Construction of the Automatic Control System of a Single-Screw Extruder

[1]Zablodskiy M., [2]Klendiy P., [3]Dudar O., [1]Shvorov S.
[1]National University of Life and Environmental Sciences of Ukraine,
Kyiv, Ukraine
[2] Separated subdivision "Berezhany Agrotechnical Institute" National University of Life and Environmental Sciences of Ukraine,
Berezhany, Ukraine
[3]Separated structural subdivision “Berezhany professional college of National University of Life and Environmental Sciences of Ukraine”
Berezhany, Ukraine

Abstract. The purpose of the work is to build the rational system for regulating technological parameters of the single-screw extruder using the frequency-regulated electric drive with limited use of sensors. This goal is achieved by the way of solving the following problems: development the method for controlling the technological parameters of the extruder with a controllable electric drive; development of a structural diagram of a model for estimating the speed of rotation a rotor of the engine without the use of velocity-type transducers; development of a functional diagram of the vector frequency-regulated electric drive with an observer that is built on the basis of a voltage equation corresponding to the main magnetic flux; development of a simulation model of the system of adjustable electric drive of the extruder and carrying out simulations with using the Matlab software package in the environment of Simulink. The most significant results of the researches are: the proposed algorithm for controlling the technological parameters (dynamic viscosity and pressure) by the way of calculating of the electrical power parameters of the adjustable electric drive of the extruder without the use velocity-type transducers; the functional diagram of the vector frequency-regulated electric drive of the single-screw extruder with the observer that was built on the basis of balance of the reactive capacity provides the necessary values of the technological parameters of the extruder. Changes in dynamic viscosity and pressure in the material, provides flexible adjustment without the use of speed sensors and rational use of electricity.

Keywords**:** vector control, extrusion, dynamic viscosity, energy efficiency, simulation model.

DOI: https://doi.org/10.52254/1857-0070.2024.4-64.04
UDC: **621.3.62-5.681.5**

Construcția sistemului rațional de reglare a parametrilor tehnologici ai unui extruder cu un singur șurub prin intermediul acționării electrice reglate în frecvență

Zablodskiy M.[1], Klendiy P.[2], Dudar O.[3], Șvorov S. [1]
[1]Universitatea Națională de Științe ale Vieții și Mediului din Ucraina, Kiev, Ucraina
[2] Subdiviziune separată „Institutul Agrotehnic Berezhany” Universitatea Națională de Științe ale Vieții și Mediului din Ucraina, Berezhany, Ucraina
3 Subdiviziune structurală separată „Colegiul profesional Berezhany al Universității Naționale de Științe ale Vieții și Mediului din Ucraina”, Berezhany, Ucraina

Abstract. Scopul lucrării este de a construi sistemul rațional de reglare a parametrilor tehnologici ai extruderului cu un singur șurub, folosind unitatea electrică reglată în frecvență cu utilizare limitată a senzorilor. Acest scop este atins prin modalitatea de rezolvare a următoarelor probleme: dezvoltarea metodei de control al parametrilor tehnologici ai extruderului cu acționarea electrică reglabilă; elaborarea unei diagrame structurale a unui model pentru estimarea vitezei de rotație a unui rotor al motorului fără utilizarea traductoarelor de tip viteză; elaborarea unei scheme funcționale a acționării electrice vectoriale reglate în frecvență cu un observator care este construit pe baza unei ecuații de tensiune corespunzătoare fluxului magnetic principal; elaborarea unui model de simulare a sistemului de antrenare electrică reglabilă a extruderului și realizarea de simulări cu utilizarea pachetului software Matlab în mediul Simulink. Cele mai semnificative rezultate ale cercetărilor sunt: algoritmul propus pentru controlul parametrilor tehnologici (vâscozitate dinamică și presiune) prin modul de calcul al parametrilor de putere electrică ai antrenării electrice reglabile a extruderului fără utilizarea traductoarelor de tip viteză; Schema funcțională a acționării electrice vectoriale reglate în frecvență a extruderului cu un singur șurub cu observatorul care a fost construită pe baza echilibrului capacității reactive oferă valorile necesare ale parametrilor tehnologici ai extruderului. Modificările vâscozității dinamice și ale presiunii din material oferă o reglare flexibilă fără utilizarea senzorilor de viteză și utilizarea rațională a electricității.

Keywords**:** control vectorial, extrudare, vâscozitate dinamică, eficiență energetică, model de simulare.

Построение рациональной системы регулирования технологических параметров одношнекового экструдера средствами частотно-регулируемого электропривода

Заблодский Н.[1], Клендий П.[2], Дудар О.[3], Шворов С.[1]
[1]Национальный университет биоресурсов и природопользования Украины, Киев, Украина
[2]Отделенное подразделение «Бережанский агротехнический институт» Национального университета биоресурсов и природопользования Украины, Бережаны, Украина,
[3]Отделенное структурное подразделение «Бережанский профессиональный колледж Национального университета биоресурсов и природопользования Украины», Бережаны, Украина.

Аннотация. Целью работы является построение рациональной системы регулирования технологических параметров экструдера одношнекового средствами частотно-регулируемого электропривода с ограниченным использованием датчиков. Поставленная цель достигается путём решения следующих задач: разработка способа управления технологическими параметрами экструдера с регулируемым электроприводом; разработка структурной схемы модели для оценки скорости вращения ротора электродвигателя без использования датчиков скорости; разработка функциональной схемы векторного частотно-регулируемого электропривода с наблюдателем, построенным на основе уравнения напряжений, соответствующих основному магнитному потоку; разработка имитационной модели системы регулируемого электропривода экструдера и проведение моделирования с использованием программного комплекса Matlab в среде Simulink. Наиболее значимыми результатами исследований являются: предложенный алгоритм контроля технологических параметров (динамическая вязкость и давление) путем расчетов электроэнергетических параметров регулируемого электропривода экструдера без использования датчиков скорости; функциональная схема векторного частотно-регулируемого электропривода одношнекового экструдера с наблюдателем, построенным на основе баланса реактивной мощности, обеспечивает необходимые значения технологических параметров экструдера. изменениях динамической вязкости и давления в материале, обеспечивает гибкую регулировку без использования датчиков скорости и рациональное использование электроэнергии.

Ключевые слова**:** векторное управление, экструзия, динамическая вязкость, энергоэффективность, имитационная модель.

INTRODUCTION

To improve the fermentation of biomass, it is carried out its pre-treatment. The purpose of pre-treatment of substrates is allotment for fermentation bacteria easier access to materials that are decomposed into compounds. One of the methods of pre-treatment is extrusion [1]. Grinding is a process by which the size of particles of the material to be processed is reduced. As a result, the degree of crystallization and polymerization of cellulose decreases and there rises a larger specific surface of the substrate, which can be affected by microorganisms [2]. Extrusion is a baro-thermal process in which raw material (lignocellulose, fats, proteins) are exposed to mechanical force (shear, compression), high temperature (40–200^{0}C) and pressure change (from several to several tens of MPa) [3]. Pre-treatment preparation of the substrate from the straw of various crops by the method of extrusion should be carried out under the control of such technological parameters as the pressure and viscosity of the melt, which affects on the heat balance of the extruder, that leads to the change in the amount of released heat as a result of friction during homogenization, plasticization, shearing and compression in the process of treatment the material[4]. Leszek Mosicki [5] notes that the following factors play a key role in the process of extrusion in the single-screw extruders: humidity; viscosity and composition of raw material that are subjected to extrusion; the construction of the extruder screw and its frequency rotation ; temperature of flowing the process of extrusion and pressure.

Extrusion and grinding increase the yield of the methane from processed substrates. However, the implementation of these technologies in a biogas plant involves additional costs.Investment costs depend on the efficiency of the specific technology and range from several tens to several hundred thousand euros depending on the efficiency of the machines (mill, extruder). The economic balance of such investments should also take into account the amount of energy that is consumed by the machine, according to calculations — from 30 to even 90 kWh per ton of substrate. [6]. Using the process of extrusion for biogas substrates increases the efficiency of biogas and methane in the fermentation process by 7.50 and 8.51%, respectively, and reduces the fermentation time by approximately 8 days. Taking into account the amount of energy that is spent for pre-treatment and the amount of produced methane, the energy balance of the process gives an idea about the economics of the operation. Despite on the increase in efficiency of fermentation, the authors of the work [7] consider that the use of extrusion in Poland is economically unjustified due to the high energy consumption of pre-treatment. In order to fully utilize the potential of extrusion, it is necessary thoroughly to know the influence of process of the extrusion on the energy efficiency of biogas production and propose the methods of regulating this process [8]. Pre-treatment of the substrate by extrusion brings energy benefits in the process of fermentation, as viscosity and energy required for mixing are reduced. In addition, grinding has a positive effect on the quality of mixing in the reactor and prevents partial droping and formation of floating layers. It was established that when is mixing coarsely chopped straw, the viscosity in the reactor is 2260 mPa s (millipascal second), and when is using extruded straw it was decreased to 880 mPas [9].At the same time, the capacity consumption is reduced, and the quality of the mixture can be improved.

ANALYSIS OF RECENT RESEARCHES AND PUBLICATIONS

What strategies of optimization can be used in the systems of control by the electric drive with vector and direct control by torque are considered in the work [10]. The drive of an asynchronous motor (AM) with vector control is currently the most perfect, but its algorithms in most cases do not fully take into account current changes in the technological parameters of the systems in the structure of which they work. Since screws of the extruder are more often used in the industry, it is necessary to optimize both constructions of the screws and the control system for improving productive capacity and ensure technological parameters. For this method, trials and errors is not enough, and it becomes necessary clearly understand and, if it is possible, to calculate what happens in the machine during the process of extrusion.

According to the proposals of the authors of the work [11], the control of output pressure and temperatures, as well as the control scheme by these parameters consists of a control loop on the base of Single Input Single Output Proportional Integral Derivative (SISO PID). The measured (controlled) variables are the output pressure and temperatures in different zones of the active part of the extruder, the input variable is the command voltage of the inverter to power the motor of extruder.

In the work [12], based on the results of experiments and simulation, it was shown that the quality and energy efficiency of extrusion is affected by the frequency rotation of screw of the extruder, and the dynamic viscosity of the processed material is directly proportional to the capacity of the single-screw extruder. Therefore, in order to minimize energy consumption for the extrusion of rape and corn straw, the dynamic viscosity of the material must be minimal.It is necessary to take into account the fact that the pressure and temperature increase sharply at high rotations. This leads to burning of the biopolymer, rapid wear of parts of the extruder, and excessive consumption of electrical energy. It is emphasized that in order to ensure rational mode of the operation of the extruder, it is necessary to develop an automatic control system that would take into account the pressure and temperature in the die during stochastic loading of the extruder.

The authors of the work [13] carried out simulation of the extrusion of pea flour and the mixture of pea starch and protein isolate with the help of twin-screw extruders, which made it possible accurately predict the variables of extrusion (temperature and specific mechanical energy) based on the parameters of extrusion (feed speed, speed of the screw, temperature of the stem). This research shows that simulation of extrusion with a rheological model can be used as a tool for development extruded food products with a target structure.

The problem of clarity of stabilization and regulation parameters of the technological process with using extrusion also exists in other industries. In the work [14], an adaptive neurofuzzy system (ANFIS) controller was developed to ensure a constant speed of line during the process of extrusion of casing of the cable. The controller ANFIS was compared with an ordinary proportional-integral-derivative controller and a Fuzzy Logic controller for checking the reliability with the help of MATLAB/Simulink software.

Currently available models of extrusion are not general in nature due to the limitations of the type of extrusion, the specific material, and the specific operating and geometric conditions of the process. Therefore, the question arises whether it is possible to solve the problem of global modeling of the process of extrusion without referring to the specific mechanism of flow of the solid substance /melt , which is determined by the extrusion method, the type of material, and conditions of the process [15].

The requirements to the electric drive of the extruder have a versatile character. This is due to difficult operating conditions, low accuracy support of the parameters at the output of the unit, and low qualification of service personnel. In such conditions, the reliable operation of sensors of technological processes in the extruder - productivity, pressure and temperature - is problematic.

The purpose of the work is to build the rational system for regulating the technological parameters of the single-screw extruder by means of the frequency-regulated electric drive with limited use of sensors.

MATERIALS AND METHODS OF RESEARCH

The solution to the mentioned problem can be achieved due to the fact that in the method of controlling the technological parameters of the extruder for the implementation of the algorithm, the signals are received directly from the frequency converter with vector control, the principle of operation of which involves obtaining the electromechanical parameters of the electric drive (electromagnetic moment and speed of the electric motor), with the help of which the calculation is carried out according to the given algorithm by absolute values.

The functional scheme of the control system of the proposed method is shown in Fig. 1.

The method of controlling by he technological parameters of the extruder with the adjustable electric drive is implemented as follows.

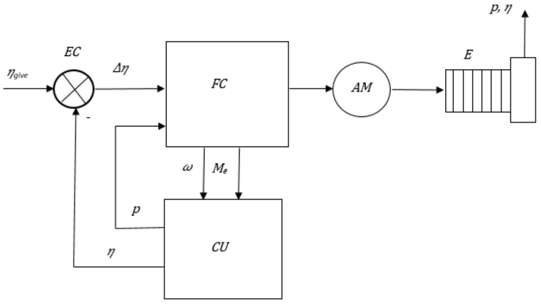


Fig. 1. Functional diagram of the system for regulating the operating modes of the extruder without sensors of the technological parameters.

E – extruder; AM - asynchronous motor; FC - frequency converter; CU - computing unit; EC - element of comparison; η_{give} - the given value of the dynamic viscosity of the material; $\Delta\eta$ – deviation of the dynamic viscosity of the material; p – the actual value of the pressure; η – the actual value of the dynamic viscosity.

When the operating modes of the extruder are changed in accordance with the requirements of the technological process, the electric power parameters of AM are changing, which, in turn, are controlled by the frequency converter with vector control, and based on their values, the quantities of the electromagnetic moment M_e and the angular velocity ω are calculated, which enter into the CU, where is implemented the algorithm based on the expression:

$$(M_e - M_м)\cdot\omega = \frac{\pi^2}{2}D^2 n h_2 p\cdot tg\alpha + \\ +\pi^3 D^2 n^2 \eta L_2\left(\frac{D}{h_2\cos\alpha} + \frac{e}{\delta tg\alpha}\right), \qquad (1)$$

where D- is outer diameter of the screw, m;
n – frequency of rotation of the screw, rad/s;
h_2 – is depth of cutting of the screw, m;
p – pressure, Pa;
α – the angle of inclination of the helical cutting line of the screw;
η - the dynamic viscosity of the material, N· s /m^2;
L_2– is length of the screw, m;
e – is thickness of the coil, m;
δ – the gap between the wall of the cylinder and the coil of the screw, m;
M_e – electromagnetic moment AM, N·m;
M_m – mechanical wastes of the moment AM, N·m; ω – angular velocity of the extruder, s^{-1} .

According to the equation (1), the real values of pressure p are calculated, which are compared in the element (CE) with the given value of p*giv , the error signal ΔP is fed to the input of the frequency converter and is a function of the set speed of rotation.

To implement the algorithm (1), in depending on the angular speed of the extruder, for the corresponding biopolymers are determined the parameters p and ŋ , which are obtained experimentally or from the reference literature, and are approximated by the following expressions:

$$p = A + B \cdot \omega, \quad (2)$$

$$\eta = \frac{D}{\omega} + C, \quad (3)$$

where A, B, C, D -are coefficients of approximation which are determined for the specific extruder.

The coefficients of the expression (2) are determined from the system of equations:

$$\left.\begin{aligned} \sum p &= An + B\sum \omega \\ \sum p\omega &= A\sum \omega + \sum \omega^2 \end{aligned}\right\} \quad (4)$$

where n- is number of members of the empirical series of regression.

The coefficients of the expression (3) are determined from the system of equations:

$$\left.\begin{aligned} \sum \eta &= D\sum \frac{1}{\omega} + Cn \\ \sum \frac{\eta}{\omega} &= D\sum \frac{1}{\omega^2} + C\sum \frac{1}{\omega} \end{aligned}\right\} \quad (5)$$

The implementation of this method is possible by the way of using the adjustable electric drive, when the value of the moment of the motor M and its angular speed ω is derived from the control system. We get then:

$$P = \omega \cdot \mathrm{M} \quad (6)$$

The solution of the equations (1), (2), (3) and (6) with known M, ω allows to determine the pressure in the active zone of the extruder.

It is reasonably to use the asynchronous electric motor with frequency control to drive the extruder. The improvement of such drive is possible by using the laws of the second level, which include laws that ensure a constant value of various magnetic flux- linkages of the asynchronous motor: stator ψ_1 (corresponds to the constant value of the ratio E_s./f,), rotor ψ_2 (E_r./f).

where E_s - electromotive force of the stator; f – frequency; E_r - electromotive force of the rotor.

The last law allows direct control by the torque of the electric motor and at the same time the quality of control of the electric drive in static and dynamic modes is significantly increased in comparison with other laws.

The simplicity of the presentation of the frequency-controlled electric drive increases with the rational choice of the angular velocity and orientation of the coordinate axes in the transition mode. With a sinusoidal voltage supply, the resulting vectors of currents, voltages and flux - linkages of the stator and rotor in the steady state are mutually stationary, then any coordinate system tied to one of these vectors (let's call it "basic") is suitable for optimization [16]. The basic vector in the implementation of the law $|\psi_2| = const$ is the vector of flux- linkage of the rotor. Let's direct the vectorψ_2 along the axis d, and the axis q - in leading it direction by 90^0. At the same time, the equations of the electric drive are simplified, since the projection of the generalized base vector - the flux- linkage of the rotor - on the axis q is equal to zero.

The system of these equations in the coordinate system d, q, which rotates at synchronous speed, in relative to units has the form [17]:

$$\begin{cases} u_{1d} = r_1 i_{1d} + \dfrac{1}{\omega_{он}} \cdot \dfrac{d\psi_{1d}}{dt} + f^* \psi_{1d} \\ u_{1q} = r_1 i_{1q} + \dfrac{1}{\omega_{он}} \cdot \dfrac{d\psi_{1q}}{dt} - f^* \psi_{1q} \\ 0 = r_2 i_{1q} + \dfrac{1}{\omega_{он}} \cdot \dfrac{d\psi_{2d}}{dt} + \left(f^* - \omega^*\right)\psi_{2d} \\ 0 = r_2 i_{2q} + \dfrac{1}{\omega_{он}} \cdot \dfrac{d\psi_{2q}}{dt} - \left(f^* - \omega^*\right)\psi_{2q} \\ \psi_{1d} = \left(\left(1 + l_1\right) i_{1d} + i_{2d}\right) f^* \\ \psi_{1q} = \left(\left(1 + l_1\right) i_{1q} + i_{2d}\right) f^* \\ \psi_{2d} = \left(\left(1 + l_2\right) i_{2d} + i_{1d}\right) f^* \\ \psi_{2q} = \left(\left(1 + l_2\right) i_{2q} + i_{1q}\right) f^* \\ \mu = \dfrac{2}{3} P_n \left(\psi_{2q} i_{2d} - \psi_{2d} i_{2q}\right) \\ \mu = \mu_c + \dfrac{\mathrm{J}\omega^2_{он}}{M_б} \cdot \dfrac{d\omega^*}{d\overline{t}} \end{cases} \quad (7)$$

where nominal values of stator current I_{1n}, synchronous speed ω_{0n} and frequency f_{1n} of applied voltage are taken as basic units.

Output ratios:

$$\mathrm{i}_1 = \frac{\mathrm{I}_1}{\mathrm{I}_{1н}}; \quad f^* = \frac{f_1}{f_{\mathrm{i}н}}; \quad \omega^* = \frac{\omega}{\omega_{он}}; \quad f^* = \frac{\omega_о}{\omega_{он}};$$

$$\mathrm{U}_б = \omega_{он}\mathrm{L}_m\mathrm{I}_{1н}; \quad \mathrm{Z}_б = \omega_{он}\mathrm{L}_m;$$

$$\mathrm{u}_1 = \frac{\mathrm{U}_1}{\mathrm{U}_б}; \quad \mathrm{M} = \mathrm{U}_б \cdot \mathrm{I}_{1н} / \omega_{он}; \quad \mathrm{l}_1 = \frac{\mathrm{L}_1}{\mathrm{L}_{1н}}; \quad \mathrm{l}_2 = \frac{\mathrm{L}_2}{\mathrm{L}_m},$$

where ω_0 - is the angular velocity of field of the stator of the electric motor at frequency f_1 of the supplied voltage, rad/s; L_1, L_2, L_m - are inductances of the dissipation of the stator and rotor windings and the inductance of the magnetization circuit, Hn.

The vector of flux - linkage of the stator can be written in the shape[16]:

$$\overline{\psi}_1 = \overline{I}_1 l_1' + \kappa_2 \overline{\psi}_2 , \qquad (8)$$

where: $l_1' = l_1 + \kappa_2 l_2 ; \kappa_2 = \frac{1}{(1+l_2)}$.

The equations (7) are written in vector form in the shape:

$$\begin{cases} \overline{U}_1 = r_1 \overline{i}_1 + \frac{d\overline{\psi}_1}{d\overline{t}} + jf^* \overline{\psi}_1 \\ 0 = r_2 \overline{i}_2 + \frac{d\overline{\psi}_2}{d\overline{t}} + j(f^* - \omega^*)\overline{\psi}_2 \\ \overline{\psi}_1 = (1+l_1)\overline{i}_1 + \overline{i}_2 \\ \overline{\psi}_2 = (1+l_2)\overline{i}_2 + i_1 \\ m = \frac{3}{2} P_n I_m (\overline{\psi}_2 \overline{i})_2 \\ \overline{T}_\mu \frac{d\omega^*}{dt} = \mu - \mu_c \end{cases} \qquad (9)$$

where $T_\mu = \frac{J\omega_{OH}^2}{M_б}$

In the coordinate system d – q, which rotates at the speed of the stator field, system (9) will be written in the form:

$$\begin{cases} u_{1d} = r' i_{1d} + T_l' \frac{di_{1d}}{dt} - l_1' f^* i_{1q} - \frac{r_2}{T_2}\psi_{2d} - k_2 \omega^* \psi_{2q}; \\ u_{1q} = r' i_{1q} + T_l' \frac{di_{1q}}{dt} - l_1' f^* i_{1d} - \frac{r_2}{T_2}\psi_{2q} - k_2 \omega^* \psi_{2d}; \\ 0 = -k_2 r_2 i_{1d} + \frac{1}{T_2}\psi_{2d} + \frac{d\psi_{2d}}{dt} - (f^* - \omega^*)\psi_{2q}; \\ 0 = -k_2 r_2 i_{1q} + \frac{1}{T_2}\psi_{2q} + \frac{d\psi_{2q}}{dt} + (f^* - \omega^*)\psi_{2d}; \\ \mu = k_2(\psi_{2d} i_{1q} - \psi_{2q} i_{1d}); \\ \mu - \mu_c = T_\mu \frac{d\omega^*}{dt} \end{cases} \qquad (10)$$

$at, t = t_0,$

$i_{1d} = i_{1d0}, i_{1q} = i_{1q0}, \psi_{2d} = \psi_{2d0}, \psi_{2q}$

$\omega^* = \omega^*_0 .$

where: $r_1' = r_1 + \kappa_2^2 r_2$,

$$T_l' = \frac{l_1'}{r'}; T_2 = \frac{L_{2\sigma}}{R_2}; L_{2\sigma} = L_2 + L_m$$

When implementing the vector method of controlling the frequency of rotation of the asynchronous electric motor, when ψ2 = const, the first four equations (10) in operator form will be written in the form:

$$\begin{cases} U_{1d} = i_{1d}' r_1'(1 + pT_1') - f^* l_1' i_{1q} - \frac{r_2'}{T_2}\psi_{2d}; \\ U_{1q} = i_{1q}' r_1'(1 + pT_1') + f^* l_1' i_{1d} + \kappa_2 \omega^* \psi_{2d}; \\ 0 = -\kappa_2 i_{1d} r_2 + \frac{1}{T_2}\psi_{2d} + p\psi_{2d}; \\ 0 = -\kappa_2 i_{1q} r_2 + (f^* - \omega^*)\psi_{2d}; \end{cases} \qquad (11)$$

From the third and fourth equations of system (11), we obtain:

$$\begin{cases} \psi_{2d} = \frac{\kappa_2 r_2 T_2 i_{1d}}{T_2 p + 1}, \\ f_c^* = \omega^* + \frac{\kappa_2 r_2 i_{1q}}{\psi_{2d}} \end{cases} \qquad (12)$$

During the implementation, $|\psi_{2n}| = const$ the value of flux-linkage is calculated according to the formula:

$$\psi_{2n} = \frac{\sqrt{2} I_n L_m}{\sqrt{1 + \left(\frac{T_2 2\pi f_1 s_n}{p_n} \right)^2}} \qquad (13)$$

Since $M = \frac{L_m}{L_2}(\psi_{2a} i_{1b} + \psi_{2b} i_{1a})$, то

$M\omega = P$,

a $P = k_1 p\omega + k_2 \omega^2 \eta$, то $\eta = \frac{k_3 M}{\omega}$ at vector control $M = \frac{L_m}{L}\psi_{2m} i_{1q}$

The electromagnetic moment of the electric motor with known flux- linkages and currents in the steady coordinate system is determined by the expression:

$$M = k_2(\psi_{2a} i_{1b} - \psi_{2b} i_{1a}), \qquad (14)$$

and capacity is expressed by formula (6).

The capacity on the shaft of the electric motor, with taking into account the mechanical consumptions, is determined by the expression:

$$P_в = (1 - \kappa_{мех})P \, , \qquad (15)$$

The dynamic viscosity of the material η_{giv} affects on the temperature of the substrate and is set in such way that the burning of the material does not occur on one side, and on the other side the minimum energy consumptions for the implementation of the mode are ensured.

From expressions (15) and (1), with the known value of the capacity that is consumed by the extruder and the required pressure, the dynamic viscosity is determined as:

$$\eta = \frac{\tau}{\dot{\gamma}} = \frac{M(R_e - R_i)}{4\pi^2 R_i L\omega}\,, \qquad (16)$$

where τ - the shear stress of the material; $\dot{\gamma}$ - the shear speed of the material; R_i - is the diameter of the screw, m; ω - angular speed of the screw, s^{-1}; R_e - the diameter of the sleeve of the screw, m; M- is the torque moment applied to the screw, N·m; L- is the level of the material in the coaxial gap, m.

If $\eta_{giv}-\eta \neq 0$, then the value of the set speed rotation is corrected, if $\eta_{giv}-\eta = 0$ such correction is not conducted.

In the block p_m of the sheme K , the value of pressure is calculated at the known value of p.

Methods are described in the literature that allow, using vector control by flux of the rotor, to estimate information about the number of rotations and the angle of orientation through the voltages on the control channels.

The method [18, 19] uses the groove effect, [20] – the observer (high stationary accuracy, insensibility of parameters), [21] – the Kalman's filter (takes into account the dispersal of values of measurements, high cost), [22] – the use of special voltage and flow sensors . The particular interest causes the method that is based on the determination by the output values of the inverter of the voltage components that create the magnetic flux of the rotor [19]. This method was developed and theoretically is deepened in the works of I.M. Bogayenko. and Balyuty S.M. [23, 24, 25]. If you use to write in the coordinates of d, q the equations of the asynchronous machine the vectors of current and flux-linkage of magnetization i_m and ψ_m (with the established mode of operation in the rotating coordinate system $\omega^* = const$, $\frac{d\omega^*}{dt} = 0$, $\mu = \mu_H$, all spatial vectors are stationary and invariable in magnitude: $\bar{u}_1 = \bar{U}_1 = const$, $\bar{i}_1 = \bar{I}_1 = const$, $\bar{i}_2 = \bar{I}_2 = const$, $\bar{\psi}_1 = const$, therefore, the derivatives of flux- linkages are also equal to zero.

Then the first two equations of system (9) after transformations will take the form:

$$\begin{cases} \dfrac{\bar{U}_1}{f^*} = \dfrac{r_1}{f^*}\bar{I}_1 + j\bar{\psi}_1 = \dfrac{r_1}{f^*}\bar{I}_1 + jl_1\bar{I}_1 + j\bar{\psi}_m \\ 0 = \dfrac{r_2}{f_2^*}\bar{I}_2 + j\bar{\psi}_2 = \dfrac{r_2}{f_2^*}\bar{I}_2 + jl_2\bar{I}_2 + j\bar{\psi}_m \end{cases} \qquad (17)$$

where $\bar{\psi}_m = \left(\bar{I}_1 + \bar{I}_2\right)$; $f_2^* = f^* - \omega^* = f^* - P_n \upsilon$ absolute sliding.

The equation (17) in concrete units will be written in the form:

$$\begin{cases} \dfrac{di_{1d}}{dt} = \dfrac{U_{1d}}{\sigma L_1} - \dfrac{R_1}{\sigma L_1} i_{1d} + \omega_m i_{1q} - \dfrac{L_m}{R_1\left(L_m + L_{2\sigma}\right)}\dfrac{d\psi_m}{dt} \\ \dfrac{di_{1q}}{dt} = \dfrac{U_{1q}}{\sigma L_1} - \dfrac{R_1}{\sigma L_1} i_{1q} + \omega_m i_{1d} - \dfrac{L_m \omega_m \psi_m}{R_1\left(L_m + L_{2\sigma}\right)} \\ \dfrac{d\psi_m}{dt} = \dfrac{R_2 L_m}{L_m + L_{2\sigma}}\left(i_{1d} - i_m\right) \\ \dfrac{d\theta}{dt} = \omega_m = \dfrac{L_m R_2 i_{1q}}{\left(L_m + L_{2\sigma}\right)\psi_m} + p_n\omega = \omega_2 + p_n\omega \\ T_\mu \dfrac{d\omega}{dt} = \mu - \mu_c = \dfrac{2}{3}\dfrac{p_n L_m}{\left(L_m + L_2\right)}\psi_m i_{1q} - \mu_c \end{cases} \qquad (18)$$

where $\psi_m = L_m i_m$; $\bar{i}_m = \bar{i}_1 + \frac{L_m + L_2}{L_m}\bar{i}_2$;

$$\sigma = 1 - \frac{1}{\left(1 + L_{1\sigma}/L_m\right)\left(1 + L_{2\sigma}/L_m\right)}$$

Coefficient of dissipation of the magnetic flux .

The voltage that determines the magnetization flux from the first two equations of the system (17),

$$U_m = \frac{L_m}{L_m + L_{2\sigma}}\frac{d\psi_m}{dt} = U_1 - R_1 i_1 - \sigma L_1 \frac{di_1}{dt}$$

Let's write this equation in the coordinate system d, q:

$$U_m e^{-j\theta} = U_{md} + jU_{mq} = \frac{L_m}{L_m + L_{2\sigma}}\frac{d\psi_m}{dt} + j\frac{L_m}{L_m + L_{2\sigma}}\omega_m\psi_m;$$

$$U_{md} = \frac{L_m}{L_m + L_{2\sigma}}\frac{d\psi_m}{dt}; \qquad U_{mq} = \frac{L_m}{L_m + L_{2\sigma}}\omega_m\psi_m;$$

$$\omega_m = \frac{L_m + L_{2\sigma}}{L_m}\frac{U_{mq}}{\psi_m}.$$

For the magnetizing voltage and for the voltage U1, the components of the voltage are in coordinates d, q and a, в are written in the form

$$U_{md} + jU_{mq} = U_m e^{-j\theta} = \left(U_{ma} + jU_{mb}\right)e^{-j\theta},$$

where

$$U_{ma} = U_{1a} - r_1 i_{1a} - \sigma\left(l_1 + 1\right)\frac{di_{1a}}{dt},$$

$$U_{mb} = U_{1b} - r_1 i_{1b} - \sigma\left(1 + l_1\right)\frac{di_{1b}}{dt}.$$

The magnitude of the flow and the number of rotations of the rotor of the asynchronous electric motor can be determined by the 3-rd and 4-th equations of the system (18), which, simplified, can be written in the form:

$$\begin{cases} \dfrac{di_m}{dt} + \dfrac{1}{T_2} i_m = \dfrac{1}{T_2} i_{1d} \\ p_n \omega = \omega_m - \dfrac{i_{1q}}{\left(T_2 i_m\right)} \end{cases} \qquad (19)$$

,

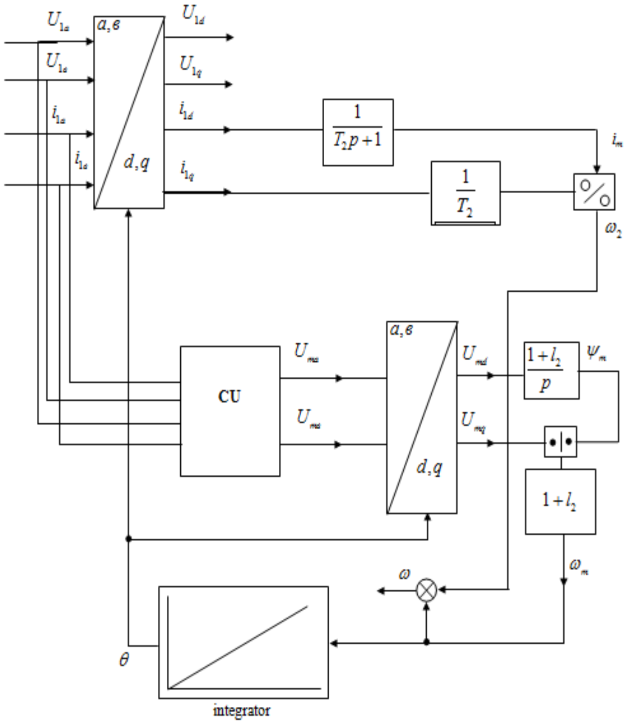


Fig. 2. Calculation of the flow and the number of rotations for schemes that do not have speed sensors.

As can be seen from this system of equations, the calculation of the angular frequency of the flow vector on the basis of balance of the reactive capacity does not require the use for the calculation of the active resistance of the stator, which is significantly dependent on the temperature. The model requires only inductances L_{11} and Lm .

In fig. 2 is showen the structural diagram of the model for estimating the speed of rotation of the rotor of the electric motor.

In the computing unit CU, the voltages that are corresponding to the main magnetic flux in the coordinate system a, в are calculated according to expressions (18).

In fig. 3 is showen a functional diagram of the vector frequency-regulated electric drive with the observer that is built on the basis of the voltages equation that is corresponding to the main magnetic flux.

Using the functional scheme fig. 3 and with the help of the "Matlab" software complex in the "Simulink" environment[26] the simulation model of the system of the adjustable electric drive of the extruder was developed, which is shown in fig. 4

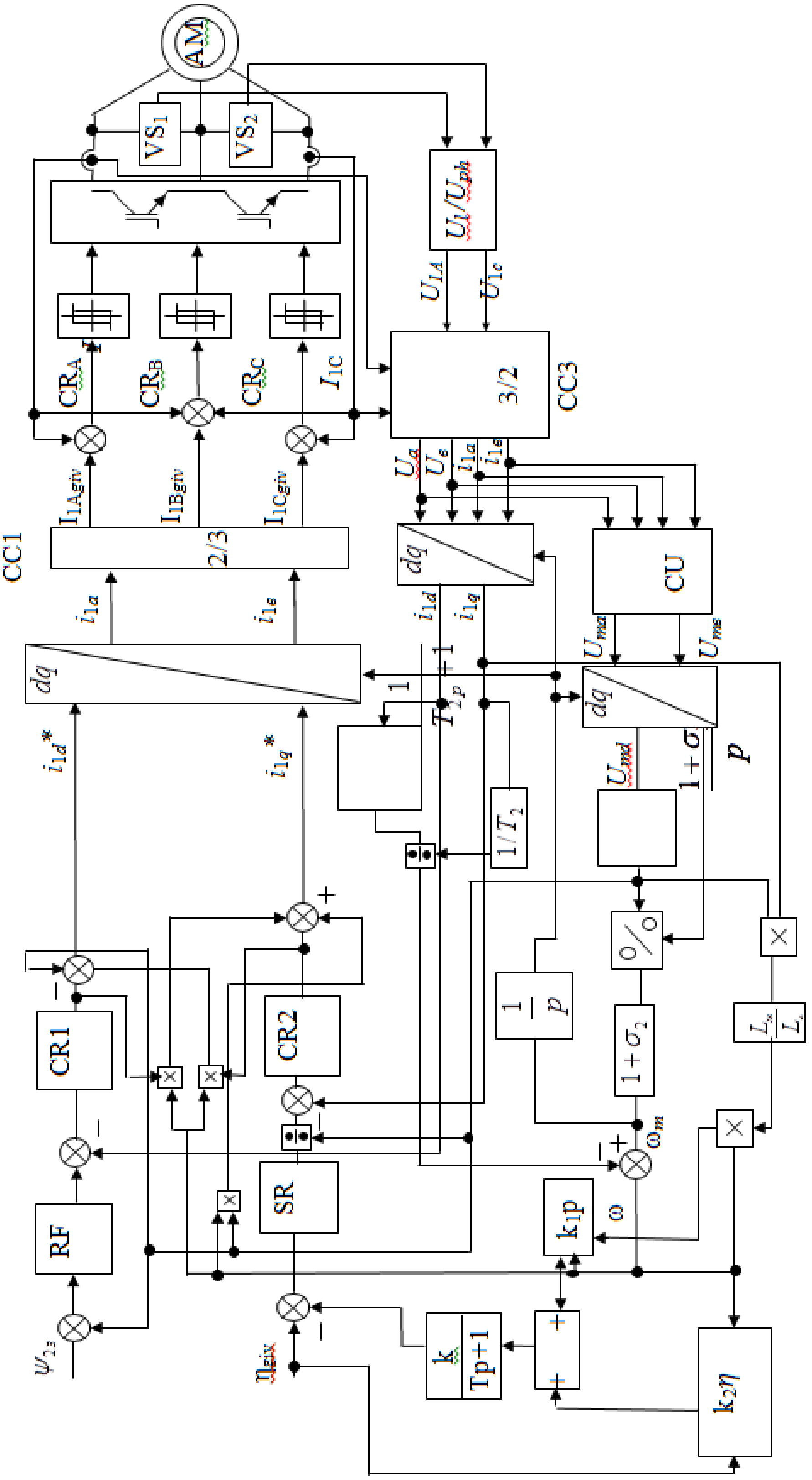
The simulation model of the frequency-regulated electric drive of the extruder consists of the following main blocks: extruder - Subsystem "extruder", asynchronous electric motor - AM, frequency converter, measuring set - Machines masurement, as well as Product and Product 1 blocks, in which the capacity and torque of the extruder are determined, respectively . Using the Constant block, the value of the dynamic viscosity is set.

THE QUALITY OF THE PROCESS WITH A GIVEN CONTROL ALGORITHM

The main indicators that characterize the process of adjustment are: the time of adjustment, over-adjustment and fluctuation.

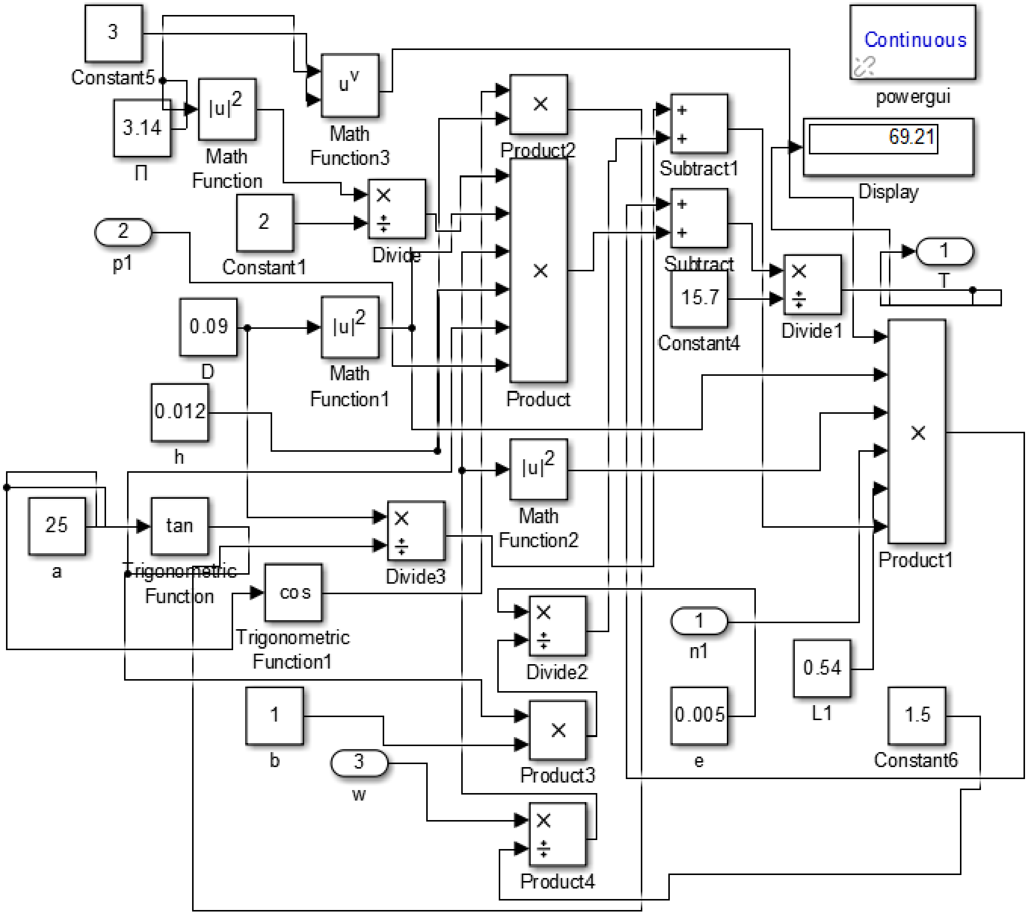
These indicators for different systems have corresponding values, which are regulated by the requirements of the technological process. In general, the quality of regulation is considered satisfactory if the over-adjustment does not exceed 30...40%, during designing the systems, fluctuations N = 1...2...and sometimes up to 3...4 are most often allowed.

The regulated value in our case is the pressure in the extruder, which is a derivative from the viscosity of product and, in turn, affects on the temperature and energy consumption on the process of extrusion.



RF - regulator of flow; SR – regulator of speed; CR1, CR2 – current regulator ; CC1,CC3 – coordinate converter; CR_A, CR_B, CR_C – current sensor; VS_1, VS_2 – voltage sensor.

Fig. 3. The functional diagram of the vector frequency-regulated electric drive with the observer that is built based on balance of reactive capacity.



Simulation model of the extruder

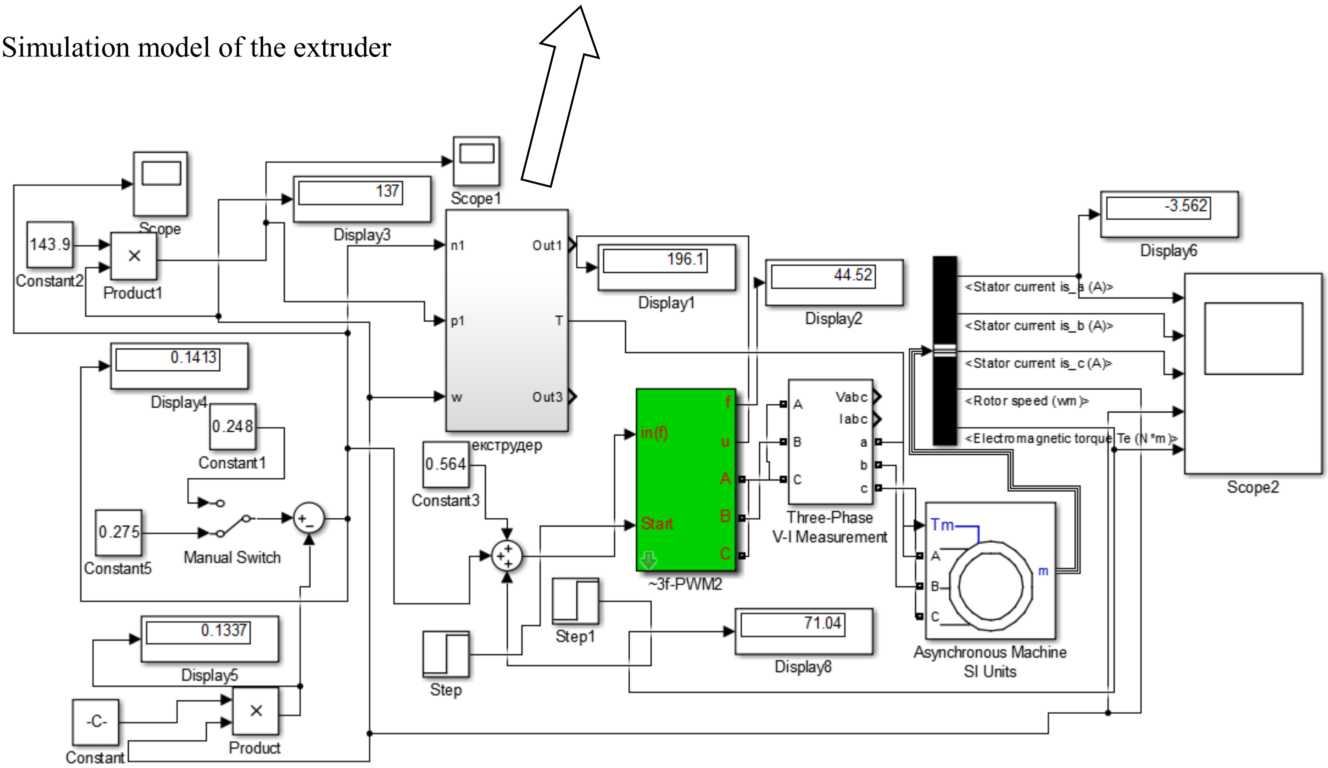


Fig. 4. Simulation model of the system of the adjustable electric drive of the extruder.

At the high temperature, organic matter burns, which worsens the quality of the substrate, therefore, over-adjustment and the time of adjustment should be minimal.

These indicators are affected by the capacity on the shaft of the electric motor and the capacity, in turn, depends on the amount of current and voltage.

The control algorithm an asynchronous electric motor by the vector control law is realized if the windings of the stator are powered from the frequency converter that is operating in the mode of current source. In this case, the equation (12) after some transformations is reduced to the form

$$\begin{aligned} i_{1d} &= T_2 p\psi_2 + \psi_2; \\ i_{1q} &= \frac{f_2 * \psi_2}{\kappa_2 r_2}; \\ \omega^* &= \frac{\mu - \mu_C}{T_\mu p}; \\ \mu &= \kappa_2 \psi_2 i_{1q}. \end{aligned} \qquad (20)$$

The flux - linkage of the rotor and stator in the dq coordinate system trough the currents $\overline{I}_1$ and $\overline{I}_2$ have the form

$$\overline{\psi}_1 = \overline{I}_1 L_1 + \overline{I}_2 L_m ; \overline{\psi}_2 = \overline{I}_1 L_m + \overline{I}_{2\sigma} L_2 \quad (21)$$

where $L_1 = L_{1\sigma} + L_m , L_{2\sigma} = L_2 + L_m , L_m = \frac{3}{2} L_{1m};$

and in relative units

$$\overline{\psi}_1 = \overline{i}_1 (1 + l_1) + \overline{i}_2 , \qquad \overline{\psi}_2 = \overline{i}_2 (1 + l_2) + \overline{i}_1 . \quad (22)$$

Expressions for currents of the rotor from (22)

$$\begin{aligned} i_{2d} &= \kappa_2 (\psi_2 - i_{1d}) \\ i_{2q} &= -\kappa_2 i_{1q}. \end{aligned} \qquad (23)$$

The amplitude of the vector current of the stator according to the equation (22) is determined by the expression:

$$i_1 = T_2 \sqrt{\left(p\psi_{2d} + \frac{\psi_{2d}}{T_2} \right)^2 + f_2^2 \psi_{2d}^2 }, \quad (24)$$

and the phase

$$\theta_1 = \omega_0 t + arctg \frac{f_2 * \psi_2}{p\psi_2 + \psi_2 / T_2} \quad (25)$$

The given equations show that in the dynamic system "asynchronous electric motor - working machine", the phase state of which is determined by the vector of flux – linkage of the rotor it is possible adjustment of the coordinates while maintaining $\psi_2 = const$ and adjusting the amplitude and phase current of the stator i_1 when the slipping changes. That is, with the vector control, it is necessary not only to stabilize the flux -linkage of the rotor at the given level, but also to control the angular position of its vector. For this, the system of equations of the electric drive is supplemented with the equations of transformation of the vector current of the stator from the fixed coordinate system *a,b* to the time system that is related to vector of flux -linkage of the rotor d,q

The total current of the stator in the fixed mode from (24)

$$I_1 = \psi_2 \sqrt{1 + f_2^2 T_2^2} . \quad (26)$$

Components of voltage at the terminals of the stator

$$\begin{aligned} U_{1d} &= \psi_2 f_c * \left[r' - \frac{r_2}{(1 + l_2)^2} - \frac{s l_1' (1 + l_2)}{r_2} \right]; \\ U_{1q} &= \psi_2 f_c * \left[\frac{r' s (1 + l_2)}{r_2} + l_1' + \frac{\omega^*}{(1 + l_2) f_c *} \right]. \end{aligned} \quad (27)$$

Research of the vector frequency control asynchronous electric drive is carried out under the following conditions:

1. Adjustment the voltage, flux- linkage, and current affect on the component of current i_{1d} that creates the magnetic flux, and through adjusting the number of rotations and the transverse component of the current, you can directly influence on the electric torque. Flow regulation can only be carried out with the time delay T_2.
2. The regulation of current in the coordinates of the rotor field (*d,q*) is justified due to lower sensitivity to the parameters, as well as smaller phase displacement during adjusting the stationary constants i_{1d} and i_{1q}. Current regulation significantly reduces the load in dynamic modes.

RESEARCH RESULTS AND THEIR DISCUSSION

Adjustment the frequency of rotation of the electric motor drive of the extruder is carried out as follows. Depending on the dynamic viscosity of the product and the pressure in the Subsystem block, the corresponding torque and frequency of rotation are created. These values are supplied to the Product block, where the necessary capacity of the extruder is determined. The value of dynamic viscosity ŋ is fed to the Sum block, where it is subtracted from the value of $ŋ_{giv}$. At the output of the Sum block, the control signal is formed, which is fed to the frequency converter. Depending on the magnitude of the signal at the output of the frequency converter, a certain value of voltage and frequency is formed, which is consumed by the electric motor drive of the extruder. This system of electrical equipment will maintain the necessary values of the technological parameters (ŋ) for normal operation of the extruder with rational use of electricity. In Fig. 5. and 6 is showen the change in dynamic viscosity (ŋ) of the product and pressure (p) in the extruder. After starting up the extruder at the dynamic viscosity of 0.14 and the pressure of 15.2 MPa,by the frequency converter sets the supply voltage to 154 V with the frequency of 35 Hz.

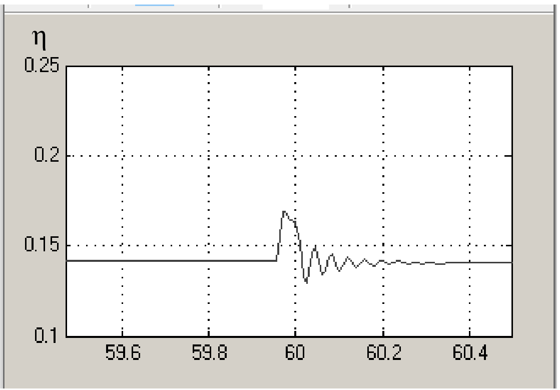


Fig. 5 Change in the dynamic viscosity of the product over time.

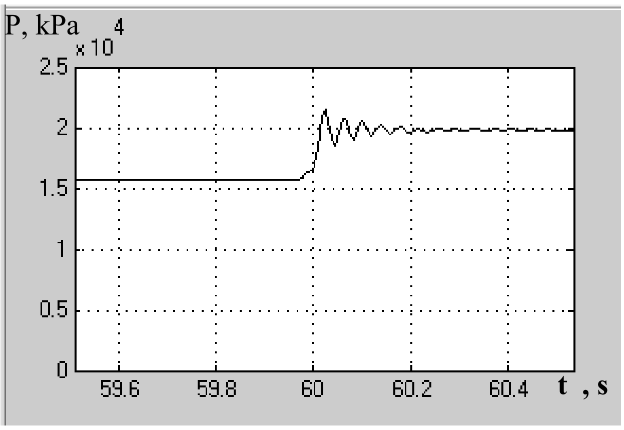


Fig. 6 Change of pressure in the compression chamber over time depending on the mode of operation of the extruder.

At the same time, the engine develops a torque of 48 Nm at the angular frequency of 109 s^{-1}, and the consumed current is 22 A (Fig. 7). If the dynamic viscosity increased to 0.17 at the time of 60 s (Fig. 5), the control system responds accordingly to the increasing of frequency rotation of the electric drive to 139 s^{-1}. At the same time, the pressure increases to 20 MPa (Fig. 6), and the dynamic viscosity returns to the set value. Accordingly, in this mode, the electric motor consumes the current of 30 A and creates a torque of 71 Nm. (Fig. 7).

The obtained results were compared with the results of similar researches [10] for the drive AM with vector control using the Matlab/Simulink software, where the flux-linkage of the rotor ψ_2 is oriented along the axis of the coordinate system, that synchronously rotates while $\Psi_{2d} = \Psi_2$, $\Psi_{2q} = 0$. From the comparison, it is possible to make the conclusion that despite on the difference in AM capacities, the identity of the behavior of system of the vector control during cycles of load change is observed. But the algorithm of the vector frequency-regulated electric drive that is proposed in this article differs in that it is formed by the observer, built on the basis of balance of the reactive capacity and tracking of the current values of the dynamic viscosity and pressure of the material in the system of regulating the modes of operating of the extruder without sensors of the technological parameters.

The indicators of the quality of regulation, which are determined from Fig. 5-7 make the following values: overshoot – 9.3 %; the time of adjustment for electromagnetic torque and the frequency rotation of the rotor up to 0.8 s, and for dynamic viscosity and pressure in the working chamber of the extruder - up to 0.4 s, fluctuation - 3. The proposed method of adjustment turns out to be significantly more effective, first of all, in terms of the time of adjustment in comparing with control method, such as the temperature mode with a PI controller and even illegible control [29], or when controlling the electromagnetic torque and frequency rotation of the rotor with using a control strategy, when LabVIEW sends the necessary input arguments to MATLAB, which executes the control algorithm and, finally , these output data of the controller are sent from the PC to the drive motor of the extruder and feed controller [30].

It is expedient for further improving the system for regulating modes of operating of the extruder to use the strategy [10] minimization of capacity loss based on dynamic programming with determination function of the loss cost.

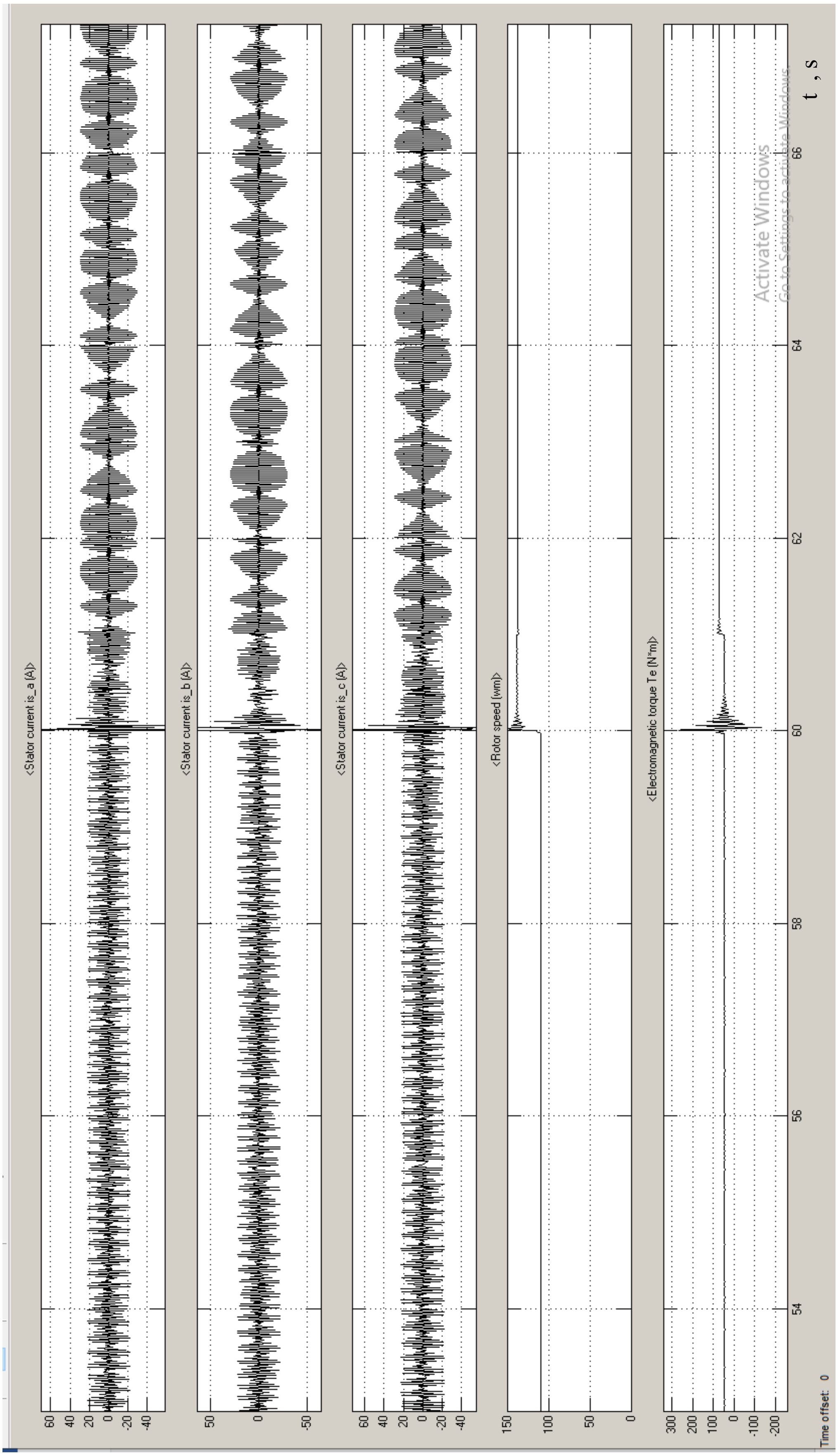


Fig. 7. Oscillograms of currents, moment and angular velocity of the electric motor during the operation of the extruder.

It should be noted that at the stage of preliminary determination by experimental method of dynamic viscosity and pressure of biopolymers in the active zone for the specific extruder, it is possible to use not onlymodels of approximation (2) - (5), in which speed is the main argument. Ostwald-de Weyl's models of power law can also be used, taking into account the influence of temperature and moisture content [13].

Note that the proposed control system selects the rational mode in terms of energy consumption when the viscosity of the material changes, in contrast to the control system with feedback and control loops based on SISO PID [11], which regulates the output variables at set values, regardless of changes in properties of the material that is fed.

It is expedient to consider some aspects that are related to specific steps to optimize the process of the extrusion. It should be noted that there hasn't exist global model of the extrusion process yet. Most of the existing researches concern to the processes of extrusion of plastic masses, where the functions of aggregation, temperature conditions of the process, the use of Pareto's curves after optimizing the working conditions are put forward in the first place in order to maximize productivity and mixing and minimize the length of the screw required for melting [27,28]. In addition, to solve this problem, it is proposed to use procedures of calculation CFD (Computational Fluid Dynamics) based on mechanics of the fluid [15].

In our case, the global objective function should be the weighted amount that maximizes the productivity of the necessary fractional composition of the biopolymer, minimizes energy consumption, and reduces the time that the biopolymer stays in the high-temperature reaction zone of the extruder. It uses statistics, regression and analysis of the surface of the response based on experimental data and computer simulation. The required pressure, dynamic viscosity and rate of the flow, quality of the product are determined, and the search is conducted with a single goal in mind - the energy efficiency of the extruder.

In fact, this will contribute to the development of the method for predicting the quality of melt in the process of extrusion [31].

In the work [27] it is noted that in some cases the results of statistical analysis give better results in comparing to the results that are obtained using artificial neural networks.

CONCLUSIONS AND PERSPECTIVES

- it is developed mathematical model of the electric drive of the extruder with the system for regulating its operating modes that allows to study the characteristics and parameters the processof extrusion of the biomass in operating and emergency modes;
- it is proposed improved method of correcting the control action of the control system, when the assessment of pressure and dynamic viscosity is determined by the parameters of the electric drive, eliminates the necessity of sensors for direct measurement of these characteristics, which increases the reliability and efficiency of operation of the extruder with rational use of electricity.
- in the future, it is advisable to conduct the research on the development of the system of control the electric drive with specific steps to optimize the extrusion process, taking into account the influence of temperature and moisture content.

ACKNOWLEDGMENTS

With the support of the National Research Fund of Ukraine competition "Science for the reconstruction of Ukraine in the war and post-war periods" grant № 202/0129.

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Information about authors.

Zablodskiy Mykola, doctor of technical sciences, scientific interest is technologies conversion of biomass into high-quality biogas with a shortened fermentation period under the influence of electromagnetic field.
E-mail: zablodskiynn@gmail.com

Klendiy Petro, associate professor of the department of power engineering and automation, candidate of technical sciences, scientific interest is renewable sources of energy.
E-mail: pklendii@gmail.com

Dudar Oksana, teacher of the cycle committee of special electrical engineering disciplines", scientific interest is renewable sources of energy.
E-mail: oksana-dydar@ukr.net

Shvorov Serhiy, National university of life and environmental sciences of Ukraine, doctor of technical sciences, scientific interest is technologies conversion of biomass into high-quality biogas with a shortened fermentation period under the influence of electromagnetic field.
E-mail: sosdok@i.ua