_z=33 000 M_w=38 700	M_z=33 000 M_w=32 000
Extension 0.015 [m]	P_z=108.5 P_w=107.9	P_z=112.1 P_w=113.5	P_z=112.2 P_w=111.7
	M_z=18 000 M_w=15 000	M_z=34 500 M_w=38 100	M_z=34 800 M_w=31 800
Extension 0.04 [m]	P_z=108.4 P_w=108	P_z=109.5 P_w=112.5	P_z=112.1 P_w=111.8
	M_z=20 500 M_w=15 300	M_z=34 400 M_w=34 400	M_z=33 000 M_w=31 500
Extension 0.06 [m]	P_z=108.9 P_w = 108.9	P_z = 111.6 P_w = 111.3	P_z=112.4 P_w=111.8
	M_z=23 300 M_w=19 500	M_z=31 700 M_w=33 000	M_z=24 500 M_w=30 500
Extension 0.08 [m]	P_z=109.1 P_w=109.5	P_z=112.8 P_w=112.5	P_z=113.9 P_w=112.8
	M_z=23 200 M_w=24 700	M_z=37 100 M_w=32 900	M_z=36 500 M_w=36 000
Extension 0.1 [m]	P_z=109.7 P_w =110.1	P_z=113.6 P_w=113.8	Pz =114.5 Pw = 115.5
	M_z=26 500 M_w=26 900	M_z=39 500 M_w=36 100	M_z=39 400 M_w=42 200

5. Simulation of impact of rate of increasing the supply voltage frequency of electric motors on their load during start up

Numerical simulations of start-up of electric motors of the chain conveyor at different rate of frequency increase were also made. The frequency was increased from 0 to 50 Hz in: 0.5; 1; 2; 5 and 10 s. The start-up of motors without change of frequency equal to 50 Hz, was also simulated. The simulation of start-up was made for the unloaded conveyor. The simulation results are presented on the example of the discharge drive in a form of time curves of the torque on the discharge driving drum (Fig. 10) and time curves of the current in the electric motor installed on the discharge end (Fig. 11).

Start-up of the electric motor installed on the discharge drive, without the frequency converter, resulted in generation of the very high torque on the driving drum. Use of frequency converters during start-up enabled decreasing the maximum torque generated on the driving drum. Already after 0.5 s of frequency increase, significant decrease of the maximum torque was observed. Increase of voltage frequency from 0 to 50 Hz in 1 and 2 s caused further decrease of the maximum torque. At longer time of frequency increase (5 and 10 s), conveyor start-up became smooth and the torque generated on the driving drum increased gradually up to the value, which was obtained at stable operation of the conveyor. In this case, no sudden dynamic overloads were observed during start-up.

Start-up of the electric motor installed on the discharge end without frequency converter resulted in huge increase of the current. Use of frequency converters and setting the proper time of frequency increase caused decrease of the maximum current. During simulations, the lowest current was recorded at start-up which lasted 1s. At start-up with frequency increase equal to 0.5 and 2 s, the maximum current was lower than at start-up without frequency converter. Extension of time of frequency increase above 2 s caused short impulse of the high current and then its drop and after this the current was stabilized (Fig. 11). Extension of start-up time (time of frequency increase) resulted in longer time of increased energy consumption by the motors. On the basis of simulations, at assumed boundary conditions, start-up at with voltage frequency of motors increased from 0 to 50 Hz in 1s was found to be most appropriate.

The maximum current P_w in the motor of the discharge drive and the maximum torque M_w on the discharge driving drum are given in Table 2 in reference to the analyzed rates of frequency increase in the conveyor motors.

Table 2.
List of maximum values of the current and the torque on the discharge drum

Start up time	P_w [A]	M_w [Nm]
0 [s]	174.5	123 810
0.5 [s]	137.16	82 002
1 [s]	131.6	48 912
2 [s]	128.2	32 011
5 [s]	132.1	22 829
10 [s]	133	18 757

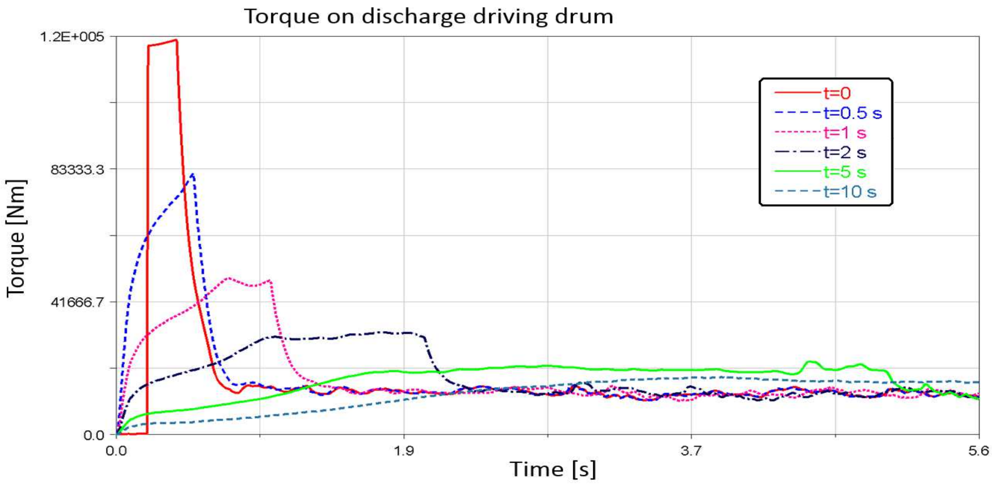

Fig. 10. Curves of the torque recorded on discharge driving drum at different time of the conveyor start up

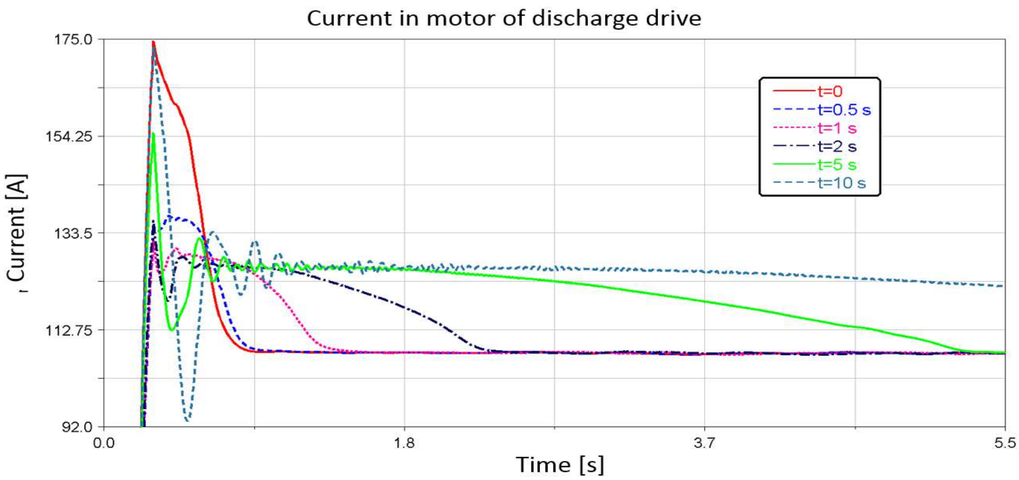

Fig. 11. Curves of current recorded in the electric motor on discharge end at different time of conveyor start up

6. Conclusions

After the start-up stage, at stable operation of the conveyor without load, the mean current amplitude in the electric motor on the discharge drive increased with increase of extension of the cylinder of the telescopic trough i.e. with elongation of the conveyor.

Also at the stage of stable operation, with load (during transportation of run-of-mine) excessive extension of the telescopic trough caused increase of loading the drives, what led to increased consumption of energy and increased wear of conveyor sub-systems.

At the time of loading the conveyor, the load to discharge drive rapidly increased. Elongation of the conveyor resulted in decrease of drive overload. The maximum current in the discharge drive of the motor was significantly lower at extension of the telescopic trough to more than 0.06m than the current in the case of the same external load at lower extension of the telescopic trough. At the stage of uneven load to the drives, elongation of the telescopic trough caused increase of load to the reversible drive. It has been confirmed by the fact that at the bigger extension of the telescopic trough, during applying the load, both the current in the electric motor on the reversible drive and the torque on the reversible driving drum increased more. Change of conveyor length by extension of the telescopic trough affects the character of load to the conveyor drives. Proper extension of the telescopic trough resulted in decrease of unevenness of load to motors, especially at the moment of applying the load. Decrease of unevenness of load to drives was reported by equalizing the current in both motors and balancing the torque on driving drums, what proves good cooperation of conveyor drives.

Increase of tension in the scrapper chain by elongation of the telescopic trough minimizes the risk of loosening the chain at the places, where it leaves the driving drums. It also enables decreasing the overload of the electric motor installed on the discharge drive in the situation of sudden load to the upper chain branch. Decrease of motor overload is possible due to quicker transfer of the torque generated by the motor on the reversible drive to the pulling force of the chain. Too high and uncontrolled elongation of the telescopic trough can lead to excessive tension of the scrapper chain, what can result in increase of resistance to motion and high changeability of the current in motors (especially in discharge drive of the motor). Such operation is unfavourable for the conveyor and leads to excessive wear of its sub-systems and excessive energy consumption as well as it increases emission of heat to the mine atmosphere.

Chain loosening (decrease of conveyor length by retraction of the telescopic trough) results in lower load to the motor installed on the reversible drive at the time of applying the load. The motor installed on the reversible drive overcomes resistance to motion at the first stage of applying the load. Such situation can lead to excessive overload of the discharge drive of the motor, when the upper chain branch is rapidly loaded, while excessive loosening the chain can lead to increased dynamics of load to motors (higher changeability of the current and the torque). During loosening the chain, its links may "stand on end", what can result in chain blocking. In extreme situations, the links may be cut or broken.

Use of frequency converters in conveyor drives enables controlling the rate of the current frequency increase in driving motors and thus control the time of conveyor start-up. Analysing the results of simulation of start-up of the electric motor installed on the discharge drive, it should be remembered that, due to simplifications of the computational model, the time of simulation can differ from the real time. However, analysis of the presented diagrams enables determining the trends and behaviour of motors and the conveyor during start-up.

Additional information

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Calculations were made in Computer Centre Academic Computer.

Selected issues related to this paper are planned to be presented at the 22nd Winter International Scientific Conference on Achievements in Mechanical and Materials Engineering Winter-AMME'2015 in the framework of the Bidisciplinary Occasional Scientific Session BOSS'2015 celebrating the 10th anniversary of the foundation of the Association of Computational Materials Science and Surface Engineering and the World Academy of Materials and Manufacturing Engineering and of the foundation of the Worldwide Journal of Achievements in Materials and Manufacturing Engineering.

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