# Magnet Synchronous Machine of Mine Belt Conveyor Gearless Drum-Motor

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**Abstract.** In the recent decades there has been a tendency for simplifying gears construction, furthermore a lot of manufacturers design gearless electric drives for traction and power mechanisms. Rejection of mechanical transmission and replacing obsolete induction motor with energy-efficient permanent magnet synchronous machine (PMSM) allow to increase electric drive reliability, reduce repair and maintenance costs, also improve the technological process and industrial safety.This article is devoted to questions of permanent magnet synchronous motor control for underground belt conveyor gearless drum-motor. The model of PMSM with special construction was created by finite elements method in Infolytica MagNet and MotorSolve environments, simulation was provided with to regard due special nature of high-torque slow-moving power machines. The last section of article contains comparison of methods for high-torque slow-moving PMSM control and simulation results of vector control system.

## 1 Introduction

The underground belt conveyor is the main method of delivering coal ore in mine tunnel. Nowadays, in coalmine manufactures of Russia the most of belt conveyor electric drives are non-regular induction electric drives with hydraulic couplings. A gear system generally consists of worm and toothed gears.

In traditional non-regular induction electric drives constantly causes start-up and load-rejection overvoltages, high start-up currents and pulsating torque lead to additional tension and slippage of belt. Therefore, total power losses increase during to distribution of load, in speed regulation and steady-state operating modes. Mechanical transmission not only limits rotation power and reduces the efficiency of electric drive, but also has considerable dimensions. In additional the most expensive part of belt conveyor gear is coupling that easily become disable because of fatigue damages [1].

In recent years, foreign researchers commonly refuse to use traditional induction machines in design of high-power electric drives, by reason of inconsistency with new energy efficiency standards of IE. The modern researches have demonstrated that high-torque permanent magnet synchronous machines (PMSM) increasingly apply as electric

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machines of drum-motors in belt conveyor systems. There is also a tendency of replacing common power-drive station of belt conveyors with more producible drum-motors and introducing gearless electric drives with direct transmission of torque to shaft of controlled component. The preceding reasons allow to confirm urgency of this article and our research [2-6].

Developing of high-torque slow-moving PMSM system control for gearless drum-motor needs to decide next questions:
1. Design high-torque slow-moving PMSM model using dimensions and parameters data of electric drive of actual underground belt conveyor.
2. On the assumption of belt conveyor system control requirement select method control.
3. Simulate slow-moving PMSM system control.

## 2 Materials and Methods

A high-torque permanent magnet synchronous machine is located into body of drive gearless drum-motor, should produce required output power with mechanical torque and fit to desired dimensions of drum-motor body. Drive roll of induction electric drive of main belt conveyor in “Taldynskaya-Kargaiskaya” coal mine (Russian Federation, Novokuznetsk) has the following parameters: width l = 1.2 m, diameter d = 1 m. Induction motor with squirrel cage parameters: Um = 6 kV, P = 680 kW, drum rotation n = 60 rpm, nominal torque Mn = 110 kNm.

The characteristics of multipolar slow-moving PMSM depend not only on magnet systems materials and location of permanent magnets, furthermore on magnetic angle, grooves depth and magnitude of tooth. High-torque slow-moving permanent magnet synchronous machine has a rotor with radial surface magnets (magnetic flux produces on radial direction) and pole tips to provide uniform distribution of magnetic flux in the air gap and protect permanent magnets from demagnetization [7-9]. The rotor of PMSM must be thin and plate, the number of pole pairs $p \leq 12$ for creating high torque with desired magnitude [10].

Simulation of PMSM was performed using finite elements method in MotorSolve and Magnet environments by Infolytica. The finite elements method based on principle of partition the area of solutions of differential and integral equations with partial differentials into finite number of elements. The form of approximating function is selected for each element, complexity of function depends on required accuracy.

Table 1 contains parameters of obtained slow-moving PMSM model. There $U$ is supply voltage of PMSM in mining electric system, $P$ is rated active power, $R_s$ is active resistance of stator windings, $L_d$ and $L_q$ are self-inductances of stator windings along dq-axes, $T_n$ is rated electromagnetic torque, $\Psi_{PM}$ is flux produced by permanent magnets, $p_n$ is number of pole pairs, $J$ is moment of inertia of rotor, $cos\varphi$ is power factor and $\eta$ is efficiency of PMSM model.

**Table 1.** Parameters of slow-moving PMSM 680 kW model

| $U$, V | $P$, kW | $R_s$, Ω | $L_d$, H | $L_q$, H | $T_e$, Nm | $\Psi_{PM}$, Wb | $p_n$ | $J$, kg·m | $cos\varphi$ | $\eta$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 6000 | 680 | 2,367 | 0,579 | 0,496 | 110330 | 52,49 | 12 | 0,025 | 0,72 | 93,8 |

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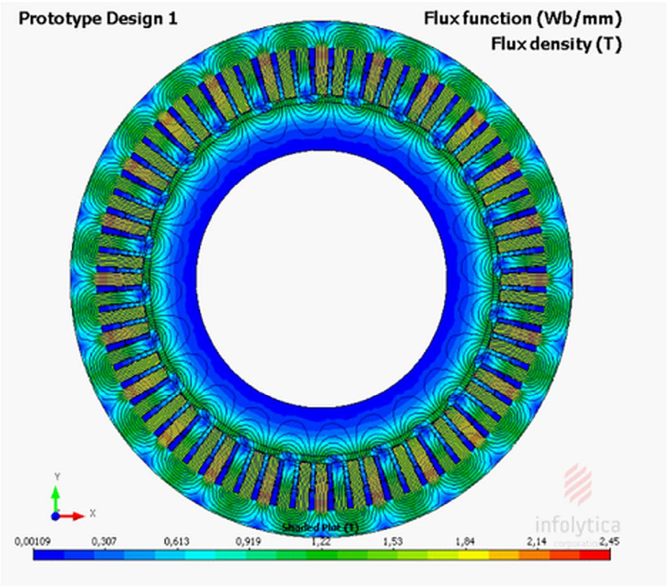


**Fig. 1.** Distribution of electromagnetic flux in the magnetic core of PMSM 680 kW at rated load

Fig. 1. represents the distribution of electromagnetic flux in the magnetic conductor of slow-moving PMSM at the rated load. We can see that most of magnetic field lines penetrates the tooth areas of stator core and magnitude of electromagnetic induction is high (yellow and red areas in the Fig. 1) because of high coercive force of permanent magnets. For these reasons tooth material is strongly magnetized, in the air gap large number of upper harmonic occurs, and distribution of electromagnetic flux becomes unequal with peaks in the tooth areas.

Fig. 2 represent machine currents, power, losses and torque versus rotor position angle relationships at rated stator current. All these characteristics, especially electromagnetic torque, have non-sinusoidal distribution. Reactive power deforms power-angle curve because of significant non-saliency of PMSM. An additional deforming reactive torque appears as upper harmonics in harmonic spectrum of electromagnetic torque because of cogging torque and non-sinusoidal back-emf in stator windings with high mutual inductions.

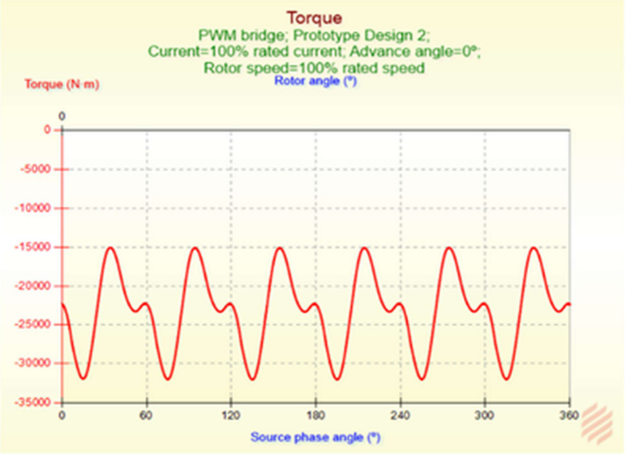


**Fig. 2.** Electromagnetic torque versus rotor position angle relationship at tared stator current

The features of electric drive of belt conveyors are high static load resistant torque and unequal dynamic loads caused by dimensions and masses of conveyor components, curing of grease, splicing of the belt with fine fraction coal, etc. There are high requirements for reliability to electric drives, particularly smooth starting and smooth braking at loads. The performing of belt speed control depends on modes of operation of the conveyor system and input flow of material.

The basic requirements to provide quality control of slow-moving PMSM of belt conveyor gearless drum-motor are next:

1. Wide torque control range for controllability at variable dynamic loads.
2. High accuracy of regulation for control at low and close-to-zero rotations.
3. Quick response time for stable control during frequent transient processes.

For control permanent magnet machine, it is necessary to know value of rotor position angle $\theta$. Sensorless control methods use indirect estimation of angle $\theta$, but implementation of estimation methods is complicated by large number of feedbacks on control system, also calculating error can be significant, especially for operation at low speed. In addition, sensorless control methods require very high computation capacity and significantly decrease response time. Sensor control methods use Hall sensors, resolvers and incremental encoders for measuring rotor position angle. The modern types of sensors measure angle $\theta$ with high accuracy and speed, consequently for control of slow-moving PMSM we will analyze only sensor control methods.

The model of control system based on mathematical representation of two-phase PMSM in *dq*-axes:

$$U_{sd} = R_s i_{sd} - \frac{d\psi_d}{dt} = R_s i_{sd} + L_{sd}\frac{dI_{sd}}{dt} - \omega_{0el} L_{sq} I_{sq},$$
$$U_{sd} = R_s i_{sq} - \frac{d\psi_{sq}}{dt} = R_s i_{sq} + L_{sq}\frac{dI_{sq}}{dt} + \omega_{0el} L_{sd} I_{sd} + \omega_{0el}\psi_{PM}, \quad (1)$$

$$T_e = \frac{3}{2} p_n \left[\psi_{PM} I_{sq} + \left(L_{sd} - L_{sq}\right) I_{sd} I_{sq}\right], \quad (2)$$

$$\omega_{0el} = \frac{1}{J}\left(T_e - T_c\right). \quad (3)$$

Scalar control based on proportional regulation of supply voltage amplitude and frequency is featured by simplicity and quick response time, but is not appropriate for slow-moving PMSM, because these methods use static models of steady-state conditions such as equivalent electric circuit and do not include dynamic processes cause in electric drive during speed control and dynamic loads.

Applying of vector control methods assumes multi-phase systems transform into two-phase systems with dq-axes. One of the most efficient control methods at low speed is field-oriented control (FOC) and direct torque control (DTC). In FOC electromagnetic torque and stator flux is indirectly controlled by control components of stator current vector, DTC method uses component of torque vector represented by stator current vector on quadrature axis and stator flux on direct current. For application of required impulses to semiconductor switch of invertor uses pulse width modulation (PWM) or space vector modulation (SVM). Comparative analyses of existing vector control systems for slow-moving PMSM, which is reproduced in article, concludes that the most appropriate methods are FOC with PWM, DTC with SVM, differential and adaptive control. However, the article gives only theoretical analyses, in computer simulation (by Matlab Simulink) FOC-PWM system shown the best result. There reference speed block produce required speed value, which depends on rotor position angle $\theta$ and load of conveyor, rated speed of slow-moving PMSM $\omega$ = 6.28 rad/s, resistance torque $T_c$ = 100 Nm that is almost equal no-load operation. As current controllers were used standard proportional-integral (PI) controllers with saturations, and we used proportional-integrated-differential (PID) controller to control speed, because it needs quick time of response and high accuracy.

In Fig. 3 are represented simulation results. As shown on plots, FOC-PWM control system performs smooth starting in 3 seconds time at no-load operation with good quality. Pulsations of electromagnetic torque not exceed 10% and describe by high cogging torque value in slow-moving power permanent magnet machine and PWM with high frequency of switching (20 kHz). Although this simulation results are appropriate to requirement of belt conveyor electric drive system control, ribbing of torque and speed will increase at working operation, by reason of unequal dynamic loads and mechanical hits. Consequently, designed vector control system requires slow-moving PMSM conditions observer and additional speed and torque controllers.

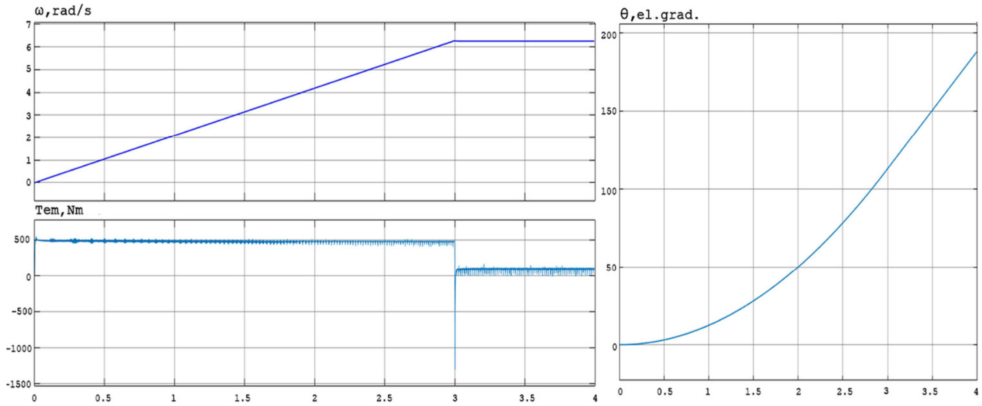


**Fig. 3**. Angle speed, electromagnetic torque and rotor position angle versus time relationships (smooth starting time t = 3 s, $T_c$ = 100 Nm)

## 3 Conclusion

In this article was considered questions of high-power slow-moving permanent magnet synchronous machine control, associated with features of slow-moving PMSM construction and electromagnetic torque, also were presented simulation results for field-oriented control system with PWM and zero stator current on direct axis for PMSM of belt conveyor power electric drive at smooth starting without load. As shown in fig. 2.2., not significant pulsations of torque cause during smooth starting, which could hugely increase al load operation, and analyzed FOC-PWM control system requires slow-moving PMSM conditions observer and additional speed and torque controllers for stable operation of belt conveyor during speed control and variable loads.

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