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MODELING OF AN INDUCTION MOTOR DRIVEN BY A FREQUENCY CONVERTER

The article presents the results of the theoretical studies conducted. A simulation model of an asynchronous electric drive with frequency regulation was created in the Matlab Simulink software environment. This model was used to develop a dual-motor electric drive for a belt conveyor. The main attention is paid to calculating the parameters of the mathematical model of the engine. The simulation model considers the characteristics of industrial equipment installed at the facilities of mining companies in the Republic of Kazakhstan. The developed model is based on the principles of vector control with cross-coupling compensation, which ensures high quality of dynamic characteristics and stability to external disturbances. Theoretical and experimental results confirming the effectiveness of the proposed control system are presented. The resulting simulation model can be used to design and modernize industrial electric drives in the mining industry. Additionally, methods for increasing the energy efficiency of the system by optimizing the control parameters are considered. Analysis of transient and stationary processes showed that the proposed approach allows minimizing the impact of external disturbances and ensuring stable operation of the equipment. The developed model can also be integrated into automated control systems to improve their functionality and reliability. The research results demonstrate the high accuracy of the model and its *applicability in industrial conditions to improve productivity and reduce energy costs.*

Keywords: induction motor, electric drive, frequency converter, energy efficiency, simulation model.

Introduction

Equipping production machines and mechanisms with an adjustable electric drive is a solution to an important scientific and technical problem, ensuring an increase in technical and economic indicators, reliability and safety of operation of the manufactured equipment. The use of an adjustable electric drive allows for the implementation of an increase in the reliability and service life of mining equipment. This technology is of particular importance for large enterprises in Kazakhstan, such as Kazakhmys and KAZZINC, where frequency-controlled systems successfully solve automation problems.

The objective of this study is to investigate the dynamic processes of electric drives during the startup mode with various types of controllers. The developed simulation model of an induction motor with a frequency converter ensures precise control, minimizes the impact of disturbances, and stabilizes equipment operation under varying load conditions.

Materials and methods

To build a simulation model of the studied object, a mathematical model of an asynchronous motor must be developed, and its parameter values calculated numerically. Parameter calculation was performed using the methodology described in [1; 2; 3; 4; 5; 6]. The object of study is a variable-speed electric drive of a belt conveyor powered by Siemens motors. In the mathematical model, a Siemens motor was used; however, the technical documentation for this motor does not provide data on the equivalent circuit parameters necessary for further calculations. To calculate the model parameters, a motor from the 4A series with similar specifications was used. The equivalent circuit parameters were taken from the handbook by A.E. Kravchik [7, p. 29]. The selected motor, 4A355M4U3, has factory characteristics similar to the motors installed in the studied object, except for the degree of protection. The Siemens motors installed at the study site have a protection degree of IP55, while the chosen analog from the handbook has an IP44 rating. This difference is due to variations in housing and winding insulation design and does not affect the motor's electromagnetic properties. The nameplate data of the motors installed in the studied object are presented in Table 1. The equivalent circuit parameters of the 4A355M4U3 motor are given in Table 2.

Table 1 – Nameplate data for the Siemens motor

Symbol	Description	Value	Unit
P_N	Rated shaft power	315	kW
$U_{s\phi N}$	Rated phase voltage (RMS)	220	V
η	Efficiency	96	%
$cos\,\phi$	Power factor	0.83	-
f_N	Rated supply frequency	50	Hz
s_N	Rated slip	0.67	%
n_N	Rated speed	1490	rpm
$J_д$	Motor inertia moment	5.4	

Table 2 – Equivalent circuit parameters for the 4A355M4U3 motor

Symbol	Description	Value	Unit
$x_{\mu r}$	Magnetizing reactance	5.7	r.u.
r'_{1r}	Active resistance of stator windings	0.012	r.u.
x'_{1r}	Inductive reactance of stator windings	0.099	r.u.
r''_{2r}	Active resistance of the rotor winding	0.014	r.u.
x''_{2r}	Inductive reactance of the rotor winding	0.14	r.u.

The rated stator winding current (RMS) is calculated using Equation (1):

$$U_{s\phi N} = \frac{P_N}{m_s \cdot U_{s\phi N} \cdot cos\,\phi \cdot \eta} = \frac{315000}{3 \cdot 220 \cdot 0.83 \cdot 0.96} = 60 \quad (1)$$

where is the number of stator winding phases.

The rated torque of the motor is determined by Equation (2):

$$M_N = \frac{30 \cdot P_N}{\pi \cdot n_N} = \frac{30 \cdot 315000}{3.1415 \cdot 1490} = 2019\ \mathrm{N \cdot m} \quad (2)$$

Conversion of parameters to the «T-shaped» equivalent circuit is carried out using Equations (3)-(8):

$$c_1 = 1 + \frac{\sqrt{r_{1r}'^2 + x_{1r}'^2}}{x_{\mu r}} = 1 + \frac{\sqrt{0.012^2 + 0.099^2}}{5.7} = 1.017 \quad (3)$$

$$x_{\mu т} = x_{\mu r} = 5.7\ \mathrm{r.u.} \quad (4)$$

$$r_{sт} = \frac{r_{1r}'}{c_1} = \frac{0.012}{1.017} = 0.012\ \mathrm{r.u.} \quad (5)$$

$$x_{s\sigma т} = \frac{x_{1r}'}{c_1} = \frac{0.099}{1.017} = 0.097\ \mathrm{r.u.} \quad (6)$$

$$r_{rт} = \frac{r_{2r}''}{{c_1}^2} = \frac{0.014}{1.017^2} = 0.0135\ \mathrm{r.u.} \quad (7)$$

$$x_{r\sigma т} = \frac{x_{2r}''}{{c_1}^2} = \frac{0.14}{1.017^2} = 0{,}135\ \mathrm{r.u.} \quad (8)$$

where , the number of motor pole pairs.

Results and discussion

The construction of a simulation model of a two-motor belt conveyor with a frequency-controlled asynchronous electric drive begins with the creation of a model of one asynchronous motor operating in conjunction with a frequency converter. This simulation model of a single motor will serve as the foundation for building the dual-motor system. To ensure high-quality dynamic transient processes and minimal sensitivity to external influences, the control of a variable-frequency electric drive must meet certain requirements.

The model of an asynchronous motor with a frequency converter was developed as a system with vector control and cross-coupling compensation. The simulation model of a variable-frequency asynchronous motor was created based on data from several sources [8; 9; 10; 11; 12]. The structure of the closed-loop control system is shown in Figure 1 [6, p. 172].

The dynamic behavior of the asynchronous motor is described by two dynamic elements and one gain element, expressed by equations (9)-(11).

Considering the dynamic characteristics of the frequency converter requires the use of an external filter, which changes the time parameters of the system and is determined by the transfer function described by equation (12).

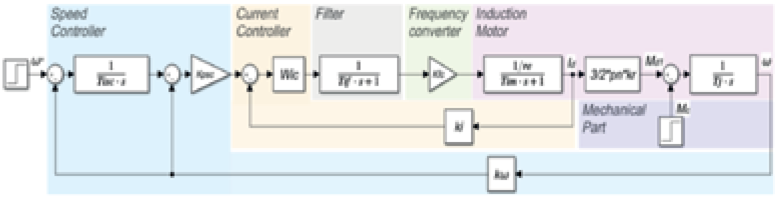

Figure 1 – Block diagram of the vector control system for a frequency-controlled asynchronous electric drive

The frequency converter is modeled as a gain element with a gain of . The current PI controller is described by a dynamic link and a feedback loop with a gain .

The speed controller is implemented as a PI controller, which includes a proportional element with a gain of and an integrating element . Each element of the speed controller is placed in its own feedback loop with a gain of .

$$W_1(s) = \frac{1/r_e}{T_{im} \cdot s + 1} \tag{9}$$

$$M_{d1} = \frac{3}{2} \cdot p_n \cdot k_r \cdot I_d \tag{10}$$

$$W_2(s) = \frac{1}{T_j \cdot s} \tag{11}$$

$$W_3(s) = \frac{1}{T_{if} \cdot s + 1} \tag{12}$$

In the block diagram of the closed-loop control system of the frequency-controlled asynchronous electric drive, the following designations are used:

$W_1 (s)$ – transfer function describing the motor's electromagnetic processes.

$W_2 (s)$ – transfer function of the motor's electromechanical part.

$W_3 (s)$ – transfer function of the filter.

ω* – reference input.

ω – controlled variable, the rotational speed of the motor shaft.

Md_1 – electromagnetic torque of the motor.

Mc– static resistance torque.

ld – current in the motor's stator winding.

p_n – number of pole pairs of the motor.

k_r – rotor coupling coefficient.

r_e – equivalent phase resistance of the motor.

T_j – mechanical time constant of the motor.

T_{im} – electromagnetic time constant of the motor.

Kfc – frequency converter transfer coefficient.

T_{if} – filter time constant.

K_{psc} – proportional gain of the speed regulator.

T_{isc} – speed regulator time constant.

The system's motion equation is as follows:

$$J \cdot \frac{d\omega}{dt} = M_{d1} - M_c \tag{13}$$

where J – is the reduced moment of inertia.

The frequency converter transfer coefficient Kfc, as well as the feedback loop gain coefficients k_i and k_ω, are assumed to be equal to one since these parameters are compensated by the regulators and do not affect process dynamics.

For tuning the current regulator to modular optimum, its transfer function must be [13, p. 82–91]:

$$W_{ic}(s) = \frac{T_{im} \cdot s + 1}{2 \cdot \frac{1}{r_e} \cdot T_{if} \cdot s} \tag{14}$$

The modular optimum for the speed regulator is achieved by adjusting the proportional gain:

$$K_{psc} = \frac{T_j}{4 \cdot \frac{3}{2} \cdot p_n \cdot k_r \cdot T_{if}} \quad (15)$$

To avoid a static error (Figure 3) under disturbance, an integrating component was added to the speed regulator, enclosed in an additional feedback loop (Figure 1). Maintaining the set speed regardless of the load and ensuring a smooth start-up of the conveyor is crucial. Introducing an integrator into the speed regulator increases the regulation time by 0.6 seconds but eliminates the static error (Figure 3). The time constant of the integrating component is calculated as follows:

$$T_{isc} = 8 \cdot T_{if} \quad (16)$$

The parameter calculations were performed using the equations presented in [1, p. 197–201].

The mechanical time constant of the motor:

$$T_j = \frac{\Omega_b}{p_n \cdot M_б} \cdot J_д = \frac{314{,}15}{2 \cdot 2019} \cdot 5{,}4 = 0{,}42\ \mathrm{s} \quad (17)$$

The scattering inductance of the stator phase winding:

$$L_{s\sigma} = \frac{X_{s\sigma}}{\Omega_b} = \frac{0{,}036}{314{,}15} = 0{,}00011\ \mathrm{H} \quad (18)$$

Rotor winding leakage inductance:

$$L_{r\sigma} = \frac{X_{r\sigma}}{\Omega_b} = \frac{0.05}{314.15} = 0.00016\ \mathrm{H} \quad (19)$$

Equivalent leakage inductance of the Motor phase:

$$L_э = L_{s\sigma} + k_r \cdot L_{r\sigma} = 0.00011 + 0.977 \cdot 0.00016 = 0.00027\ \mathrm{H} \quad (20)$$

Equivalent Active resistance of the Motor phase:

$$R_э = R_s + k_r^2 \cdot R_r = 0.004 + 0.977^2 \cdot 0.005 = 0.009\ \mathrm{Ohm} \quad (21)$$

Electromagnetic time constant of the motor:

$$T_{im} = \frac{L_{э}}{R_{э}} = \frac{0.00027}{0.009} = 0.03\ s \tag{22}$$

The parameters used to construct the simulation model, calculated in per-unit values, are given in Table 3.

Table 3 – Parameters for constructing the simulation model

Parameter	Value
	0.42
	0.977
	2
	0.024
	0.03
	0.06

The filter time constant was selected empirically based on the oscillogram of the real object presented in [6, p. 178].

Figures 2 and 3 show the oscillograms of the transient process of the motor's angular velocity under a unit step input with and without the use of an integrator in the speed regulator. A disturbance is applied to the system at t = 2 s (Figure 3).

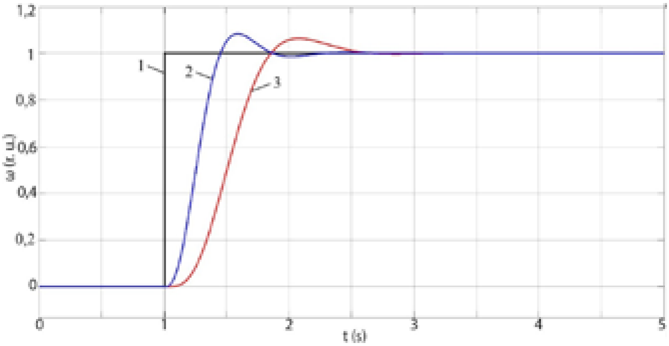

Figure 2 – angular velocity of the motor without load (0 r. u.)
1 – reference input ; 2 – angular velocity of the motor without the integrator in the regulator; 3 – angular velocity of the motor with the integrator in the regulator

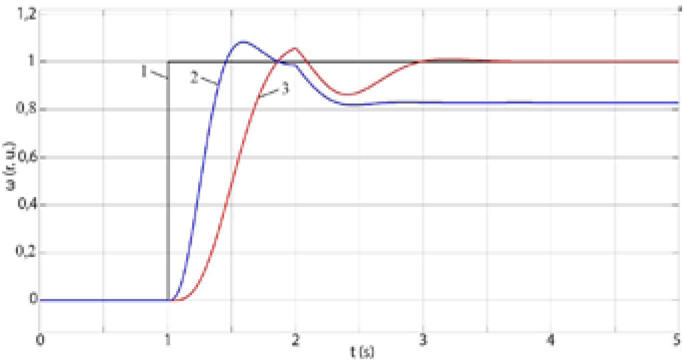

Figure 3 – Angular velocity of the motor under load (0,3 r. u.)
1 – reference input ; 2 – angular velocity of the motor without the integrator in the regulator; 3 – angular velocity of the motor with the integrator in the regulator

As shown in Figure 3, the created closed-loop control system of an asynchronous electric drive with frequency regulation ensures stable dynamic transient processes and demonstrates low sensitivity to external disturbances. The simulation model can be used for further research.

The developed simulation model of the frequency-controlled asynchronous electric drive exhibits high efficiency in managing dynamic processes. The vector control system with cross-coupling compensation provides high-quality transient processes and operational stability under disturbances. The main contribution of the proposed model is to minimize the static error and ensure smooth acceleration of the conveyor, which is confirmed by the oscillograms of transient processes.

Comparison with existing models confirmed that the use of controllers with individual feedback loops increases the stability of the system, and that tuning parameters according to the principle of modular optimum helps to increase energy efficiency. Unlike similar works, the proposed model is focused on practical application in industrial conditions, considering the characteristics of mining equipment.

The obtained results demonstrate the applicability of the model for analyzing various operational scenarios and optimizing the operation of conveyor equipment. Prospects for further research include the development of adaptive control systems capable of dynamically responding to load changes.

Conclusions

The paper calculates the parameters of the equivalent circuit of an asynchronous motor considering its characteristics. A procedure for converting parameters into relative and absolute units is proposed, which ensures high accuracy of modeling.

A model of an asynchronous electric drive with frequency regulation and a vector control system has been developed in the Matlab Simulink environment, including dynamic compensation of cross-links. This made it possible to minimize the static error, ensure smooth acceleration and resistance to load disturbances.

The modeling results confirmed that the control system provides high-quality transient processes, meets the requirements of reliability and energy efficiency. The model is suitable for analyzing various scenarios of conveyor equipment operation and optimizing its operation, including adaptive control systems.

The created model allows to increase the efficiency of work, reduce energy consumption and extend the service life of equipment, which makes it attractive for use in industry.

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МОДЕЛИРОВАНИЕ АСИНХРОННОГО ДВИГАТЕЛЯ УПРАВЛЯЕМОГО ПРЕОБРАЗОВАТЕЛЕМ ЧАСТОТЫ

В статье представлены результаты проведенных теоретических исследований. Создана имитационная модель асинхронного электропривода с частотным регулированием в программной среде Matlab Simulink. На основе данной модели разработан двухдвигательный электропривод ленточного конвейера. Основное внимание уделено расчету параметров математической модели двигателя. В имитационной модели учтены характеристики промышленного оборудования, установленного на объектах горнодобывающих компаний Республики Казахстан. Разработанная модель основывается на принципах векторного управления с компенсацией перекрестных связей, что позволяет обеспечить высокое качество динамических характеристик и устойчивость к внешним возмущениям. Приведены теоретические и экспериментальные результаты, подтверждающие эффективность предложенной системы управления. Полученная имитационная модель может быть *использована для проектирования и модернизации промышленных электроприводов в горнодобывающей отрасли. Дополнительно рассмотрены методы повышения энергоэффективности системы за счёт оптимизации параметров управления. Анализ переходных и стационарных процессов показал, что предложенный подход позволяет минимизировать влияние внешних возмущений и обеспечить стабильную работу оборудования. Разработанная модель также может быть интегрирована в системы автоматизированного управления для повышения их функциональности и надёжности. Результаты исследований демонстрируют высокую точность модели и её применимость в условиях промышленной эксплуатации для улучшения производительности и снижения энергозатрат.*

Ключевые слова: асинхронный двигатель, электропривод, преобразователь частоты, энергоэффективность, имитационная модель.

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ЖИІЛІКТІ ТҰРҒАНДЫРУШЫМЕН БАСҚАРАЛАТЫН АСИНХРОНДЫҚ МОТОРДЫ СИМУЛАУ

Мақалада жүргізілген теориялық зерттеулердің нәтижелері берілген. Matlab Simulink бағдарламалық жасақтама ортасында жиілікті реттейтін асинхронды электр жетегінің имитациялық моделі жасалды. Осы үлгінің негізінде таспалы конвейерге арналған екі моторлы электр жетегі әзірленді. Негізгі назар қозғалтқыштың математикалық моделінің параметрлерін есептеуге аударылды. Имитациялық модельге Қазақстан Республикасындағы тау-кен компаниялары объектілерінде орнатылған өнеркәсіптік *жабдықтардың сипаттамалары енгізілді. Әзірленген модель айқас байланыстарды өтеу арқылы векторлық басқару принциптеріне негізделген, бұл динамикалық сипаттамалардың жоғары сапасын және сыртқы әсерлерге төзімділікті қамтамасыз етеді. Ұсынылған басқару жүйесінің тиімділігін растайтын теориялық және эксперименттік нәтижелер келтірілген. Алынған имитациялық модель тау-кен өнеркәсібіндегі өнеркәсіптік электр жетектерін жобалау және жаңғырту үшін қолданылуы мүмкін. Сонымен қатар, басқару параметрлерін оңтайландыру арқылы жүйенің энергия тиімділігін арттыру әдістері қарастырылған. Өтпелі және стационарлық процестердің талдауы ұсынылған тәсіл сыртқы әсерлердің әсерін барынша азайтуға және жабдықтың тұрақты жұмысын қамтамасыз етуге мүмкіндік беретінін көрсетті. Әзірленген модель автоматтандырылған басқару жүйелеріне олардың функционалдығы мен сенімділігін арттыру үшін интеграциялануы мүмкін. Зерттеу нәтижелері модельдің жоғары дәлдігін және оның өнеркәсіптік жағдайларда өнімділікті арттыру және энергия шығындарын азайту үшін қолданылуын көрсетеді.*

Кілтті сөздер: асинхронды қозғалтқыш, электр жетегі, жиілік түрлендіргіші, энергия тиімділігі, модельдеу моделі.

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