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DEVELOPMENT OF METHODS FOR OVERCOMING SELF- OSCILLATORY MODES IN AN ASYNCHRONOUS ELECTRIC DRIVE WITH A THYRISTOR VOLTAGE REGULATOR

The object of research is the processes of electromagnetic transformation in powerful asynchronous electric drives during controlled starting using a thyristor voltage regulator.

The problem to be solved by the research is overcoming the self-oscillating modes of powerful high-voltage asynchronous electric drives during controlled starting in the nominal slip range.

A design feature of powerful high-voltage induction motors in comparison with general-purpose motors is a small value (up to 1%) of the nominal slip. Also, such electric motors have a relatively small value of their own moment of inertia. These features create conditions for the occurrence of self-oscillations when entering a steady-state operating mode.

A mathematical model of an induction motor has been developed taking into account the influence of the rotor current displacement phenomenon to study the modes of controlled starting of an asynchronous electric drive of an industrial mechanism taking into account the influence of the enterprise's distribution network.

From the point of view of the power supply network, an induction motor is a nonlinear active-inductive resistance, the phase angle of which can quickly change over a wide range in the vicinity of the nominal slip. The mechanism of the occurrence of self-oscillations during controlled start-up of high-voltage induction motors from a thyristor voltage regulator is disclosed. Self-oscillations occur in the nominal slip region due to the transition of the thyristor voltage regulator to an uncontrolled operating mode, when the load phase angle becomes greater than the thyristor control angle, including in the quasi-generator operating mode.

To prevent the occurrence of self-oscillation modes, it is proposed to use a controlled reactive power compensator between the motor and the thyristor voltage regulator, which stabilizes the total load phase angle, which helps to improve the controllability of the electric drive.

Keywords: starting devices, self-oscillation modes, controlled reactor compensator, simulation modeling.

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1. Introduction

Starting processes of powerful electric drives have a significant impact on the technical and economic indicators of the enterprise, which is all the more noticeable, the greater the installed power of the electric drive. This is due to a significant increase in resource costs in starting modes: increased wear of electromechanical and technological equipment, increased energy consumption, additional economic risks associated with disruptions due to local reduction in the quality of the supply voltage.

Universal technical solution that allows to influence the resource costs of starting processes is the use of starting devices for electric drives, the parameters and operating mode of which affect the technical resource of equipment of all types, the frequency of scheduled repairs, and eliminates irrational energy consumption.

The issue of controlling starting processes of powerful electric drives has long attracted the attention of researchers. One of the classic works in this direction is the study [1], which considers the issue of ensuring

the transient stability of a group of asynchronous machines during instantaneous and prolonged voltage drops. For this purpose, the use of a fast voltage regulator in the form of a static VAR compensator (SVC) or a thyristor load tap changer (CTC) is proposed. The limitations of their effectiveness for maintaining continuity of operation are also shown.

The global soft starter market in 2024 was estimated at 2.16 billion USD. The average annual growth rate of this market until 2030 is planned at 6% during the forecast period and will reach 3.07 billion USD [2].

There is no publicly available report that would specifically segment the soft starter market. Most modern industrial soft starters operate in a linearly increasing supply voltage mode as the main mode, and also provide flux exchange in older models.

Soft starter systems are considered one of the main components of the modernization of drive complexes at industrial enterprises, reducing starting currents and electromechanical loads, as well as increasing the reliability of electromechanical and technological equipment.

Modern soft starters clearly demonstrate the evolutionary path from simple thyristor phase-controlled circuits to high-frequency transistor technologies integrated with control systems and reactive power compensators, which significantly minimize the negative impact on the network [3–8]. A comparative analysis between phase control and PWM-modulated starters, performed by the authors [3], proves the advantage of the asynchronous PWM AC circuit breaker in reducing harmonic distortion and torque ripple during starting.

In [4], the authors conducted a study of the harmonic composition of the starting current of an induction motor when using soft starters. The authors proved that phase-controlled voltage converters used in the above systems cause the appearance of both higher harmonics (in particular, the 5th and 7th) and interharmonic components associated with the non-stationarity of the starting process. To analyze the relevant phenomena, continuous time-frequency conversion methods were used, which allow tracking the change in spectral characteristics over time and provide a more accurate interpretation of processes compared to traditional spectral analysis. The results obtained by the authors confirm that the use of a soft starter is an effective means of limiting starting currents.

In [5], one of the most popular applications of SiC-MOSFET and structurally integrated electronic protection function in the starter structure is proposed, recently introducing a fast start circuit with a closed current loop to reduce acceleration time.

In the paper [6], the issue of feasibility study of the application of starters for powerful electric drives is considered, and a feasibility criterion for the effectiveness of soft starters is proposed.

Some papers analyze non-standard schemes, in particular, a thyristor star/delta switch as an economizer and starter [7], as well as a PWM AC circuit breaker with a minimized number of power elements along with an increase in the power factor [8].

Despite how quickly and complexly circuit solutions for starters have developed, the most common scheme of a starter for an AC electric motor is still a thyristor voltage regulator (TVR) [9]. This is explained by the fact that it has a simple power part in the starter unit, and therefore a low initial cost, and can also be used to start both types; both induction and synchronous electric motors.

The problem of the influence of starting modes on the quality of electricity is very important, especially in industrial networks with a high concentration of powerful drives. Thyristor starters can generate harmonics, reactive power and even current asymmetry in large values, which again requires solutions for filtering and compensation.

References [4, 10–16] provide an overview of methods for improving the quality of electricity when using starting devices.

In paper [10], the choice of the optimal control strategy for an induction motor during soft start through a thyristor soft starter is considered. The thyristor disconnects the phase at zero current in the absence of a control pulse on the gate. Control methods for angles α and γ are considered.

The authors of paper [4] focused on the spectral analysis of harmonics in the starting current. They showed the importance of its identification for reliable diagnostics of the condition of drives.

In [11], the possibility of using fully controlled thyristors in soft starters to solve the problems of electromagnetic compatibility with the network due to capacitors in the thyristor switching circuits is considered. In [12], a multifunctional series compensator is proposed as a comprehensive solution for current limitation and voltage sag compensation, having experimentally verified the effectiveness of the virtual resistance input and voltage compensation mode.

The paper [13] is devoted to solving the problem of starting high-voltage high-power motors, such as large starting current, low power factor, waste of resources and lack of harmonic control. A current-limited soft-start method for a high-power high-voltage motor is proposed. The method integrates functions such as autotransformer voltage-reducing starting, magnetron voltage-limiting starting, and reactive power compensation during starting.

The paper [14] analyzed the importance of directly calculating voltage dips during starting of high-power motors, developing analytical relations for estimating voltage in such networks with a high concentration of motors. This was shown in [15], where the $I \times \cos\phi$ algorithm was applied and the results of experimental tests on adding active filters to compensate for reactive power and harmonics during thyristor starting were presented.

The paper [16] considers the problem of optimizing the starting processes of high-power electric drives from the point of view of energy efficiency. An operational approach to start-up control is proposed. This approach is based on determining the resources expended, the result obtained in a comparable system of measurement units, and its duration.

The analysis conducted on the basis of the considered scientific sources confirms that the most common circuit-technical solution of soft starters for controlling the start-up processes of AC electric motors remains thyristor voltage regulators with a linear sweep of the supply voltage. A significant part of modern research is aimed at the problem of improving the quality of electricity in distribution networks of industrial enterprises.

However, research into the theoretical principles of the functioning of thyristor voltage regulators with a complex nonlinear load, which is an AC motor, has been lacking in recent times, despite a significant change in the technical characteristics of new types of induction motors, primarily high-voltage ones.

The development of mathematical modeling technologies for electric drives with semiconductor converters has made it possible to establish a new phenomenon - the emergence of self-oscillating modes during the controlled start-up of powerful asynchronous electric drives in the vicinity of the nominal slip.

Self-oscillations of the electric drive have a significant impact on various characteristics of the starting process, affect the reliability of electromechanical and technological equipment. Self-oscillations also negatively affect the quality of electricity in distribution networks. This makes the study of the conditions for the emergence of self-oscillating modes in asynchronous electric drives with TVR and methods for their elimination important and relevant.

The object of research is the processes of electromagnetic conversion in powerful asynchronous electric drives during controlled start-up using a thyristor voltage regulator (TVR).

The aim of research is to develop methods for overcoming self-oscillating modes of an asynchronous electric drive with a thyristor voltage regulator. Self-oscillating modes are considered when using powerful high-voltage asynchronous electric drives.

To achieve the set aim, it is necessary to solve the following problems:

1. To determine the general design features of powerful high-voltage asynchronous electric motors from different manufacturers.
2. To develop a mathematical model of an induction motor taking into account the phenomenon of rotor current displacement to clarify the calculation of starting modes of asynchronous electric motors.
3. To develop a simulation model for studying the modes of controlled starting of an asynchronous electric drive of an industrial mechanism taking into account the influence of the enterprise's distribution network.
4. To investigate the influence of the electric drive parameters on the indicators of the self-oscillating mode of operation.
5. To find ways to prevent the appearance of self-oscillations with simultaneous improvement of the quality indicators of electricity in the distribution network.

2. Materials and Methods

The subject of research is self-oscillating processes in a powerful asynchronous electric drive, which is started through a soft starter based on a thyristor voltage converter. The research was carried out by synthesizing analytical and numerical methods of theoretical electrical

engineering with modern means of mathematical modeling. Determination of the parameters of filter-compensating devices and active reactor compensator included calculations (using classical Kirchhoff equations and the method of complex amplitudes) of harmonic current components, reactive power and impedances of circuit elements.

Modeling of electromechanical and electromagnetic processes was performed in the MATLAB/Simulink R2024a environment (Mathworks, USA), using the Simscape Electrical library. The dynamic model of the system "network – electric drive – soft starter – compensator" was developed based on the circuit equations that allow analyzing the impact of starting processes on the quality of electricity. To implement a closed-loop system for automatic control of the angular velocity of an electric motor, the methods of the classical theory of automatic control were used, in particular, synthesis according to the criterion of the minimum integral square error using a PID-reactive power regulator. The model takes into account the real values of the parameters of the network elements, as well as the inertia of the actuators and time delays in the measuring channels, which confirms the adequacy of the obtained data.

3. Results and Discussion

3.1. Design features of powerful high-voltage induction electric motors ABB and WEG

The use of thyristor voltage regulators as soft starters has undeniable economic advantages, due to the relatively low initial cost of the equipment. But such a technical solution also has a number of technical disadvantages that complicate the practical operation of soft starters based on TVR. Part of the technical problems is associated with the unsatisfactory starting properties of induction motors, especially when

the supply voltage is reduced. The second part of these problems is due to the specifics of the operation of the TVR on an active-inductive load. It is known [17] that the TVR loses its controllability if the phase angle of the load becomes greater than the TVR control angle. It should be taken into account that the induction motor is a nonlinear load, the phase angle of which depends on the slip and changes during the controlled start-up process within wide limits. Thus, the electromagnetic and electromechanical transient processes that occur during the controlled start-up of the AM from the TVR are largely determined by its electromagnetic parameters.

Powerful high-voltage induction motors due to their specific area of use have very specific design features and differ significantly from general-purpose AMs. This necessitates an in-depth study of the controlled start-up processes specifically for powerful high-voltage AMs.

Table 1 shows the technical characteristics of some high-voltage induction motors manufactured by ABB and WEG, obtained from the manufacturers' technical documentation [18, 19].

Using the *T*-shaped equivalent circuit for these motors, the dependences of the load phase angle in the vicinity of the nominal slip were calculated for both the driving and generating modes of operation. The results obtained are shown in Fig. 1.

The obtained data allow to make the following generalizations. The nominal slip of high-voltage induction motors is within 0.4–0.9%, which is significantly less than the similar indicator for general-purpose AM ($s_{RATED} \approx 5\%$). The high value of the gradient of the dependence of the AM phase angle on its slip in the vicinity of the nominal slip is noteworthy. This fact, combined with the relatively small intrinsic moment of AM inertia, creates the prerequisites for sharp fluctuations in the AM load phase angle, which will negatively affect the operation of the thyristor voltage regulator in this zone.

Technical characteristics of high-voltage AM switches from ABB and WEG, $U = 10$ kV

Table 1

No.	Motor type	P , kW	n , rev/min	I , A	Efficiency, %	$\cos\phi$	S , %	Sk , %
1	AXR 500MQ2	1320	2988	85	97	0.92	0.400	1.598
2	AXR 500MP4	1400	1494	94	97	0.88	0.400	1.686
3	AXR 500ML4	1150	1490	79	96.7	0.87	0.667	2.985
4	AXR 500MQ6	1175	996	83	96.8	0.85	0.400	1.686
5	AXR 500MM6	950	994	69	96.5	0.83	0.600	2.412
6	WEG-2500-2	2500	1488	168	96.2	0.88	0.800	3.600
7	WEG-3550-2	3550	1489	238	96.3	0.89	0.733	3.126
8	WEG-2500-3	2500	993	175	96.1	0.82	0.700	2.665
9	WEG-3550-3	3550	993	253	96.5	0.83	0.700	3.609
10	WEG-2500-4	2500	743	182	95.7	0.82	0.933	4.006

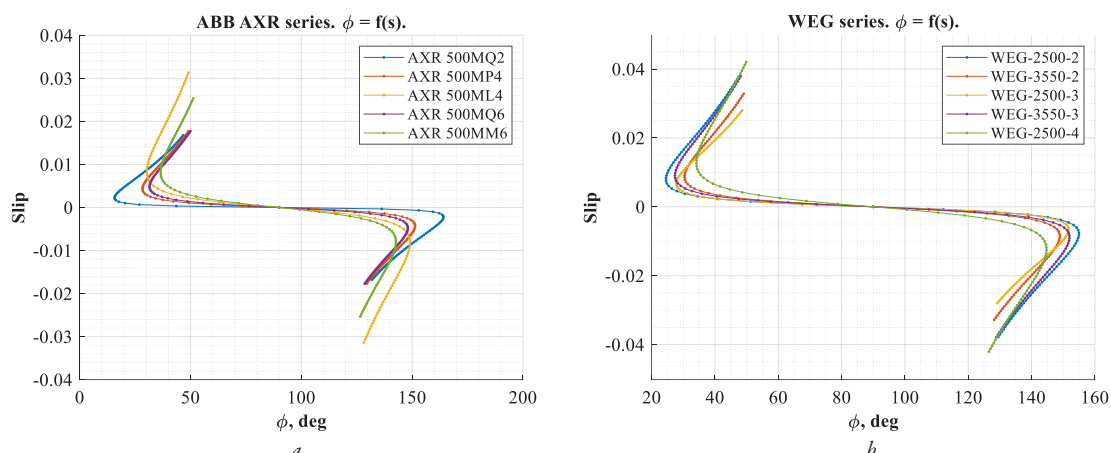


Fig. 1. Dependence of the phase angle of an induction motor in the vicinity of the nominal slip: *a* – electric motors manufactured by ABB; *b* – electric motors manufactured by WEG

The research of the starting modes of powerful high-voltage AM is impossible without detailed consideration of the context in which the operation of energy-intensive equipment occurs, namely the design and parameters of the enterprise's distribution network, which will significantly affect the electricity quality indicators of the supply network.

It is also necessary to pay attention to the need to take into account the phenomena of saturation of the magnetic system and displacement of rotor currents, which significantly affect the starting processes of powerful AC electric machines.

3.2. Development of a mathematical model of an induction motor taking into account the phenomenon of rotor current displacement

The phenomenon of current displacement (surface effect or skin effect) in the rotor rods of an induction motor consists in the uneven distribution of current density over the conductor cross-section when alternating current flows. This effect is due to electromagnetic induction and manifests itself in the fact that the current, depending on the frequency, is displaced to the peripheral layers of the conductor, leaving the central part of the cross-section less loaded [19, 20].

In the squirrel-cage rotor of an induction motor, the winding rods are made of copper or aluminum and have a relatively large cross-section. When the rotor rotates, an alternating current with a slip frequency f_2 is induced in the rods

$$f_2 = f_1 \cdot s,$$

where s – the motor slip; f_1 – the power supply frequency.

In the rotor core, an alternating current flowing through the conductor creates an alternating magnetic field around it. This field, according to Faraday's law of electromagnetic induction, induces eddy electromotive forces (EMFs) in the conductor itself. The direction of these EMFs, according to Lenz's law, is such that the currents they create oppose the change in the magnetic flux.

As a result, in the lower (deeper) layers of the core, which are covered by a larger magnetic flux, greater EMFs are induced than in the upper layers. These EMFs are directed opposite to the main current, which leads to a decrease in the resulting current in the lower layers and an increase in it in the upper layers of the conductor.

The intensity of the current displacement depends on the frequency of the current, the magnetic permeability of the material and the geometric dimensions of the core. The higher the frequency, the more pronounced the displacement effect.

To quantify the displacement effect, the displacement coefficient k_R is introduced, which characterizes the ratio of the active resistance of the rod when taking into account the displacement to its resistance at constant current

$$k_R = R_2(f_2) / R_2(0). \quad (1)$$

The depth of current penetration into the conductor is determined by the following expression

$$\delta = \sqrt{\frac{2 \cdot \rho}{\omega_2 \cdot \mu_0 \cdot \mu_R}}, \quad (2)$$

where ρ – the resistivity of the rod material; $\omega_2 = 2\pi f_2$ – the angular frequency of the rotor current; μ_0 – the magnetic constant; μ_R – the relative magnetic permeability.

For a rectangular rod with height h and width b , the displacement coefficient can be determined through the following parameter

$$\xi = \frac{h}{\delta} = h \cdot \sqrt{\frac{\pi \cdot f_2 \cdot \mu_0 \cdot \mu_R}{\rho}}. \quad (3)$$

For large values of the parameter ξ (strong displacement), the displacement coefficient is approximately determined as follows

$$k_R = \frac{\xi}{3} = \frac{h}{3} \cdot \sqrt{\frac{\pi \cdot f_2 \cdot \mu_0 \cdot \mu_R}{\rho}}. \quad (4)$$

The phenomenon of current displacement significantly affects the operating characteristics of an induction motor. At start-up, when the slip $s \approx 1$, the current frequency in the rotor is maximum ($f_2 \approx f_1$), and the displacement effect is most pronounced. This leads to an increase in the active resistance of the rotor winding and a decrease in the inductive resistance.

Increasing the active resistance at start-up is a useful effect, as it leads to:

- increasing the starting torque;
- reducing the starting current;
- improving the power factor at start-up.

In the nominal mode, when the slip is small ($s < 0.05$), the current frequency in the rotor is low, displacement is almost absent, and the motor operates with minimal active rotor resistance, which ensures high efficiency.

Special rod designs

To enhance the current displacement effect, special shapes of the rotor slots are used:

- deep narrow slots;
- double "lightning-shaped" cage;
- pear-shaped slots.

In motors with a double short-circuited winding, the upper (starting) cage is made of a material with a higher resistivity (brass, bronze), and the lower (working) one is made of copper. During start-up, the current acts mainly in the upper cage, providing a large starting torque, and in the operating mode – in the lower one, providing high efficiency.

Approximate formula for the dependence of rotor resistance on slip

Considering that the current frequency in the rotor $f_2 = f_1 \cdot s$, and taking into account equation (4), the displacement coefficient is calculated by the following formula

$$k_R = \frac{h}{3} \cdot \sqrt{\frac{\pi \cdot s \cdot f_1 \cdot \mu_0 \cdot \mu_R}{\rho}} = K \cdot \sqrt{s}, \quad (5)$$

where the design factor is $K = \frac{h}{3} \cdot \sqrt{\frac{\pi \cdot f_1 \cdot \mu_0 \cdot \mu_R}{\rho}}$.

Taking into account (1), the final formula for determining the required additional active rotor resistance takes the form

$$R_{add} = R_{2RATED} \cdot \left(\sqrt{\frac{s}{s_{RATED}}} - 1 \right), \quad (6)$$

where R_{2RATED} – the active rotor resistance at the nominal slip s_{RATED} .

This approximate formula shows that the active rotor winding resistance increases in proportion to the square root of the slip, which explains the improvement of the starting characteristics of induction motors with a deep groove or double short-circuited winding.

To take into account the phenomenon of current displacement in the mathematical model of an induction motor implemented in the MATLAB/Simulink/Simsape/Electrical library, it is necessary to add a controlled resistance to the rotor circuit with a value calculated in the slip function according to (6). The idea of taking into account current displacement using additional resistance is illustrated in Fig. 2, a.

The controlled resistance block (Fig. 2, b) is composed according to Ohm's law $U = R_{VAR} \cdot i$ and is implemented using blocks for measuring the instantaneous value of the current, multiplying by a given resistance value and a controlled voltage source.

Fig. 3 shows comparative diagrams of the angular velocity and electromagnetic torque during AM direct start without taking into account the displacement of the rotor currents and with it.

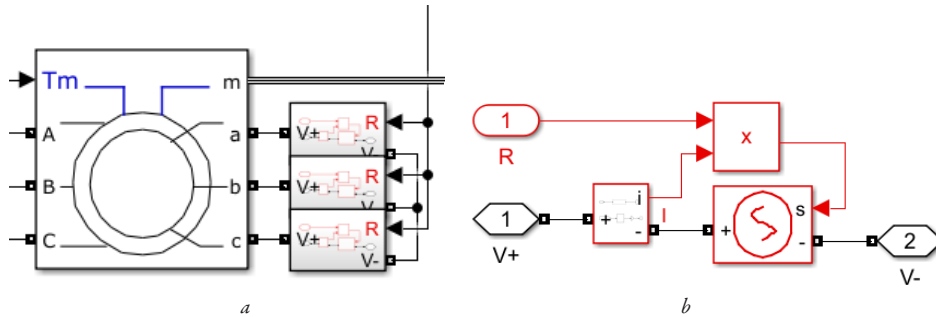


Fig. 2. Taking into account the phenomenon of current displacement in the mathematical model of an induction motor: *a* – simulation model of an induction motor taking into account the displacement of the rotor current; *b* – implementation of the controlled resistance in Simulink/Simscape/Electrical

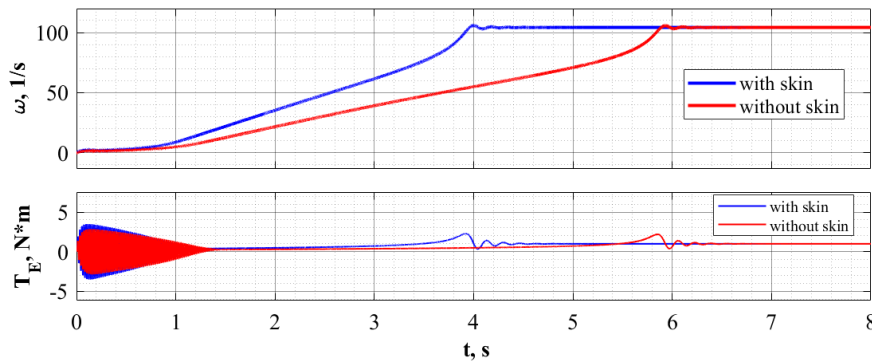


Fig. 3. Comparison of angular velocity and electromagnetic torque during direct start of the exhaust gas turbine without taking into account the displacement of rotor currents (red lines) and with it (blue lines). (IM_Exhauster_Skin_demo.slx)

As can be seen from Fig. 3, when taking into account the displacement of rotor currents, the duration of the start-up process of the exhaust gas turbine was reduced from 6.2 s to 4.1 s, which is 33.8%.

3.3. Study of controlled start-up and the impact on the network of an asynchronous electric drive of a powerful exhaust gas turbine

Practical calculations and mathematical modeling were performed based on the materials of the project for the reconstruction of the sintering plant of PJSC "ArcelorMittal Kryvyi Rih", (Ukraine, Kryvyi Rih municipal district). This project provides for the implementation of a starting device for an electric drive with a capacity of 3500 kW for the exhaust gas turbine 9000-11-5 (Ukraine). Information on the technical characteristics of the drive motor of the exhaust fan 9000-11-5 is given in Table 2.

It is advisable to conduct research on the starting modes of powerful electric drives taking into account the practical configura-

tion of the distribution network in which the exhaust fan electric drive operates.

The final mathematical model of the exhaust fan electric drive 9000-11-5 is shown in Fig. 4 and additionally includes a power transformer TDTN-63000/150/10 kV (Ukraine), a current-limiting reactor RB-10 1000/0.56 (Ukraine), and elements of cable lines.

Fig. 5 shows diagrams of the operation of the distribution network with direct start of the asynchronous electric drive of the exhauster 9000-11-5.

The process of direct start of an exhauster AM is accompanied by a voltage drop on the secondary winding of the power transformer by 400 V ($\approx 4\%$). Due to this, the start-up duration is slightly increased compared to starting from an ideal power source. It is also important to note the fact that the voltage drop in the network node practically coincides with the change, first of all, of the reactive power. This is due to the use of an induction motor with a large shift angle between voltage and current to the critical slip point.

Table 2

Technical characteristics and parameters of the replacement circuit of the drive motor of the exhaust fan 9000-11-5

No.	Parameter	Units of measurement	Value
1	Motor type	–	1RQ7636-6JA800CGO
2	Power	kW	3500
3	Supply voltage	V	10000
4	Mains frequency	Hz	50
5	Rated current	A	245
6	Shaft speed	rev/min	994
7	Power factor	–	0.85
8	Efficiency factor	%	96.9
9	Starting current ratio	–	5.5
10	Overload capacity	–	2.1
11	Moment of inertia	kgm ²	185

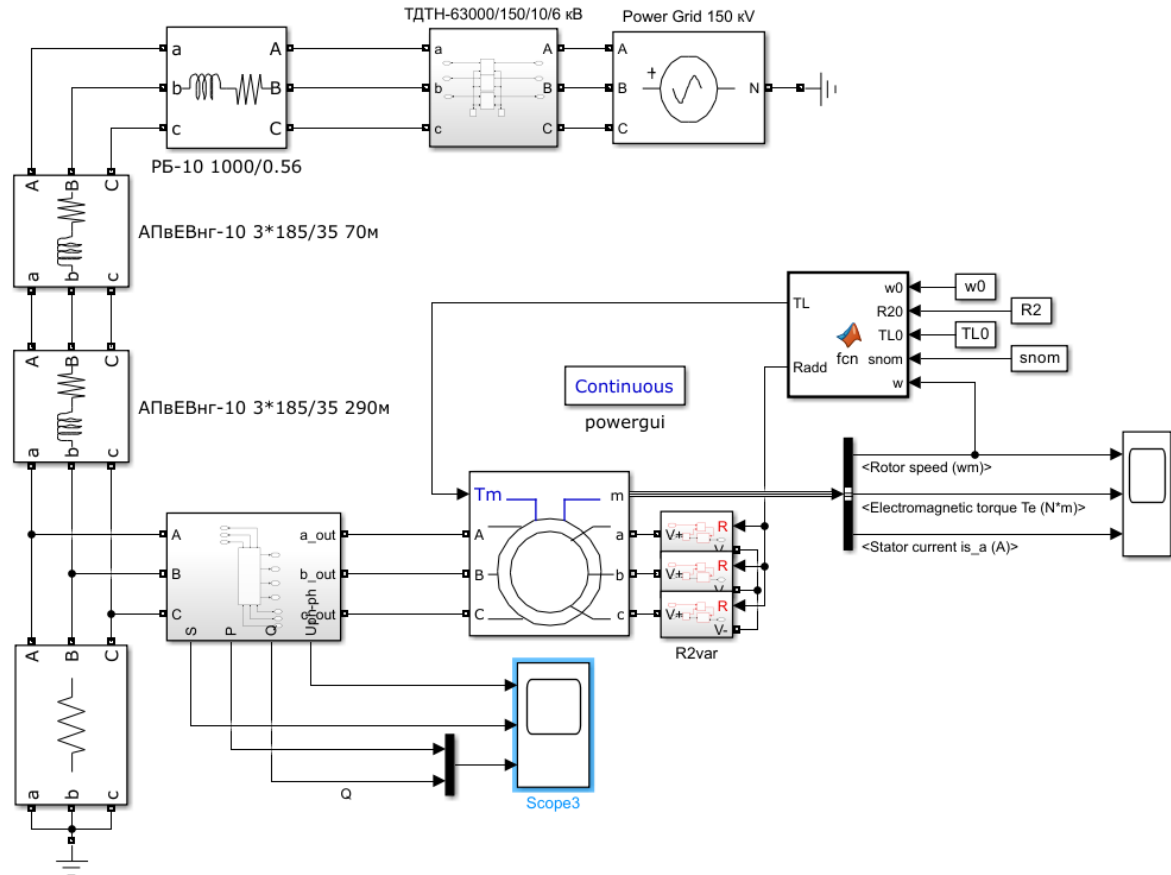


Fig. 4. Mathematical model of the distribution network of a sintering plant with direct start of an asynchronous electric drive

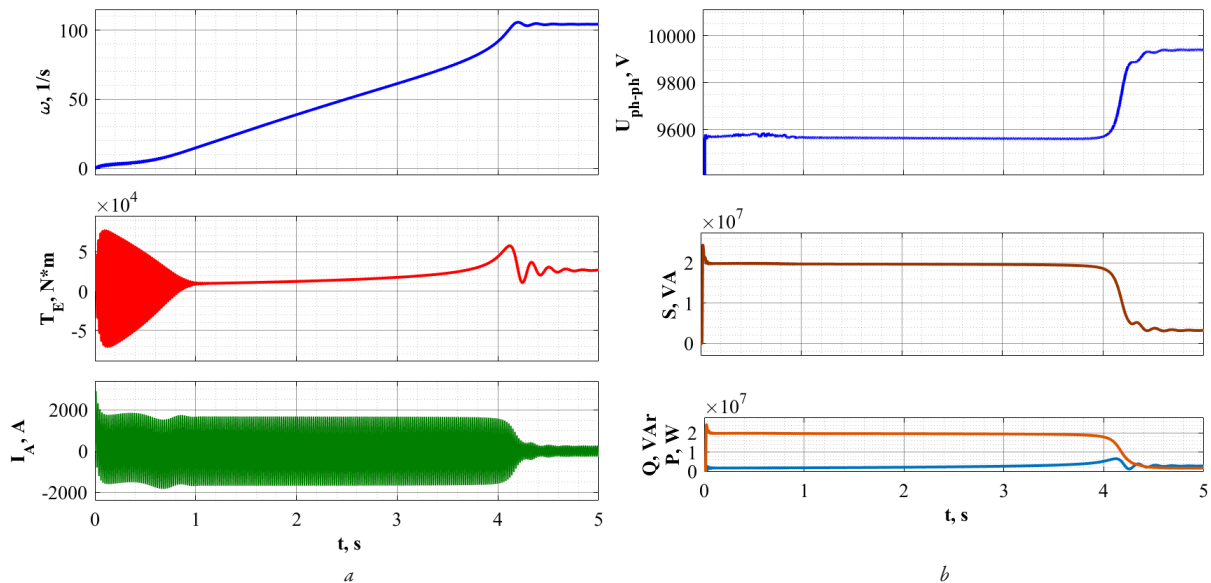


Fig. 5. Transient graphs of direct start of an induction motor of an exhauster in the distribution network of a sintering factory: *a* – angular velocity, electromagnetic torque and stator current; *b* – linear voltage of the secondary winding of the transformer, full power, reactive and active power of the AM

But according to technological requirements in the exhauster mechanism, the start-up should take much longer – from 18 to 25 s. Therefore, a soft start device based on a thyristor voltage converter is used.

To study the power quality indicators in the distribution network of a sintering factory with controlled start of an asynchronous electric

drive, a thyristor voltage converter TVR was added to the previously created model (Fig. 4).

The simulation model for studying the controlled start modes of the asynchronous electric drive of the exhauster 9000-11-5 is shown in Fig. 6.

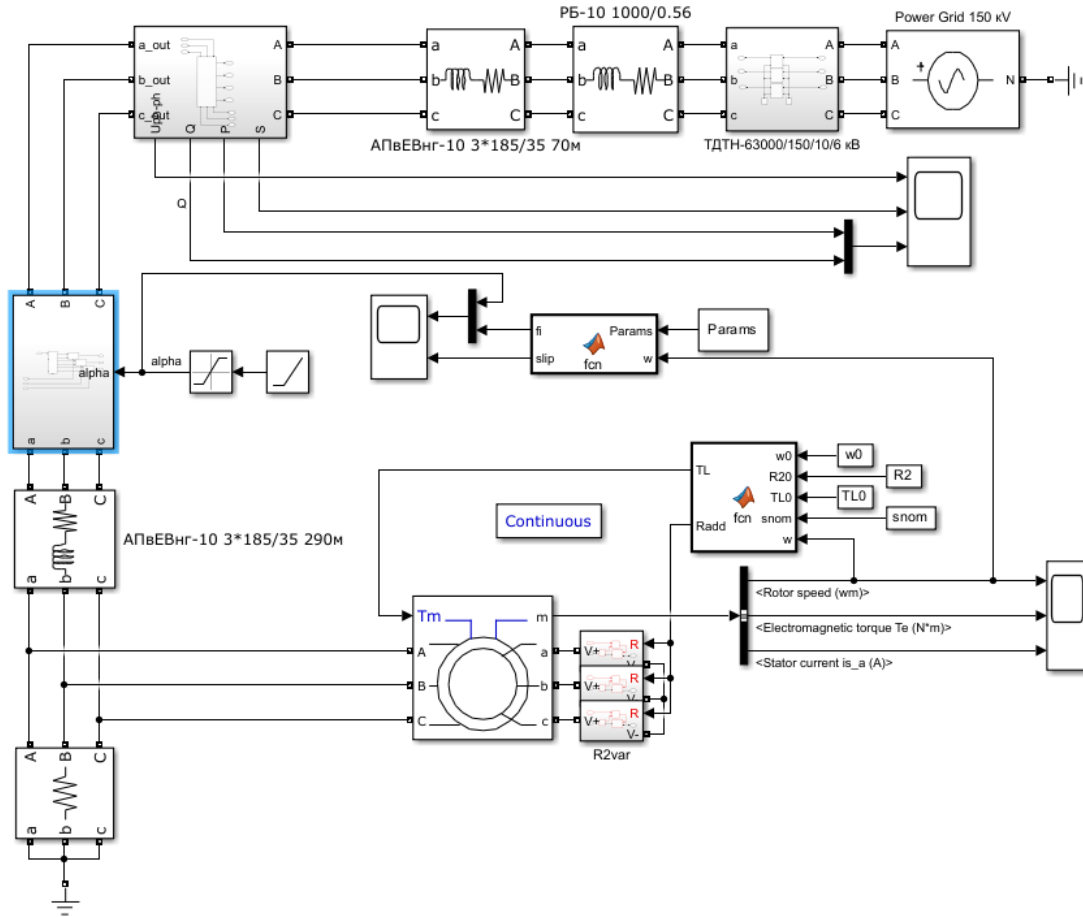


Fig. 6. Mathematical model of the distribution network of a sintering factory with controlled start of an asynchronous electric drive

3.4. Study of the influence of the parameters of the electric drive on the indicators of the self-oscillating mode of operation

The first attempts to simulate the smooth start of the exhaust electric drive using a thyristor voltage regulator demonstrated a rather strange phenomenon – the occurrence of self-oscillations of the induction motor when exiting the vicinity of the nominal speed, Fig. 7, *a*. Numerical simulations confirmed that the obtained result is not a consequence of the instability of numerical methods or other digital artifacts. The main condition for the occurrence of self-oscillating modes of operation of an asynchronous electric drive was the use of powerful high-voltage motors with specific electromagnetic and electromechanical parameters, which determine the high value of the motor efficiency and a small value of the nominal slip.

Mathematical modeling of the soft start of a general industrial motor with a power of 5.5 kW, the results of which are shown in Fig. 7, *b*, confirm that under the same relative conditions in electric drives with general industrial motors, the probability of self-oscillations of the specified nature is practically absent.

Thus, low-frequency (units and fractions of hertz) self-oscillating modes of an asynchronous electric drive during soft start from a TVR arise precisely when us-

ing powerful high-voltage electric motors. This is due to the small value (up to 0.7%) of the nominal slip and a relatively small own moment of inertia.

Modeling the smooth start of an exhaust fan electric drive with the simplest control option – a linear change in the thyristor opening angle from maximum to minimum – allowed to obtain a number of important results, illustrated in Fig. 8.

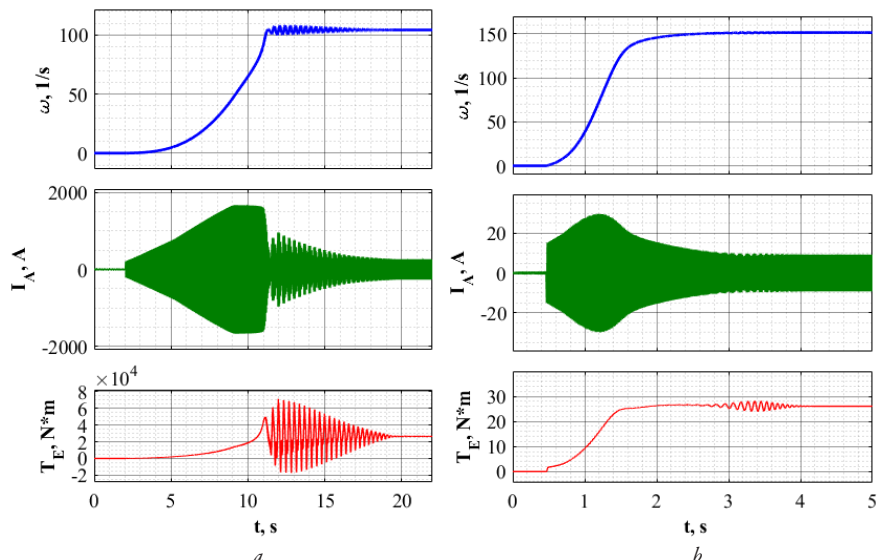


Fig. 7. Before the occurrence of the self-oscillating mode of operation during soft start of an induction motor from a TVR: *a* – induction motor 10 kV, 3500 kW; *b* – induction motor 400 V, 5.5 kW

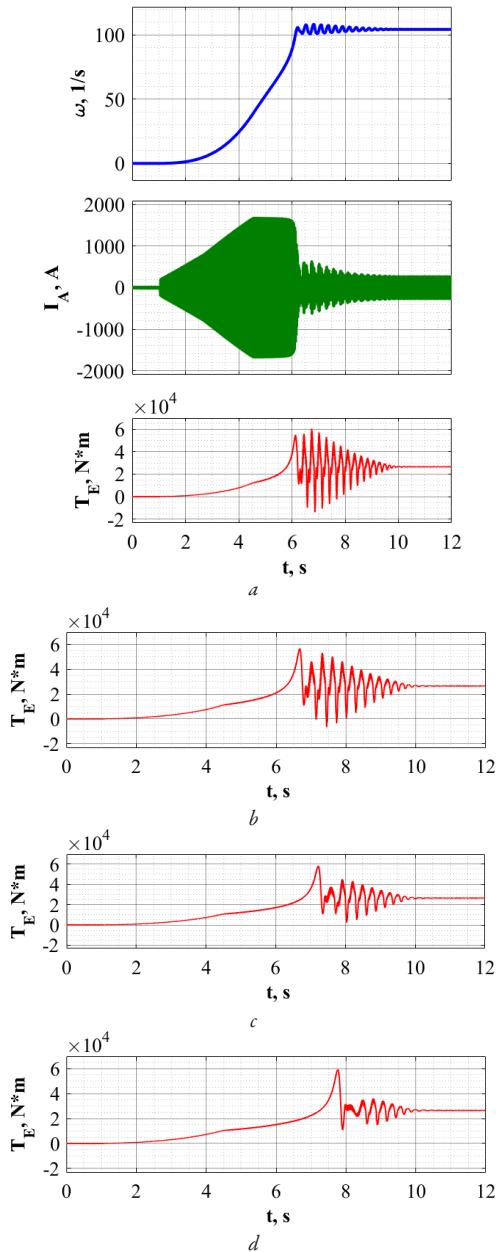


Fig. 8. Graphs of transient processes of angular velocity, stator phase current and electromagnetic torque of the motor at different values of the total moment of inertia of the electric drive: $a - J^* = 1.5 \cdot J_{EM}$; $b - J^* = 1.8 \cdot J_{EM}$; $c - J^* = 2.1 \cdot J_{EM}$; $d - J^* = 2.4 \cdot J_{EM}$

Of the results shown in Fig. 8 diagrams clearly show how, upon completion of the start-up process, self-oscillations of the electric drive occur, the parameters of which are determined by the electromagnetic parameters of the induction motor. This operating mode negatively affects the operation of all elements of the electromechanical equipment, due to the alternating pulsations of the electromagnetic torque and the vibration caused by them. The amplitude and duration of the self-oscillation process are significantly affected by the total moment of inertia of the electric drive. Diagrams of controlled start-up of the electric drive are given at values of the total moment of inertia of the electric drive of 1.5, 1.8, 2.1, 2.4 from the own moment of inertia of the drive electric motor J_{EM} . Since the diagrams of the speed and stator current do not differ significantly, only for the first case a full set of graphs is given, and for the others – only the graphs of the change in the electromagnetic torque, as the most informative.

Mathematical modeling showed that the self-oscillating process indicators are significantly influenced by the rate of controlled start.

Fig. 9 shows the time diagrams of controlled start of the electric drive with a moment of inertia of $2.4 \cdot J_{EM}$ and a control angle sweep time of 10 s and 20 s, respectively.

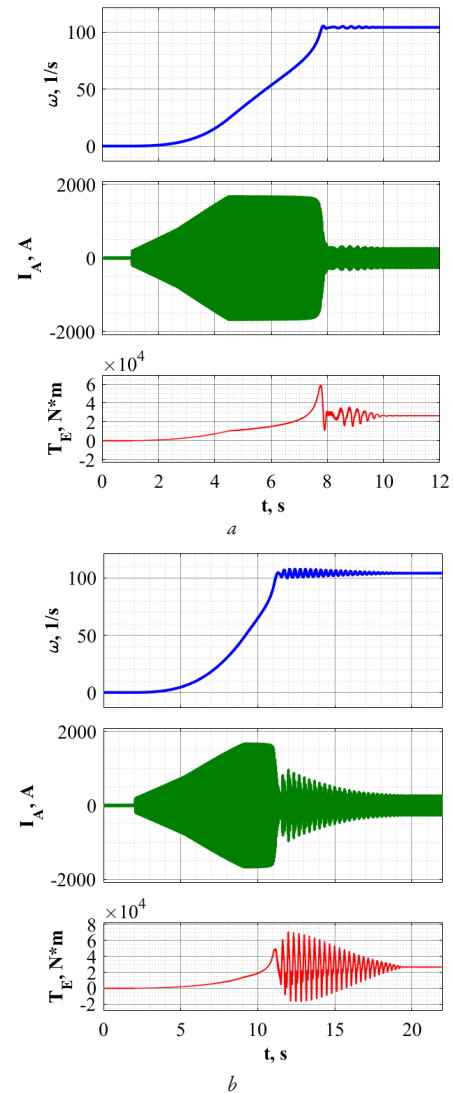


Fig. 9. Transient processes in angular velocity, electromagnetic torque, and motor stator phase current at the moment of inertia of the electric drive $J^* = 2.4 \cdot J_{EM}$ and different linear sweep times of the thyristor opening angle: a – sweep time 10 s; b – sweep time 20 s

Slowing down the start-up rate negatively affects the nature of self-oscillating processes, increasing their duration and the amplitude of the alternating component of the electromagnetic torque.

The cause of self-oscillations is a rapid decrease in the phase angle of the induction motor when approaching the critical slip point. And when this angle becomes less than the thyristor opening angle, the thyristors open completely, the voltage increases to the mains voltage, the motor torque increases, the speed increases, and the slip becomes less than critical. The phase angle rapidly becomes greater than the opening angle, the voltage and torque fall. The speed of the motor under the influence of the load decreases. The process is repeated, but with some gradual attenuation of the amplitude. Obviously, the smaller the moment of inertia, the greater the amplitude and duration of self-oscillations.

3.5. Using a controlled reactive power compensator to prevent the occurrence of self-oscillations

Among the ways to suppress the detected self-oscillations is the construction of closed-loop control systems for the voltage and speed

of an induction motor. But these systems do not eliminate the cause of the oscillations, but only allow to reduce their amplitude and duration due to controlled voltage fluctuations close to the antiphase with those arising as a result of physical processes in the TVR-AM system.

The most effective way to improve the quality of a number of indicators of a controlled electric drive is the joint use of voltage or speed feedback and a controlled dynamic reactive power compensation device (RPCD). Schematic diagrams of promising compensators can be constructed according to the schemes given in [21]. In the general case, they are connected to the control object in parallel and reduce the total reactive power of the consumer from the point of view of the distribution network.

For the TVR-AM system, it is obviously possible to use such a compensator in two variants:

- 1) when connecting the RPCD between the power source and TVR;
- 2) when connecting the compensator between TVR and AM.

In the first variant, such a compensator allows to reduce the reactive power of the electric drive to a given level relative to the distribution network, but it will not in any way affect the control processes in the TVR-AM system.

Therefore, it is advisable to consider only the second variant. The simulation model of such a system is shown in Fig. 10.

Fig. 11 shows the transient processes in the constructed system.

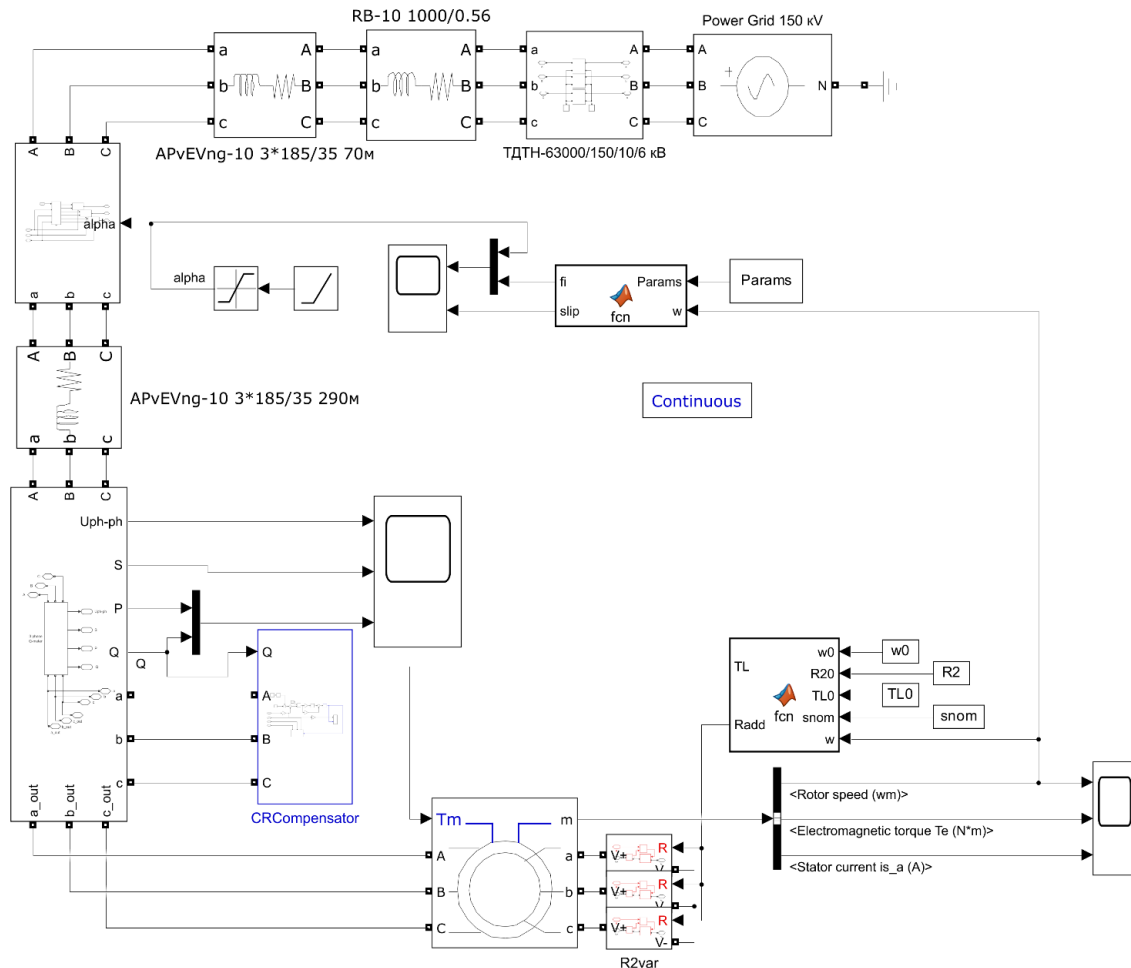


Fig. 10. Simulation model of the electric drive of the exhaust fan 9000-11-5 with a reactive power compensator located between the soft starter and the motor

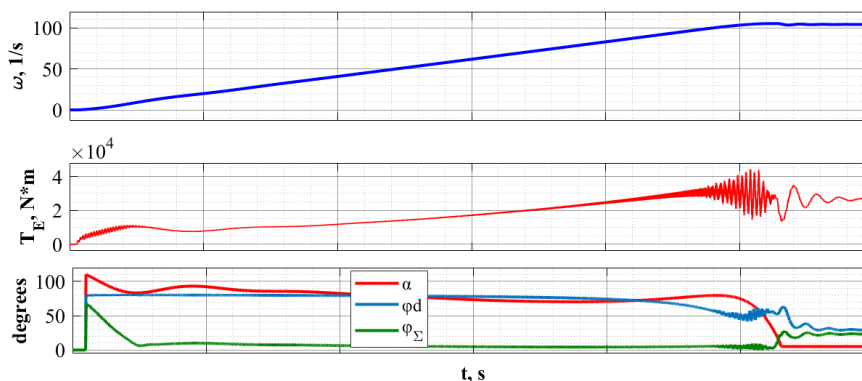


Fig. 11. Graphs of transient processes of starting an electric drive of an exhaust fan with a reactive power compensator located between the soft starter and the motor

A comparison of the torque and speed graphs from Fig. 9, *b* shows a significant decrease in the amplitude and duration of oscillations. Below are graphs that explain the reason for such a positive effect. The total phase shift angle of the motor and the reactive power compensator at the beginning of the process is 20 degrees less than the motor angle, and at the end of the start-up process (exactly at the time of oscillations) the difference reaches 50 degrees, i. e. the controllability zone of the TVR is significantly expanded. As a result, a significant part of this interval passes when the thyristor turn-off angle is less than the motor phase angle, but greater than the total phase angle of the motor and the compensator, which maintains the TVR controllability and prevents the occurrence of self-oscillations.

3.6. Discussion of research

The analysis of the parameters of high-voltage powerful induction motors made it possible to identify the features of these motors compared to general industrial ones and to develop a detailed model of the 9000-11-5 exhaust fan electric drive, taking into account both the effect of current displacement in the rotor and the influence of the electric drive on the distribution network of the enterprise.

It is shown that during direct start of an induction motor, the duration of the transition process is about 4 s; the voltage drop on the secondary winding of the power transformer reaches about 4%. To ensure the start-up duration in accordance with the technological requirements of the exhaust fan mechanism (18–25 s), a thyristor (triac) soft start device is used in the electric drive, which, by reducing currents, allows to significantly reduce the voltage drop on the secondary windings of transformers, but at the same time, harmonic distortions of voltage and current significantly increase.

During the study of the process of controlled starting with linear control of the thyristor firing angle, it was found that during starting, self-oscillation modes arise in the critical slip zone. The cause of self-oscillations is sharp jumps in the phase angle of the induction motor.

The parameters of self-oscillations are determined by the characteristics of the asynchronous electric drive, in particular, the moment of inertia, as well as the specified duration of the motor acceleration process.

The analysis of ways to prevent the occurrence or reduction of the amplitude and duration of self-oscillations showed that it is necessary to complicate the control system of the TVR-AM electric drive. The most effective way to suppress such oscillations is to use a controlled reactive power compensator located between the soft starter and the induction motor, which provides a solution to a number of problems:

- compensation of reactive power at a given level is ensured, which is consumed by the electric drive from the network;
- voltage stabilization is ensured in the network node;
- reactive power compensation eliminates the conditions for the occurrence of self-oscillations of the electromagnetic torque of an induction motor when passing the critical slip point;
- the range of adjustment of the thyristor opening angle is expanded from 105–85 degrees to 120–40 degrees, which improves the controllability of the soft starter.

The practical significance of the results obtained is in determining methods for eliminating self-oscillating modes during controlled start-up of powerful asynchronous electric drives. This will increase the reliability of electromechanical equipment and reduce operating costs for scheduled preventive maintenance.

A limitation of research is the lack of research into the influence of the self-oscillating mode of operation on the reliability indicators of electromechanical equipment.

Prospects for further research are related to the search for additional methods for overcoming self-oscillating modes during controlled start-up of an asynchronous electric drive.

4. Conclusions

1. An analysis of the technical characteristics of powerful induction motors manufactured by ABB and WEG has been performed, on the basis of which it was determined that the nominal slip of such motors is approximately 0.5%. This value is practically an order of magnitude less than the nominal slip of general industrial induction motors of low and medium power. The phase angle of an induction motor with a *T*-shaped equivalent circuit varies in the range of 30–90 degrees in the nominal slip zone.

2. The mechanism of the current displacement phenomenon has been analyzed and a mathematical model for accounting for this phenomenon in an induction motor in the MATLAB/Simulink environment has been proposed. When taking into account the displacement of rotor currents, the duration of the AM direct start process from an ideal power source was reduced from 6.2 s to 4.1 s, which is 33.8%.

3. A simulation model has been developed to study the modes of controlled start-up of the asynchronous electric drive of the exhaust fan 9000-11-5 with a capacity of 3500 kW, taking into account the influence of the enterprise's distribution network. A three-phase thyristor voltage regulator with a linear sweep of the control voltage was used as a soft start device.

4. The influence of the parameters of the exhaust fan 9000-11-5 electric drive on the indicators of the self-oscillating mode of operation has been studied. The decisive influence on the parameters of self-oscillations is the total moment of inertia of the electric drive and the start-up duration, which depends on the requirements of the technological process. Slowing down the start-up rate negatively affects the nature of the self-oscillating processes, increasing their duration and the amplitude of the alternating component of the electromagnetic moment. Reducing the moment of inertia also negatively affects the nature of the self-oscillating processes.

5. Mathematical modeling methods have shown that self-oscillation reduction is possible when using a controlled reactive power compensator connected between the motor and the thyristor voltage regulator. Such a technical solution not only prevents the occurrence of self-oscillations, but also increases the range of adjustment of the thyristor firing angle in the electric drive and improves the quality of electricity in the distribution network of the enterprise.

Conflict of interest

The authors declare that they have no conflict of interest regarding this research, including financial, personal, authorship or other, which could affect the research and its results presented in this article.

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The manuscript has no related data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

Authors' contributions

Victor Busher: Conceptualization, Formal analysis; *Vladyslav Baranovskiy*: Data curation, Formal analysis; *Oleksiy Gromovyy*: Funding acquisition, Investigation; *Valeriy Druzhinin*: Resources, Software;

Lubov Melnikova: Supervision; **Andrii Tkachuk:** Methodology, Project administration; **Andrii Romanets:** Validation, Software, Data curation; **Oleksandr Pidtychenko:** Visualization; **Anna Humeniuk:** Writing – original draft, Resources; **Ilya Kolysnychenko:** Writing – review and editing, Resources.

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