Research into the Influence of the Laws of Changing the Stator Supply Frequency on the Electromechanical Processes of an Asynchronous Motor During Controlled Starting

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Abstract. The aim of the work is to obtain graphical dependences of the electromechanical response of an asynchronous motor during controlled start-up using frequency control, to analyze the influence of the laws of changing the stator supply frequency on the dynamic characteristics of the electric drive of the mechanical mixer of a biogas reactor, under conditions of quadratic growth of the resistance moment and increased starting torque. To achieve the objective, the following tasks were carried out: a mathematical model of the electromagnetic processes in an asynchronous motor was synthesized; frequency-dependent reactance functions were applied; the equations of motion were numerically integrated using the Runge-Kutta method; and a model of the load torque for a mixer operating in a viscous medium was developed. The working hypothesis posits that applying exponential and S-shaped laws for stator frequency regulation will minimize the motor's energy consumption during startup. The most significant results are the graphical dependencies of the electrodynamic parameters of the asynchronous motor driving the biogas reactor mixer; these dependencies were constructed using exponential and S-shaped functions for the variation of the stator winding supply frequency, based on a mathematical model presented in the study. The significance of the results lies in the ability to analyze the dynamics of asynchronous motors (currents, rotational speed, electromagnetic torque) under various stator control laws. An S-shaped profile for the stator frequency variation of the mixer's asynchronous motor reduces starting energy consumption by an average of 45.3% compared to an exponential profile.
Keywords: controlled start, frequency control, asynchronous electric motor, modeling, electrodynamic parameters.

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Cercetare privind influența legilor de modificare a frecvenței de alimentare a statorului asupra proceselor electromecanice ale unui motor asincron în timpul pornirii controlate

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Rezumat. Scopul lucrării este de a obține dependențe grafice ale răspunsului electromecanic al unui motor asincron în timpul pornirii controlate prin reglarea frecvenței, pentru a analiza influența legilor de variație a frecvenței de alimentare a statorului asupra caracteristicilor dinamice ale acționării electrice a mixerului mecanic al unui reactor de biogaz, în condițiile creșterii pătratice a momentului de rezistență și ale creșterii cuplului de pornire. Pentru atingerea obiectivului, au fost realizate următoarele sarcini: a fost sintetizat un model matematic al proceselor electromagnetice dintr-un motor asincron; au fost aplicate funcții de reactanță dependente de frecvență; ecuațiile de mișcare au fost integrate numeric folosind metoda Runge–Kutta; și a fost dezvoltat un model al cuplului de sarcină pentru un mixer care funcționează într-un mediu vâscos. Ipoteza de lucru postulează că aplicarea legilor exponențiale și în formă de S pentru reglarea frecvenței statorului va minimiza consumul de energie al motorului în timpul pornirii. Cele mai semnificative rezultate constau în obținerea dependențelor grafice ale parametrilor electrodinamici ai motorului asincron care acționează mixerul reactorului de biogaz. Aceste dependențe au fost construite folosind funcții exponențiale și în formă de S pentru variația frecvenței de alimentare a înfășurărilor statorului, pe baza modelului matematic prezentat în studiu. Semnificația rezultatelor constă în posibilitatea de a analiza dinamica motoarelor asincrone (curenți, viteză de rotație și cuplu electromagnetic) în condițiile aplicării unor legi diferite de comandă a frecvenței statorului. Un profil în formă de S al variației frecvenței statorului motorului asincron care acționează mixerul reduce consumul de energie la pornire cu o medie de 45.3% comparativ cu un profil exponențial.
Cuvinte-cheie: pornire controlată, reglaj de frecvență, motor electric asincron, modelare, parametri electrodinamici.

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Исследование влияния законов изменения частоты питания статора на электромеханические процессы асинхронного двигателя при управляемом пуске

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Аннотация. Целью работы является получение графических зависимостей электромеханического отклика асинхронного двигателя при управляемом пуске с использованием частотного регулирования и анализ влияния различных законов изменения частоты питания статора на динамические характеристики электропривода механического смесителя биогазового реактора с квадратичным увеличением момента сопротивления и увеличенным начальным пусковым моментом. Для достижения поставленной цели были решены следующие задачи: синтезирована математическая модель электромагнитных процессов в асинхронном двигателе, применена частотная функция для определения реактивных сопротивлений электродвигателя, проведено числовое интегрирование уравнения движения методом Рунге-Кутты, сформирована математическая модель момента нагрузки, соответствующая характеристике мешалки вязкой среды. Рабочая гипотеза исследования заключается в установлении возможностей применения экспоненциальных и S-образных законов изменения частоты питания обмоток статора электроасинхронного двигателя с целью снижения энергопотребления в пусковом режиме. Наиболее важными результатами являются полученные графические зависимости электродинамических параметров асинхронного двигателя, привода механического смесителя биогазового реактора с квадратичным увеличением момента сопротивления и увеличенным начальным пусковым моментом, с использованием экспоненциальных и S-образных законов изменения частоты питания обмоток статора на основе представленной в данной работе математической модели и расчетных соотношений. Значимость полученных в работе результатов исследований заключается в том, что на основе полученных математических зависимостей можно анализировать динамическое поведение асинхронных двигателей и оценивать динамику токов, частоты вращения вала электродвигателя и электромагнитного момента при различных законах изменения частоты питания обмоток статора. Использование S-образного закона изменения частоты питания обмоток статора трехфазного асинхронного двигателя, являющегося вращающимся двигателем смесительного устройства, позволяет снизить энергопотребление в среднем на 45,3% в пусковой период по сравнению с экспоненциальным законом.

Ключевые слова: управляемый пуск, частотное регулирование, асинхронный электродвигатель, моделирование, электродинамические параметры.

INTRODUCTION

Asynchronous motors are one of the most common types of electric machines used in industry in different countries [1]. Simplicity of design, reliability and low cost are the main factors of the spread of asynchronous motors as rotating mechanisms of industrial facilities [2]. A wide range of asynchronous motors with different powers and electrical characteristics is another advantage of asynchronous electric motors. Asynchronous electric motors have become widespread in renewable energy facilities, namely in biogas technologies [3-6]. Efficient fermentation of the raw materials is achieved by creating the necessary microclimatic conditions in the reactor and ensuring homogeneity using mixing devices [7-10] driven by asynchronous electric motors. Previous studies show that during fermentation, the raw materials stratify and their physicochemical composition changes, leading to compaction and unpredictable torque changes on the electric motor shaft, especially during transient operating conditions (start-up periods).

Overloading of an asynchronous motor, impacts, or rotor seizure lead to winding overheating, insulation failure, and other malfunctions [11-14], which corresponds to emergency operation of the electric motor and the need for repairs. The duration of the transient process during direct starting of asynchronous motors is determined by the law of increasing shaft load.

Rapid increase in load increases the duration of the transient process, which, in turn, leads to a longer flow of high current in the stator windings, causing significant energy overconsumption and reduced electric drive efficiency. From an energy point of view, a relevant issue is research aimed at assessing the stator current and energy consumption during direct start-up and determining the rational law of increase in the load on the shaft of an electric motor. In the context of the rapid development of the Industry 5.0 concept, artificial intelligence and machine learning methods are becoming increasingly widespread and are used in various systems, such as monitoring, control and detection of emergency situations during the operation of asynchronous electric motors [15–24]. The use of equivalent circuits of electric motors allows you to obtain the values of operating characteristics, namely: currents, powers, electromagnetic moments and establish the amount of losses. It is

the use of equivalent circuits that makes it possible to simulate various operating modes of electric machines, and by replacing physical magnetic and mechanical processes with electrical elements, the cost of conducting experimental research is reduced [25]. The works [26–34] present the results of a study of the operational characteristics of electric motors, provide the results of an analysis of their behavior in starting, braking and steady-state modes, as well as the development of control systems for electric motors. The equations of equivalent circuits of electric motors are the basis for building frequency or vector control algorithms. During direct start, motors consume significant starting currents, which leads to additional losses of electrical energy, voltage sags in the network and increased electromechanical loads on the equipment. At the same time, the nature of the change in the load torque on the motor shaft significantly affects the duration of the starting process, the magnitude of the starting currents and the total energy consumption.

The work [26] presents the results of studies of the behavior of electric motors during fluctuations in the supply voltage. An equivalent equivalent circuit using Fourier coefficients, which are time-varying, was used. The authors of [26] found that voltage fluctuations generate additional losses in the rotor and stator windings, and also reduce the efficiency of the motor, which leads to changes in the torque, speed and power factor of the motor with changes in the modulation frequency. The works also present variants of equivalent circuits of an asynchronous electric motor, taking into account losses caused by the load, as well as losses in the steel of the electric motor [27].

The authors of [28] note that in addition to the possibility of quantitatively understanding the impact of load and losses in the steel on the operation of a machine with mains power and vector control, the proposed model makes it possible to develop improved vector control algorithms.

In the article [29, 30], examples of dynamic modeling and parameter estimation for creating electric drive control systems are considered. However, the dynamic analysis of electric motors is associated with difficulties caused by the appearance of transient processes, which play a significant role in the design of the model and the identification of a rational speed control mode of the electric motor. Studies [30-32] propose using various models to estimate the parameters of three-phase asynchronous motors using algorithms that minimize the difference between measured signals and simulation results. In the article [35] notes the relevance of developing methods for regulating automatic speed controllers for electric machines integrated into alternative energy sources.

When considering electric motor control systems under conditions of unpredictable changes in the load on the mixing system shaft, the use of such models requires collecting a large array of experimental data for subsequent modeling and determining the optimal rotation speed. This requires significant hardware and computational costs.

Given that asynchronous motors are used in a variety of industrial settings, modeling their operating processes is critical for the development of business and science [36-40].

Given the interest of scientists from around the world, which is supported by a significant number of scientific publications, the issue of studying and determining the parameters of electric motors during operation is relevant from the standpoint of energy efficiency and energy conservation.

The relevance of the study is due to the widespread use of asynchronous motors in industry and the need to increase the energy efficiency of electric drives.

The use of frequency control during engine start-up allows you to reduce starting currents, mechanical loads on equipment and increase the reliability of electromechanical systems.

At the same time, the choice of the law of changing the supply frequency significantly affects the dynamic characteristics of the electric drive, the duration of transients and the quality of control.

Therefore, the study of the influence of various laws of changing the stator supply frequency, in particular exponential and S-shaped, on the electromechanical characteristics of an asynchronous motor is an urgent task of modern electric power engineering and automated electric drives.

The aim of the work is to obtain graphical dependencies of the electromechanical response of an asynchronous motor during controlled starting using frequency regulation and to analyze the influence of various laws of changing the stator supply frequency on the dynamic characteristics of the electric drive of a mechanical mixer of a biogas reactor with a quadratic increase in the resistance torque and an increased initial starting torque.

RESEARCH METHODOLOGY

To achieve the stated objective, a comprehensive approach was employed, combining methods from electric drive theory, mathematical modeling, and numerical techniques for solving differential equations under various control laws for the stator supply frequency of an electric motor.

Determining the impact of control laws on the electromechanical processes within an electric motor requires accounting for the variations in torque and rotor angular velocity.

A. Mathematical Model of an Electric Motor

The nominal electromagnetic moment was determined by the expression:

$$T_n = \frac{P_n}{\omega_n} \quad (1)$$

where P_n – nominal engine power, W; ω_n – nominal angular speed of the rotor, rad/s.

The nominal angular speed of the rotor was determined from the dependence:

$$\omega_n = \frac{2\pi \cdot n_n}{60} \quad (2)$$

where n_n – nominal rotor speed, rpm.

To analyze the macrodynamics of an electric drive during controlled variable-frequency starting (with a transient process duration of 5.5 seconds), it is appropriate to employ a quasi-static description of the electromagnetic processes. Since the electromagnetic time constants of the stator and rotor are significantly smaller than the mechanical time constant of the drive, high-frequency transient currents in the stator windings can be neglected when the frequency changes gradually (over 5.5 seconds).

On this basis, the mathematical model of the motor's electromagnetic component is formulated using an equivalent circuit derived from Thevenin's theorem. This approach allows us to study starting modes and calculate instantaneous values of steady-state currents and moments at each step of integration of mechanical motion without resorting to the full system of equations in dq-coordinates.

Taking into account the active resistance of the stator (r_s), the inductive resistance of the stator leakage (x_1), and the magnetic inductive resistance (x_m), the complex resistances of the stator (z_1) and magnetic (z_m) branches of the electric motor were determined [25-31].

When recalculating the inductive resistance of an electric motor, it is necessary to take into account the frequency dependence f(t).

The equivalent voltage and equivalent Thevenin resistance were determined as:

$$U_{th} = U_1 \cdot \frac{z_m}{z_1 + z_m}, \quad (3)$$

$$z_{th} = \frac{z_m \cdot z_1}{z_1 + z_m}, \quad (4)$$

where z_1 – complex resistance of the stator branch, Ohm; U_1 – phase voltage, V.

The synchronous angular velocity is determined by the frequency of the supply voltage:

$$\omega_{sync} = \frac{2 \cdot \pi \cdot f(t)}{p}, \quad (5)$$

where *f(t)* – stator power frequency depending on its change over time, Hz; *p* – number of stator winding pole pairs.

The slip was calculated using the expression:

$$s = \frac{\omega_{sync} - \omega_n}{\omega_{sync}}, \quad (6)$$

where ω_n – rotor angular velocity, rad/s.

The electromagnetic torque was determined by the classical expression for an induction motor through the Thevenin equivalent:

$$T_e = \frac{3}{\omega_{sync}} \cdot \frac{U_{th}{}^2 \cdot \left(\frac{r_r'}{s}\right)}{\left(r_{th} + \frac{r_r'}{s}\right) + \left(x_{th} + x_2\right)^2}, \quad (7)$$

where r_r' – active reduced rotor resistance, Ohm; x_2 – inductive rotor leakage resistance, Ohm.

To determine the input resistance of the electric motor (z_{in}), the values of the complex resistances of the stator (z_1) and magnetic (z_m) branches of the motor, the inductive resistance of the rotor dissipation (x_2), and the active reduced resistance of the rotor ($r_r^{'}$) were used [25-31].

The effective value of the stator current was calculated as:

$$I = \left| \frac{U_1}{z_{in}} \right|, \quad (8)$$

B. Mathematical Description of the Load Torque

The dynamics of the rotor were described by the equation of mechanical motion:

$$J \frac{d\omega_n}{dt} = T_e - T_L - D_\omega \cdot \omega_n, \quad (9)$$

where J – rotor moment of inertia, kgm^2; T_L – load moment, Nm; T_e – electromagnetic torque of the engine, Nm; D_ω – viscous mechanical damping coefficient, Nms/rad.

In the study, the viscous mechanical damping coefficient was taken equal to 0 Nms/rad.

Since the main influence on the mechanical dynamics in the starting mode was formed by the difference between the electromagnetic moment and the load moment.

Numerical integration of the equation of motion was performed by the Runge-Kutta method with a small integration step, which ensured stable reproduction of transient processes.

The description of the load on the shaft of the electric motor corresponds to the model characteristic of a viscous medium mixer, which is typical for biogas reactors.

The load in the form of a viscous medium mixer is the most appropriate for studying the effect of its change on the stator current and energy performance of an asynchronous motor.

Since such a load takes into account the presence of a starting resistance moment and a quadratic increase in torque with increasing speed.

The load moment is mathematically described as a function of time and speed:

$$T_L(t,\ \omega_n) = \left[T_{break} + \right.$$
$$\left. + (T_{nom.load} - T_{break}) \cdot \left(\frac{\omega_{sync}}{\omega_n} \right)^2 \right], \quad (10)$$

where T_{break} – starting torque, Nm; $T_{nom.load}$ – load moment at rated speed, Nm.

The work adopted: $T_{break} = 0.08 \cdot T_n$, $T_{nom.load} = T_n$.

C. Frequency Control Laws

According to the purpose of the work, an inverse problem was solved, under the conditions of which the electromechanical response of the electrical motor to various laws of changing the stator supply frequency was investigated, using controlled starting of an asynchronous electrical motor using frequency regulation.

The function $g(t)$ describes the change in the law of increase in the power frequency.

The study was conducted for two laws of change, namely exponential and S-shaped, the mathematical notation of which is given below.

Exponential:

$$g_{\exp}(t) = 1 - e^{-\frac{4 \cdot t}{t_r}}, \quad (11)$$

S-shaped:

$$g_s(t) = 3\xi^2 - 2\xi^3, \quad (12)$$

Where

$$\xi = \frac{t}{t_r}, \quad (13)$$

For both laws of change, it was assumed that the growth coefficient (ξ) is in the range from 0 to 1.

At the same time, after the end of the growth interval, we assumed $g(t) = 1$.

The power supply frequency was specified as a function of time and took into account the function $g(t)$, which describes the change in the frequency increase law:

$$f(t) = f_{start} + \left(f_{target} - f_{start} \right) \cdot g(t), \quad (14)$$

where f_{start} – initial power supply frequency, Hz;

f_{target} – nominal power frequency, Hz;

Since the paper considers two laws of change, namely exponential and S-shaped, the mathematical representation of the change in power frequency is given below.

Exponential:

$$f_{\exp}(t) = f_{start} + \left(f_{target} - f_{start}\right) \cdot g_{\exp}(t), \quad (15)$$

S-shaped:

$$f_s(t) = f_{start} + \left(f_{target} - f_{start}\right) \cdot g_s(t), \quad (16)$$

D. Object of Research

The object of the research is a three-phase asynchronous motor AIR160S4 with a power of 15 kW, which is used as an electric drive for a mixer in a biogas reactor. The passport and parametric data of the equivalent equivalent circuit were used for the motor: nominal voltage 380 V, nominal frequency 50 Hz, number of poles 4, nominal speed 1460 rpm, nominal slip 0.0287, nominal current 30 A, active stator resistance 0.1062 Ohm, active reduced rotor resistance 0.0764 Ohm, inductive leakage resistance of the stator 0.219 Ohm, inductive leakage resistance of the rotor 0.597 Ohm, magnetic inductive resistance 5.8339 Ohm, rotor moment of inertia 2.8 kgm^2.

An example of the recalculation of reactances (at frequencies of 10, 25, and 50 Hz) the reactance values at a frequency of 10 Hz are: x_1 = 0.044 Ohm for the stator and x_2 = 0.119 Ohm for the rotor; at 25 Hz: x_1 = 0.11 Ohm for the stator and x_2 = 0.298 Ohm for the rotor; at 50 Hz: x_1 = 0.219 Ohm for the stator and x_2 = 0.597 Ohm for the rotor. During the study, the law governing the variation of the supply frequency was specified, while the voltage was determined in accordance with a linear law (U/f = const).

When conducting the research, it was assumed that the value of the initial frequency is not zero, but equal to f_{start}=*3 Hz*, nominal power frequency f_{target}=*50 Hz*.

To obtain graphical dependencies for each law of change of the supply frequency of an asynchronous motor, the mechanical equation of rotor motion was solved with current values $f(t)$, and the electromagnetic torque and current at each time step were calculated from the equations of the motor model (1-16).

The graphical dependences of the change in the laws of increase in the supply frequency $f(t)$ of the stator windings of an induction motor are shown in Fig. 1.

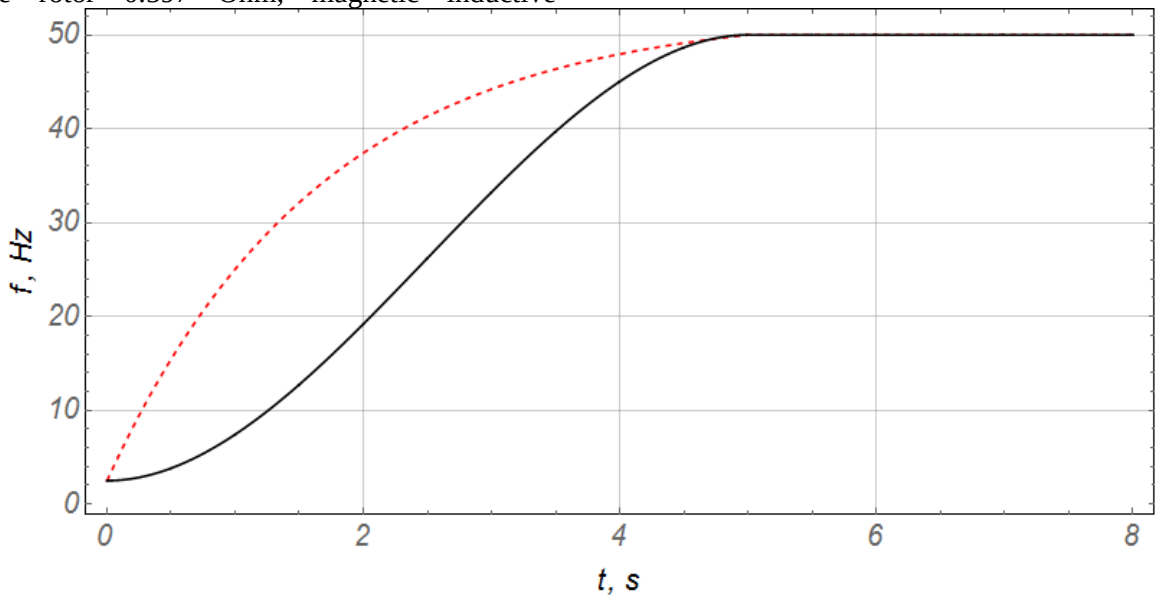


Fig. 1. Graphical dependences of the change in the laws of increase in the supply frequency of the stator windings of an induction motor $f(t)$: – S-shaped law; - - - - exponential law.

The starting energy was determined by integrating the input power:

$$W_{start} = \int_0^{t_{start}} P_{in}(t)dt, \quad (17)$$

where t_{start} – start completion time, s.

The start-up was considered complete if two conditions were met: the rotor speed reached at least 95% of the nominal and remained within ±1% of the target value during a given small time interval.

As a result of the research, graphical dependences (Fig. 2 – Fig. 5) of the change in current in the stator windings, the frequency of rotation of the electric motor shaft, the torque on the motor shaft, and the change in slip during the start-up time were obtained.

RESULTS AND DISCUSSION

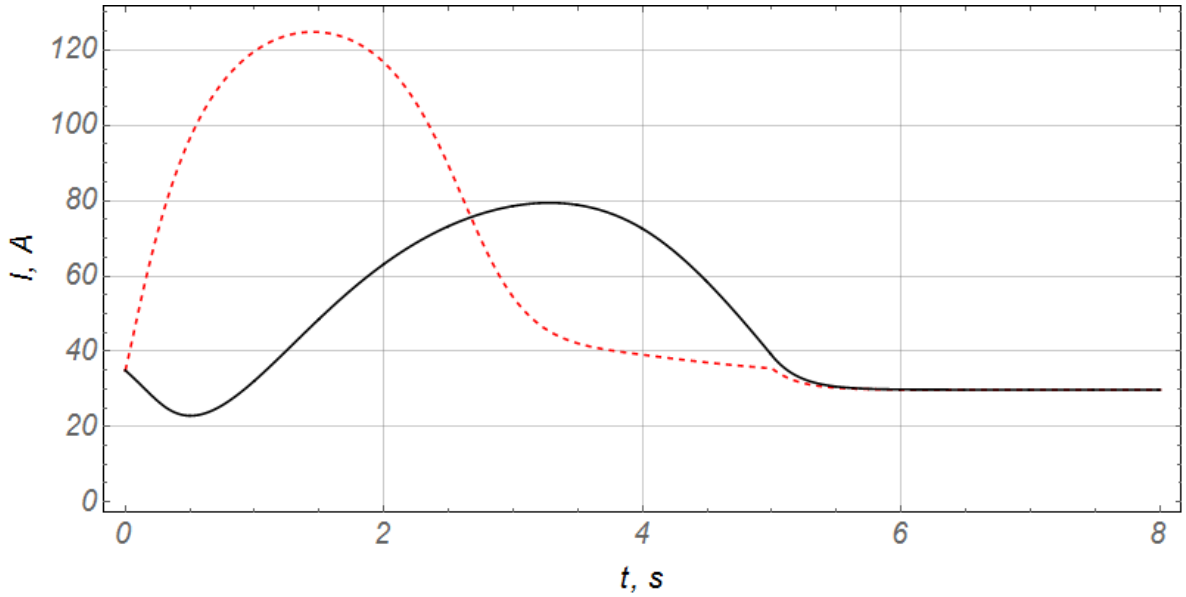


Fig. 2. Graphical dependences of the change in the stator current of an electric motor during starting when the supply frequency changes according to: – S-shaped law; - - - - exponential law.

After analyzing the graphical dependence (Fig. 2), it was found that when the supply frequency of the windings of the electric motor changes according to the exponential law, the stator current increases to a value of 125 A, which exceeds the nominal current of the asynchronous motor by 4.1 times.

Whereas, when the power supply frequency of the electric motor windings changes according to the S-shaped law, the stator current gradually decreases to a value of 22 A, with a further increase to a maximum value of 79 A at a time point (3.1 seconds) and a decrease to nominal values of 30 A at a time point (5.5 seconds).

It was found that the average value of the stator current during the start-up time (5.5 seconds) for the exponential law is 78.6 A, while for the S-shaped one it is 49.9 A, which is 36.5% less than for the exponential law (Fig. 2).

When using the exponential law of supply frequency change, the average value of the stator current of the induction motor is 2.62 times greater than the nominal value. Then, when using the S-shaped law of supply frequency change, the average value of the stator current of the induction motor is 1.66 times greater than the nominal value.

Comparing the two laws of changing the frequency of power supply of the stator windings, it was established that the average value of the current during the start-up period, when using the S-shaped law, is 36.5% less than with the exponential law.

According to the Joule-Lenz law, the release of heat is proportional to the square of the current, accordingly, a decrease in the average value of the current by 36.5% leads to a decrease in the release of heat in the motor windings during start-up by an average of 59.7%.

This affects the durability of the windings and, accordingly, of the electric motor. For drives of mechanical mixers for biogas reactors, this is an especially important indicator, since there are no downtimes associated with repair work.

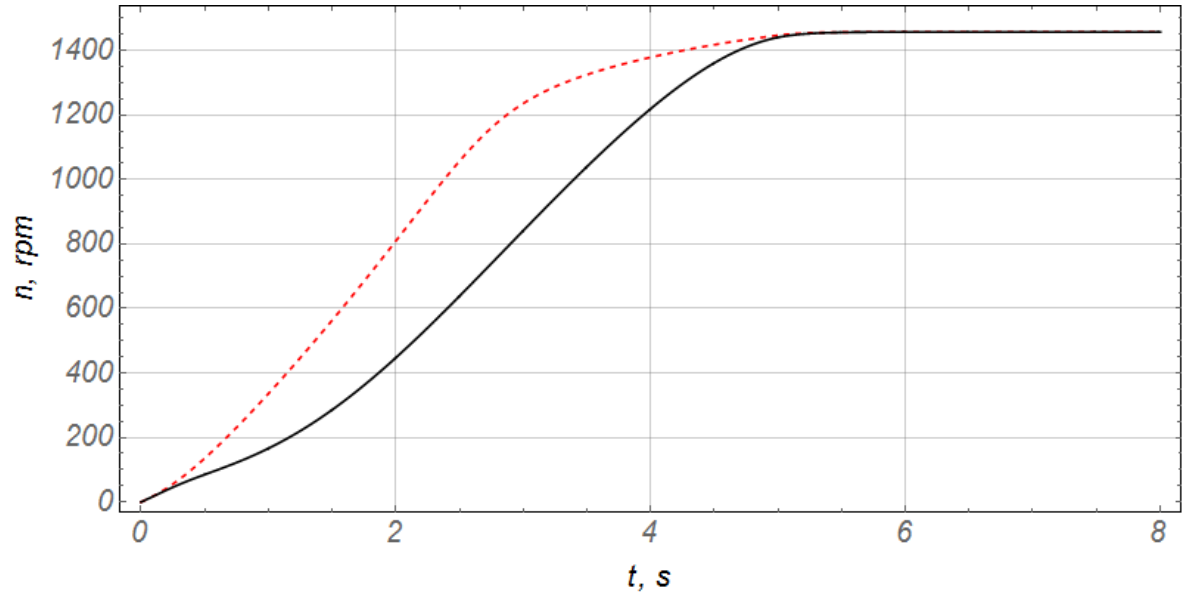


Fig. 3. Graphical dependences of the change in the frequency of rotation of the electric motor shaft during start-up when changing the supply frequency according to: – S-shaped law; - - - - exponential law.

After analyzing the graphical dependence (Fig. 3), it is noticeable that regardless of the law of change of the supply frequency of the motor windings, the nominal speed of the electric motor shaft is reached at the moment of time (5.5 seconds). It was established that the average value of the shaft speed during the start-up for the exponential law is 991.9 rpm, while for the S-shaped one – 810.1 rpm, which is 18.3% less than for the exponential law.

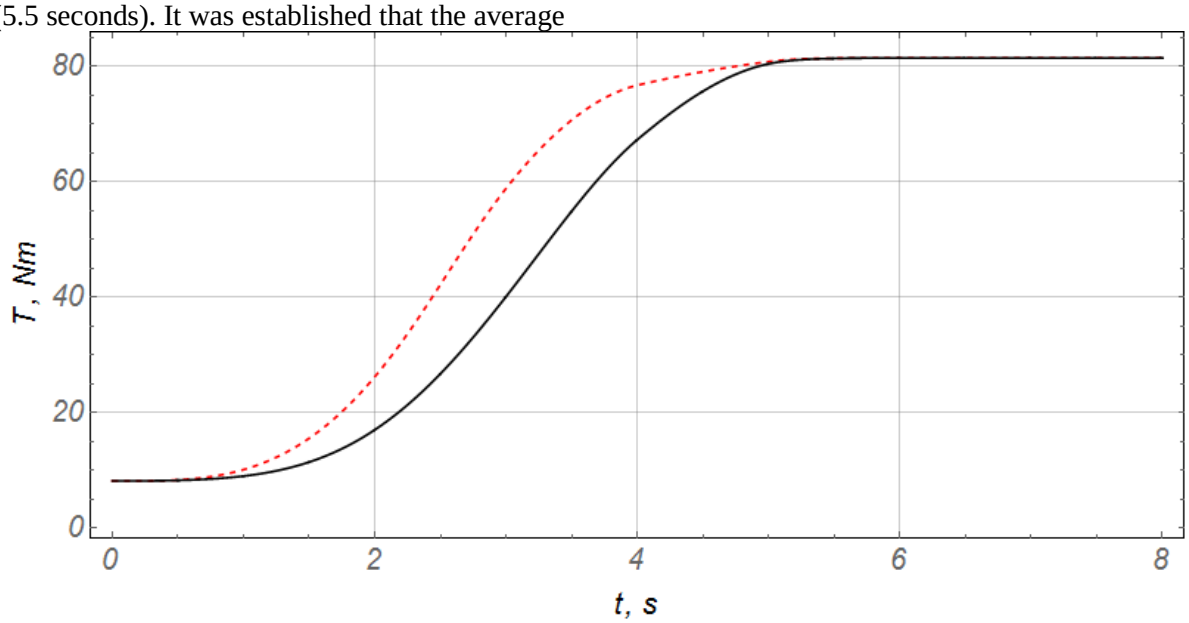


Fig. 4. Graphical dependences of the change in torque on the shaft of an electric motor during start-up when changing the supply frequency according to: – S-shaped law; - - - - exponential law.

After analyzing the graphical dependence (Fig. 4), it is noticeable that regardless of the law of changing the frequency of power supply to the motor windings, the nominal torque on the shaft of the electric motor is achieved at the time (5.5 seconds). It was established that the average

value of the torque on the shaft of the electric motor during the start-up for the exponential law is 49.6 Nm, while for the S-shaped one – 3.1 Nm, which is 13.1% less than for the exponential law.

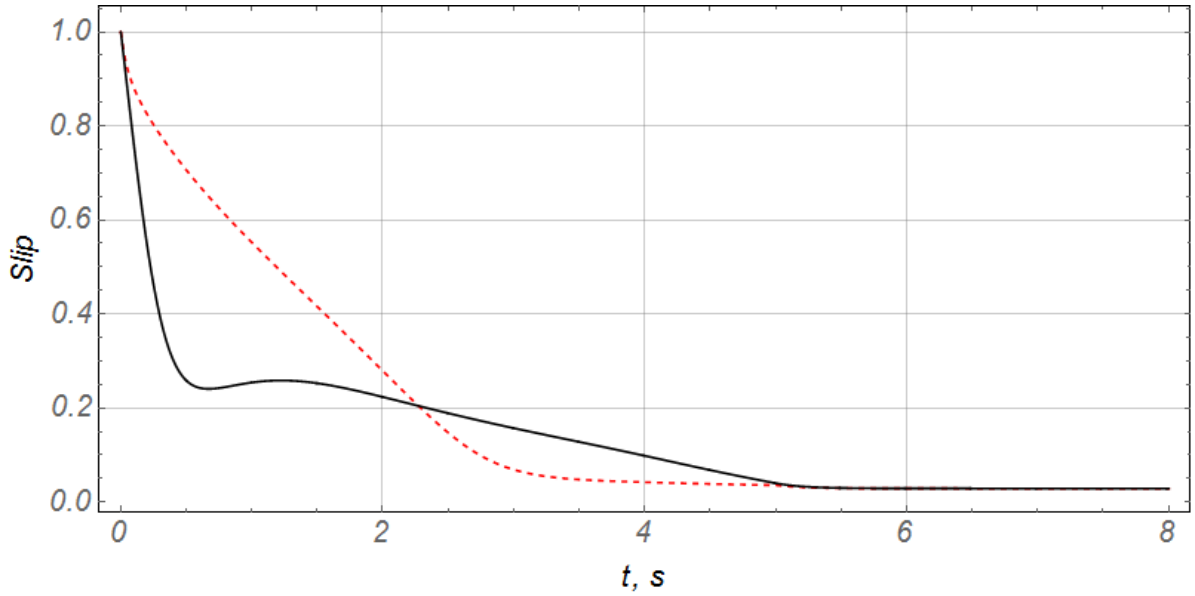


Fig. 5. Graphical dependences of the slip change during the start-up time when the power supply frequency changes according to: – S-shaped law; - - - - exponential law.

After analyzing the graphical dependence (Fig. 5), it is noticeable that the change in slip during the start-up time under different laws of changing the supply frequency occurs differently. Thus, under the exponential law, the slip value smoothly decreases to almost 0, while under the S-shaped law, the change in slip sharply decreases to a value of 0.29 at the time point (0.4 seconds).

Subsequently, there is a smooth decrease in slip to a value close to 0.

The average slip value during the start-up time for the exponential law is 0.24, while for the S-shaped one it is 0.18, which is 25% less than for the exponential law. According to the results of the research, an analysis was conducted to determine the energy consumption of the electric motor during the start-up time (5.5 seconds).

It was found that for the exponential law, the energy consumption is 77.9 kJ, and for the S-shaped law – 42.6 kJ, which is 45.3% less than for the exponential law.

To verify the practical feasibility of applying the results proposed in this study, a comparison was made between the current variation curves for the direct starting of an electric motor and those obtained using an S-shaped law for varying the supply frequency of the motor windings. The results are presented in Fig. 6.

A comparative analysis of the graph shown in Fig. 6 indicates that during direct starting, the current rises rapidly to 168 A, which is 5.6 times the rated current.

The average current value during the start-up period (5.5 s) is 55.2 A, while for the S-shaped start this figure is 49.9 A, which is 9.6% less than in the case of direct start. Furthermore, the duration for which the current exceeds five times the rated value during direct starting spans the interval from 0 to 3 seconds.

It has been established that the S-shaped law of changing the supply frequency of the stator winding provides a decrease in the average current value, which leads to a decrease in heat generation in the motor windings during start-up.

This significantly affects the temperature regime of the windings and prevents a sharp increase in current and their overheating, which has a positive effect on the durability of the motor.

From an economic and energy point of view, the S-shaped law of changing the supply frequency is more advantageous for use in technological processes, namely: mixing raw materials with mechanical mixers during anaerobic fermentation of raw materials in biogas reactors.

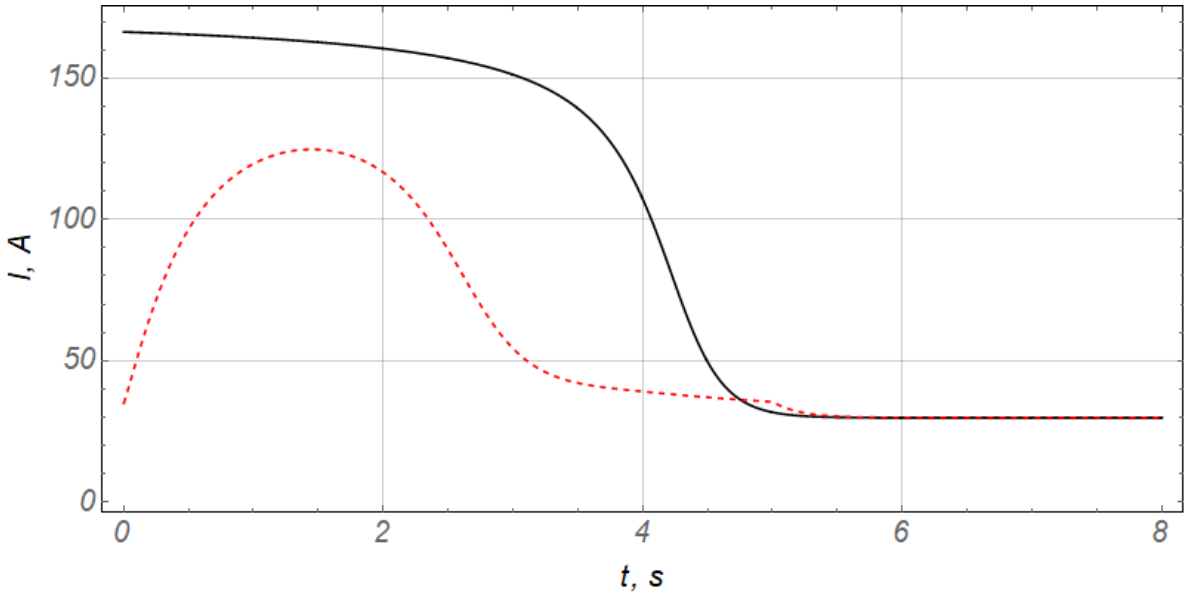


Fig. 6. Plots showing the variation of the electric motor stator current during startup as a function of supply frequency: – direct-on-line starting mode; - - - - S-shaped law.

CONCLUSIONS

The work conducted a study of the electromechanical response of an asynchronous motor during controlled start-up using frequency control. The influence of the exponential and S-shaped laws of changing the supply frequency of the stator winding on the dynamic characteristics of the electric drive of a mechanical mixer of a biogas reactor with a quadratic-increasing resistance torque and an increased initial starting torque was analyzed. It was established that the proposed S-shaped law of changing the supply frequency of the stator winding provides a decrease in the average current value by 36.5%, which leads to a decrease in heat generation in the motor windings during start-up by an average of 59.7%. This affects the durability of the windings and, accordingly, the electric motor. For drives of mechanical mixers of biogas reactors, this is a particularly important indicator, since there are no downtimes associated with repair work. The influence of the law of changing the supply frequency of the electric motor windings does not affect the speed of achieving the rated speed of rotation of the electric motor shaft. The average value of the torque on the electric motor shaft during start-up for the S-shaped law of changing the supply frequency of the stator windings is 13.1% less than for the exponential law. It was established that the total energy consumption during start-up using the S-shaped law is spent on average by 45.3% less energy than under the exponential law. The directions of further scientific research are established, which are associated with conducting experimental studies of the rational law of changing the supply frequency of the stator windings of the electric motor to achieve a reduction in electricity consumption for the processes of mixing raw materials in biogas reactors and other technological processes.

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