Application of the soft starter for the asynchronous motor of the belt conveyor

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Abstract. The purpose of the work is to justify the need for a smooth start of the conveyor belt. Based on the technological features of the transportation process, the direct start of the conveyor with a loaded undercarriage entails an increase in inertial forces, overload of the traction chains and the drive. Due to the increased starting torque, there is a danger of slipping, the occurrence of an oscillatory transient of the escaping branch of the tape, slipping between the tape and the drive drum. This leads to significant wear of the tape and breakdowns of other equipment, which requires high repair costs. With a smooth start of the conveyor, the acceleration lasts longer, but the movement of the concentrated masses of the belt is more consistent, less oscillatory, which indicates less dynamic forces in the belt. Also, with a smooth start, energy losses in the engine and its heating are reduced. The main results of the work – the transients in the currents of the stator and rotor, in the speed of rotation of the motor and in the speed of movement of the conveyor belt were obtained. The developed model allows us to investigate the dynamic operating modes of the engine and the mechanical part of the conveyor, to analyze the forces arising in the belt during direct and smooth start of the conveyor, to evaluate the slip of the belt and the magnitude of the traction factor. Conclusions – the results of this work should be the basis for controlling the tension in the belt and maintaining the traction factor of the conveyor belt in the start-brake operating modes. In addition, the results obtained can be used in the development of a belt speed control system depending on the amount of random freight traffic entering the conveyor.

1. Introduction
Due to the depletion of reserves, the development of deposits goes to great depths or moves away from the shafts. In addition, the enterprises are forced to mine individual local ore bodies located at a distance from the main production. To preserve the permanence of the process of extracting mineral resources and individual technological processes: uninterrupted supply of the filling mixture to the spent chambers [1]; delivery of finished ore and its receipt at the processing plant [2]; shipment of waste from mining and processing industries to dumps and tailings [3]; rhythmic provision of individual technological processes (for example, preparation of a backfill mixture) [4] and others, the use of continuous mining equipment is required. When operating the pipeline, it is necessary to take into account the increased wear of parts and mechanisms due to the increased education of the pulp [5]. In mines, pipeline transportation causes air strikes and pipeline damage. In connection with the supply of slurry to great depths, the question arises of a sharp fluctuation in pressure associated with the starting and stopping modes of the slurry supply. There is often a blockage in the pipeline [6]. In this regard, the use of conveyor transport is seen as the most promising option. However, the conveyor is slow to start. In this regard, the development of mechanisms that ensure smooth start-up, and, as a consequence, reliability and uninterrupted operation, and an increased service life, is a very urgent task.
2. Justification of the need for a smooth start of the belt conveyor

In the modern world, it is very difficult to imagine an industrial production that would not have electric motors. The most widespread are asynchronous motors with a squirrel-cage rotor (hereinafter referred to as AM SC).

However, due to the peculiarity of the squirrel-cage rotor (the aluminum alloy is poured into the grooves simultaneously with the short-circuiting rings), the AM SC has a specific starting mode: the absence of a rotor winding means that there is no back-EMF induction induced at the moment of switching on the stator windings and the occurrence of high inrush currents (multiplicity starting and rated currents can reach eight units).

Such an unfavorable mode has a number of disadvantages: when choosing and detuning protections, it is necessary to take into account the starting mode, the service life of the motor itself decreases, the substations are overloaded and the voltage drops in the network, and severe dynamic modes of operation of the driven mechanisms occur.

In some mechanisms, it is fundamentally important that the start is smooth, without jerks and impacts. This applies, first of all, to technological equipment, which has a high moment of inertia at start-up. For example, conveyors with a load, powerful pumps and fans. The high starting current of the motor and the high moment of inertia of the mechanical load on the shaft are interrelated things that often need to be disposed of. Let us dwell on the conveyor belt [7, 8]. Belt conveyors are continuous transport mechanisms. Quite high requirements are imposed on individual parts and conveyor mechanisms in terms of reliability [9], safety [10], increased service life [11], since the release of one part or mechanism leads to a stop of the entire technological process. Conveyors are an elastic mechanical system, therefore, in dynamic modes in belt conveyors, elastic waves propagate along the belt. The belt is the most expensive part of the conveyor, and vibration during start-up will shorten the life of the belt.

One of the main requirements of the control system is the smooth start of the conveyor with limited acceleration. As mentioned above, with a direct start of the IM, a starting current occurs, which is 5-8 times higher than the nominal one. This current creates mechanical shock loads that are transmitted through the gearbox to the conveyor. Shock loads can lead to insulation breakdown and damage to the stator windings of the motor, as well as destruction of connecting shafts and couplings, gearboxes and other damage. In addition, the starting current reduces the voltage of the supply network, and this negatively affects the stability of the operation of all consumers of this network, especially in the case of their power supply from networks of limited power.

Starting the conveyor with a loaded running gear entails an increase in inertial forces, overloading of the traction chains and drive. Therefore, it is advisable not to stop the loaded conveyor unnecessarily. This is especially important for conveyors of long length, which have the danger of slipping and the risk of an oscillatory transient process of the running down strand of the belt. When starting with direct voltage, there is a high risk of slipping between the belt and the drive drum due to the increased starting torque. This leads to significant wear and tear and high repair costs. When starting long belt conveyors, due to the elastic compliance of the belt, starting from the place of the runaway branch can begin after the engine, the drive drum and the oncoming branch have reached a steady speed. In this case, longitudinal fluctuations of speed begin in the empty branch, which leads to premature wear of the belt and even its burst. The danger of slipping, as well as the occurrence of unacceptable fluctuations in speed due to elastic deformation of the belt, requires that the drive and control system provide a strict limitation of the amount of acceleration when starting the conveyor.

Hydraulic dampers are sometimes used to reduce starting torque, but these devices are expensive and difficult to maintain.

3. Simulation of the joint motion of an asynchronous motor and a conveyor belt.

To visually verify the negative impact of direct start of an asynchronous motor, we simulate its start using the software environment Matlab (Simulink, SimPowerSystem) [12, 13].

Let's choose the RA200LB2 engine, its passport data are presented in the table below.
Table 1. Passport data of the RA200LB2 engine

| $P_n$, kW | mass, kg | $n_n$, rpm | $\eta$, % | $\cos \varphi$ | $I_n$, A | $I_{max}/I_n$ | $M_{max}/M_n$ | $J$, kg·m² |
|-----------|----------|------------|-----------|----------------|---------|----------------|---------------|---------|
| 37        | 230      | 2950       | 92        | 0.89           | 68      | 7.5            | 2.4           | 3       |
|           |          |            |           |                |         | 0.132          |               |         |

We will translate the passport data into the parameters of the equivalent circuit. To do this, we will write a script in the Control System Toolbox according to the well-known formulas [14], taking into account the preliminary selection of the constructive coefficient $c_1$.

Figure 1. Substitution scheme parameters obtained using a prepared script in Matlab

Now you can simulate the direct start of the RA200LB2 asynchronous motor. In the Simscape library, select the Asynchronous Machine pu Units item. The model has 4 inputs, three are supplied with three-phase voltage, and the fourth is a moment of resistance.

Figure 2. Simulation diagram of direct start of an asynchronous motor with a short-circuited rotor

The output characteristics of the engine are shown in Fig. 3 and fig. 4.
In fig. 3, it can be seen that, due to its inertia, the AM SC has an oscillatory mechanical characteristic during direct start with a rated voltage and torque on the shaft. It can also be seen that the engine overcomes the critical torque several times before reaching a stable characteristic interval.

From Fig. 4, we can conclude that the engine starts up quickly enough - only 0.3 seconds. However, according to the stator and rotor currents, it can be seen that the starting currents in the windings reach a sevenfold increase in comparison with the nominal one, which was agreed earlier and has a negative effect on the operation of the motor.
If direct starting of AM SC is required, it is recommended to switch on with minimum load in order to reduce the network overload time. Also, when the load is reduced, starting with a reduced voltage is possible, the value of which makes it possible to overcome the critical moment on the shaft.

Currently, the research uses differential approaches using multiple methods for modeling various processes [15, 16]. To study the joint motion of a belt with a drive, we will use the model of a belt conveyor developed in [17, 18, 19].

Using typical Simulink blocks, we will assemble a block diagram of a system that includes a conveyor belt circuit and an asynchronous motor. The conveyor belt model is obtained on the basis of the Lagrange equation of the second kind and is represented by a system of differential equations in the state space. As generalized coordinates, the velocities and displacements of concentrated 7 masses located on the drive and tail drums, as shown in Fig. five.

After performing algebraic transformations, we obtain the following record of the system of equations, which is a mathematical model of the movement of the conveyor belt:

\[
(2m_1 + 2m_2 + m_{wp})\ddot{x}_1 + (m_1 + m_2)\ddot{x}_2 + (2C + 0.25C_x)\dot{x}_1 - (2C + 0.25C_x)\dot{x}_2 - 0.5C_s\delta +
\]
\[
+ (0.5G \varepsilon + 0.5G_s \varepsilon)\text{sgn} \dot{x}_1 + 2\eta \dot{x}_1 - 2\eta \dot{x}_2 = \frac{M_{\text{we}}}{R_s} \text{sgn}(\dot{x}_p - \dot{x}_i),
\]
\[
(2m_1 + 2m_2)\ddot{x}_2 + (m_1 + m_2)\ddot{x}_1 - (2C + 0.25C_x)\dot{x}_1 + (2C + 0.25C_x)\dot{x}_2 + 0.5C_s\delta +
\]
\[
+ (0.5G \varepsilon + 0.5G_s \varepsilon)\text{sgn} \dot{x}_2 - 2\eta \dot{x}_1 + 2\eta \dot{x}_2 - \eta \dot{x}_3 = 0,
\]
\[
\frac{G_w}{g}\dot{\delta} - 0.5C_s x_1 + 0.5C_s x_2 + C_\delta \dot{\delta} + G_{wp} + G_{wy} f \text{sgn} \dot{\delta} = 0.
\]

To study dynamic processes, we will carry out computer simulation in the Simulink system. This software product allows you to simulate dynamic systems described by ordinary nonlinear differential equations. Using typical Simulink blocks, we will assemble a block diagram of a system that includes a belt loop and a conveyor drive.

The conveyor belt is represented by its internal model:

\[
\dot{x} = Ax + Bu,
\]
\[
y = Cx + Du,
\]

what the State-Space block was used for. The Multiplexor (MUX) block is used to form a single control signal. It combines three signals into a vector:

- Drive torque (first signal) coming from the Asynchronous Machine block, simulating an asynchronous squirrel-cage motor;
- Resistance forces (second signal), these signals are taken from the conveyor model;
- Weight of the tensioner (third signal) – the constant \( G_{wp} \).

In turn, the load moment, reduced to the motor shaft, is calculated, which is determined through the resistance forces to the movement of the conveyor belt:
As a control signal, a signal proportional to the driving torque of the drive is supplied to the belt model, and as a reference signal, a signal proportional to the rotor speed \( \omega \).

In the drive model, a transition is made from simulation in conditional time to simulation in real time to match the simulation parameters of the two subsystems. Now you can merge the models.

The simulation scheme is shown in Fig. 6. To display the necessary information, the \textit{Selektor} blocks are used, which separate the signals of the velocities of the lumped masses of the model from the vector of output signals \( y = [x_4 \ x_5 \ x_6]^T \).

![Figure 6. Simulation diagram of the direct start of the conveyor motor](image)

The results of computer simulation were transient processes in the velocities of the generalized coordinates of the tape and the tensioner, shown in Fig. 7.

![Figure 7. Change in the velocities of the concentrated masses during the direct start of the conveyor](image)

The transient processes in the velocities of the concentrated masses of the conveyor are distinguished by a rather high oscillation and a long control time, about 20 seconds when brought to the nominal speed. In the movement of the mass 2 located on the tail drum, at the moment of starting the conveyor, a movement is observed in the direction opposite to the main movement of the conveyor, which is associated with the movement of the tensioner, which takes the tail drum back due to a decrease in the
belt tension on the empty branch. Oscillatory transient processes negatively affect the service life of the belt and increase its wear. For this reason, when calculating and designing a conveyor, it is necessary to choose more expensive belts with an increased margin of safety, which is economically unprofitable.

4. Asynchronous motor soft starter - design, simulation and application

Let us now consider the process of smooth starting the engine. In the start-up and drive control circuits, a frequency converter (hereinafter referred to as FC) is generally used - it allows you to change the starting and operating characteristics by converting the supplied frequency and voltage to the stator windings of the AM SC. In the general case, the FC is a highly specialized inverter - it rectifies the input voltage, then with a given frequency and amplitude it is re-converted into an alternating voltage.

This conversion occurs due to the operation of a pulse-width modulation generator (hereinafter PWM generator). It generates rectangular pulses of a given frequency, with the help of which the power switches are controlled, which commute the rectified supply voltage to the transformer windings.

The FC is controlled by a PWM generator with feedback on the consumed current, which makes it possible to carry out a starting mode in which the starting current does not exceed the rated one. Thus, there is no previously detected overload in the mains supply.

Such a starting mode requires a significant complication of FC for the electric drive in question, therefore, in non-critical low-power drives, a soft starter is used to control AM. This device combines a number of functions: soft start and braking, protection of driven mechanisms and the electric motors themselves [20, 21].

To implement a soft starter in Matlab, consider the block diagram of a controlled drive (Fig. 8).

![Figure 8. Block diagram of an asynchronous motor drive with a soft starter](image)

A thyristor converter (hereinafter referred to as TC) for a three-phase electric motor consists of three pairs of anti-parallel thyristors included in the break of each of the phases, as shown in Fig. 9. By adjusting the angle of their opening, you can adjust the voltage supplied to the AM. The TC is the basis of the soft starter, therefore, special attention is paid to their choice.

![Figure 9. Thyristor converter installed in the phase gap](image)

The pulse-phase control system is necessary to control the angle and frequency of opening of the installed thyristors. We will implement the vertical control principle for the drive. It compares the DC control voltage with the saw AC reference voltage. At the moment of their equality, a series of rectangular pulses is formed, with the help of which the TC operation is controlled. A phase voltage is supplied from the meter. This voltage is divided into positive and negative waves and converted into a pulse signal. This signal is converted into a sawtooth signal, which will be further compared with the control signal. By adjusting the control voltage, we change the moment of supply of the opening pulses relative to the beginning of the half-wave of the sinusoid (that is, we adjust the opening angle of the thyristors).
Let’s assemble all the considered blocks into a direct start circuit using a soft starter for AM SC. It is shown in fig. 10.

**Figure 10.** Diagram of a soft-start device for an asynchronous motor with a short-circuited rotor

The obtained mechanical and operating characteristics of the electric motor are obtained in Fig. 11 and fig. 12.

**Figure 11.** Mechanical characteristics of the soft start of an asynchronous motor with a short-circuited rotor
Comparing the obtained characteristics with the characteristics of direct start (Fig. 3 and Fig. 4), first of all, it can be seen that the start-up time practically did not change. This result is satisfactory for a low to medium power engine.

Moving on to a comparison of mechanical characteristics, it can be noted that the starting characteristics also retained their oscillation. These characteristics correspond to the transition from different $U/f$ ratios, which is implemented by the SCP. Also, according to the characteristic in Fig. 10 that the critical section has become smoother and the engine does not have to overcome the critical moment several times.

It can also be concluded that the multiplicity of the starting current has greatly decreased and is $3 \cdot 4$ of the nominal. This once again confirms the advisability of using a soft starter on electric motors of a given power.

And finally, let us simulate the smooth start-up of the belt conveyor [22, 23]. The simulation scheme will be similar to that shown in Fig. 6, and the results are shown in Fig. 13.
In this paper, a very simplified model of a belt conveyor is used. It allows only preliminary conclusions to be drawn. In the future, it is planned to use a more detailed model developed [17, 18, 19], which allows you to measure the forces in the belt, stabilize the value of the traction factor of the conveyor, check more complex algorithms for regulating the speed of the conveyor [24, 25, 26, 27].

5. Conclusions.
According to the results obtained, it can be seen that the acceleration lasts longer, but the movements of the concentrated masses are more consistent, less vibrational, which indicates lower dynamic forces in the belt. At the moment of turning on the drive, there are no strong fluctuations in speed, indicating slippage of the belt on the drive drum. The second concentrated mass moves in the same direction as the first, that is, the probability of a belt break is reduced. The results of this work should be the basis for controlling the tension in the belt and maintaining the traction factor of the conveyor belt in the start-brake operating modes. In addition, the results obtained can be used in the development of a belt speed control system depending on the amount of random freight traffic entering the conveyor.

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