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DETERMINATION OF ELECTRICITY QUALITY INDICATORS IN DISTRIBUTION NETWORKS OF INDUSTRIAL ENTERPRISES WHEN USING STARTING DEVICES OF POWERFUL ELECTRIC DRIVES

The object of research is the processes of electromagnetic transformation in powerful asynchronous electric drives during controlled start-up and their impact on the quality of electricity in the power supply network. Distribution networks of industrial enterprises are considered, which have significant dynamic loads during the start-up of powerful machines.

The problem to which the research is aimed is to ensure proper quality of electricity in distribution networks of industrial enterprises when performing controlled start-up of powerful asynchronous electric drives from soft starters based on a thyristor voltage regulator.

Quantitative indicators of the influence of starting devices on the parameters of electricity quality were calculated using computer modeling in the MATLAB/Simulink environment. Soft start using a thyristor regulator, although it limits the starting current, has a negative impact on the quality of electricity in the distribution network. Reactive power consumption increases, which causes a voltage drop. For the case of starting an asynchronous motor with a capacity of 3500 kW in the network of a sintering factory, it was found that direct start causes a voltage drop of about 350 V. Harmonic voltage distortions with a distortion factor of up to 6% also appear. Power active filters allow to improve the quality of electricity by introducing antiphase currents, which is proven by the application of theoretical methods of electrical engineering.

The results obtained are applicable in the design of electric drive systems of powerful mechanisms during the modernization of the power supply of industrial enterprises, in the calculation of reactive power compensation means and in the development of energy quality standards. This will significantly contribute to increasing the reliability of technological equipment, reducing energy losses, and increasing the service life of electrical equipment at the enterprise.

Keywords: *starting devices, power quality, controlled reactor compensator, simulation modeling of the distribution network.*

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1. Introduction

The problem of ensuring reliable power supply of modern individual industrial consumers is becoming increasingly urgent. With the increase in the share of electric drives in technological processes, the introduction of converters and thyristor starters, an increase in the level of electromagnetic transients, the appearance of harmonic components in current and voltage, as well as a decrease in the voltage coefficient are achieved. The element of electrical energy consumption is changing the reliability of the last work and its service life.

The most typical problem can be solved only in a complex, organizing the flow control of different types of starters to indicate power, minimize any negative flows, and also divide the technical and algorithmic advantages for their compensation. Considerable attention is paid to the analysis of dynamic processes at the moment when electric motors are started, since it is at this moment that the flow changes and transients reach maximum values.

The global soft starter market was valued at 2.16 billion USD in 2024 and is projected to reach 3.07 billion USD by 2030, growing at a CAGR of nearly 6% during the forecast period [1].

There is no publicly available report that specifically segments the soft starter market. Most modern industrial soft starters operate in a ramp-up mode as the primary mode for heating, and also provide flux exchange in older models.

The development trends of starter designs used in electric drives have been analyzed by several authors [2–10].

Soft starter systems are considered one of the main components of the modernization of drive systems in industrial enterprises, reducing starting currents and electromechanical loads, as well as increasing energy efficiency. The traditional direct-on method involves starting currents up to 6–8 times higher than the rated current, which increases the load on the network and reduces the resource of not only electric motors, but also switching equipment. In [2] it was found that starters based on thyristors and IGBTs can significantly reduce the starting

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current, while IGBT technology provides better smooth operation with lower peak currents compared to the thyristor circuit.

A comparative analysis between phase control and PWM-modulated starter was carried out by researchers in [3], which again proves the advantage of the asynchronous PWM AC circuit breaker in reducing harmonic distortion and torque ripple during starting.

Alternative schemes are confirmed by the research of a starter based on MCR, capable of maintaining a constant current, since there is a controlled reactor in the stator circuit [4]. For high-voltage drives, a comprehensive method of current limitation during soft starting of a high-voltage powerful electric motor, integrated reactive power compensation functions, as well as harmonic filtering after the start process is completed [5]. The results demonstrate a reduction in harmonic distortion, accompanied by better controllability of the start process.

In [6], 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 scheme with a closed current loop to reduce the acceleration time.

The ETAP study [7] shows the sensitivity of the network characteristics to different starting methods and a reasonable choice that includes energy efficiency and minimum voltage drop.

Some works analyze non-standard schemes, in particular, a thyristor star/delta switch as an economizer and starter [8], as well as a PWM AC circuit breaker with a minimized number of power elements along with an increase in the power factor [9].

In work [10], the choice of the optimal control strategy for an asynchronous 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.

Modern starting systems clearly demonstrate the evolutionary path from simple thyristor phase-controlled schemes to high-frequency transistor technologies integrated with control systems and reactive power compensators, which significantly minimize the negative impact on the network.

Despite the rapid and complex development of circuit solutions for starters, the most common circuit for an AC motor starter is still a thyristor voltage regulator [11]. This is due to the fact that it has a simple power part in the starter unit, hence its low cost, and can also be used to start both types; both asynchronous and synchronous electric motors.

References [12–17] provide an overview of methods for improving power quality when using starters.

The problem of the influence of starting modes on power quality 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.

In [12], the use of thyristor AC choppers used as soft starters was considered, and their study as sources of interharmonics was performed in comparison with frequency converters. Thyristor AC choppers in the soft start mode reduce the current and temporarily limit the voltage. The wavelet-synchronously compressed conversion method was applied. In [13], in order to alleviate the influence of the starting processes of large induction motors on the operation of isolated networks, the use of parallel compensation of capacitors during starting was proposed, since large induction motors have high inductance during the starting sequence, so the supply of reactive power can be more efficient than the supply of energy.

In [14], attention was focused on the spectral analysis of harmonics in the starting current. They showed the importance of its identification for reliable diagnostics of the state of drives.

In [15], a multifunctional series compensator was investigated as a comprehensive solution for current limitation and voltage sag compensation, experimentally verifying the effectiveness of the virtual resistance input and voltage compensation mode.

In [16], the importance of direct calculation of voltage sags during the start of powerful motors was analyzed, developing analytical relations for voltage estimation in such networks with a high concentration of motors. This was shown in [17], where the $I \times cos\varphi$ algorithm was applied and the results of experimental tests on the addition of active filters for reactive power and harmonic compensation during thyristor start-up were presented.

Therefore, new methods are based on the integration of filtering systems, the use of hybrid active-passive compensators and digital identification of harmonics, which improves the quality of electricity, and also meets the requirements of electromagnetic compatibility (EMC) in accordance with the IEEE standard.

As can be seen from the analyzed and reviewed literature, most of the works consider active power filters made according to the bridge transistor inverter scheme. The main direction of control algorithms for active power filters is improvement in the direction of better operation of filtering systems. In [18] it was proposed to use an active power filter implemented in parallel with the reactor compensator to compensate for reactive power and eliminate higher harmonics, however, they did not take into account the operating mode of the reactor compensator in controlled starting modes of powerful electric drives.

This direction of development was continued in [19–24], with an emphasis on optimizing start-up processes, increasing the reliability of mathematical modeling and taking into account poor-quality electricity during starting operations of powerful electric drives.

In [19], the problem of optimizing the starts of powerful electric drives from the point of view of energy efficiency is considered and an approach to starting control is proposed that takes into account both the electromechanical characteristics of the motor and the parameters characteristic of its power supply network. The authors have proven that the optimized starting voltage and current profile reduces the integral power losses, in addition to limiting the negative impact on the network, without complicating any power part of the starting device. This is truly significant work on the formation of algorithmic tools for starting control, focused not only on current limitation, but also on minimizing energy losses. The main attention is paid to increasing the reliability of modeling the operating modes of induction motors when solving technical and economic problems [20]. Improved mathematical models are proposed that more adequately describe transient processes not only during starting, but also during operation, when the voltage deviates from its nominal value. The results are used to correctly determine the impact of various starting devices on the network and, therefore, for the rational selection of filtering and compensation means.

In [21], the problems of adaptive control of static technological objects, as well as minimizing the description of images in control systems, are considered. The research does not contain direct studies of the starting modes of the electric drive. The proposed methods of adaptive identification and reduction of computational complexity can be applied in the development of intelligent algorithms for controlling the start of active energy filters and hybrid compensators.

A dynamic electromagnetic model of an asynchronous motor operating under conditions of voltage asymmetry, harmonic distortions and fluctuations in network parameters was developed and tested in [22]. This is one of the main works that has significantly contributed to the study of the impact of low power quality on the operation of asynchronous motors. The article shows how unsatisfactory power quality affects additional losses in the motor, as well as its thermal state. Emphasis is placed on a comprehensive analysis of start-up processes with real consideration of power quality indicators.

In [23], models of asynchronous motors in conditions of poor power supply are presented, which allow assessing the impact of harmonics and voltage asymmetry on the main energy indicators. This approach is useful for studying the interaction of thyristor starters with the network and for predicting the consequences of their use without proper compensation of reactive power and harmonic distortions.

This research area was further developed in [24], where mathematical models of energy conversion processes in a parametrically asymmetric induction motor powered by an autonomous induction generator were created. Although the article considers autonomous systems, it summarizes its results, which can be applied to the analysis of starting modes in industrial networks with a high level of asymmetry and higher harmonics.

The analysis based on sources [19–24] proves that recently in scientific works much attention has been paid to the exact mathematical modeling of electric drives and algorithms for optimizing their control, taking into account the influence of power quality. At the same time, there are quite a few studies on active and reactor compensators operating directly in the controlled start-up modes of large electric drives.

The generalization of modern research shows that the direction of combining the exact mathematical modeling of electric drives, optimization control algorithms and analysis of the influence of poor-quality electricity in transient modes is promising. However, the lack of sufficiently researched practical solutions that would ensure the comprehensive operation of starting and compensation systems during controlled start-up of powerful drives justifies the feasibility of further scientific developments in this area.

The object of research is the processes of electromagnetic transformation in powerful asynchronous electric drives during controlled start-up and their impact on the power quality indicators of the power supply network.

The aim of research is to determine the power quality indicators in the distribution networks of industrial enterprises when using starting devices for powerful electric drives.

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

1. To develop a mathematical model of a powerful asynchronous electric drive taking into account the influence of the distribution network of the enterprise.

2. To investigate the power quality indicators of distribution networks during direct and controlled start-up of a powerful asynchronous electric drive.

3. To substantiate the feasibility of using active devices for controlling power quality indicators.

2. Materials and Methods

The subject of research is the distribution electrical network of an industrial enterprise with a powerful asynchronous electric drive, which is started through a soft starter based on a thyristor 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 environment using the Simscape Electrical library, MathWorks, USA. 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, methods of classical automatic control theory were used, in particular, synthesis according to the criterion of 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 makes the obtained data adequate.

3. Results and Discussion

3.1. Development of a simulation model of an asynchronous electric drive in the distribution network of an enterprise

The design of the distribution network of an enterprise and the parameters of the electrical equipment included in it significantly affect the quality of electricity. This is explained by the dependence of the parameters of the equivalent circuit of the electric drive taking into account the influence of the distribution network.

The research of the influence of starting modes of powerful electric drives on the quality of electricity in distribution networks is impossible without detailed consideration of the context in which the energy-intensive equipment operates. Practical calculations and simulation modeling were performed based on the materials of the project for the reconstruction of the sintering plant of PJSC "ArcelorMittal Kryvyi Rih" (Kryvyi Rih, Ukraine). This project provides for the implementation of a starting device for the 9000-11-5 (Ukraine) exhaust gas discharger electric drive with a capacity of 3500 kW. Information on the technical characteristics of the exhaust fan drive motor 9000-11-5 is given in Table 1.

Table 1

Technical characteristics and parameters of the equivalent circuit of the exhaust fan drive motor 9000-11-5 type 1RQ76366JA800CGO-Z SIMOTICS HV M

No.	Parameter	Units	Value
1	Power	kW	3500
2	Supply voltage	V	10000
3	Mains frequency	Hz	50
4	Rated current	A	245
5	Shaft speed	Rev/min	994
6	Power factor	–	0.85
7	Efficiency factor	%	96.9
8	Starting current factor	–	5.5
9	Overload capacity	–	2.1
10	Stator resistance	Ohm	0.2
11	Stator leakage inductance	H	0.0085
12	Rotor resistance	Ohm	0.15
13	Rotor leakage inductance	H	0.0115
14	Magnetizing circuit inductance	H	0.2455
15	Moment of inertia	kHm2	185

The simulation model of the distribution network of a sintering plant with an induction motor is shown in Fig. 1.

The influence of the technological mechanism is taken into account in a simplified way in the form of a fan resistance moment on the motor shaft.

Fig. 2 shows diagrams of the operation of the asynchronous motor and the distribution network during direct start of the asynchronous electric drive of the exhauster 9000-11-5.

The calculated transient processes are characterized by long (more than 1 s) fluctuations of the electromagnetic moment with a significant amplitude (up to 55000 Nm, which exceeds the critical static moment of the motor) at the beginning of the start-up process. The transition through the critical slip point is accompanied by a rapid increase in the electromagnetic moment and acceleration at the end of the process. The duration of the process is about 12 s, which is almost 3 s longer than from an ideal voltage source, precisely due to the voltage drop in the network node, $\Delta U \approx 350$ V.

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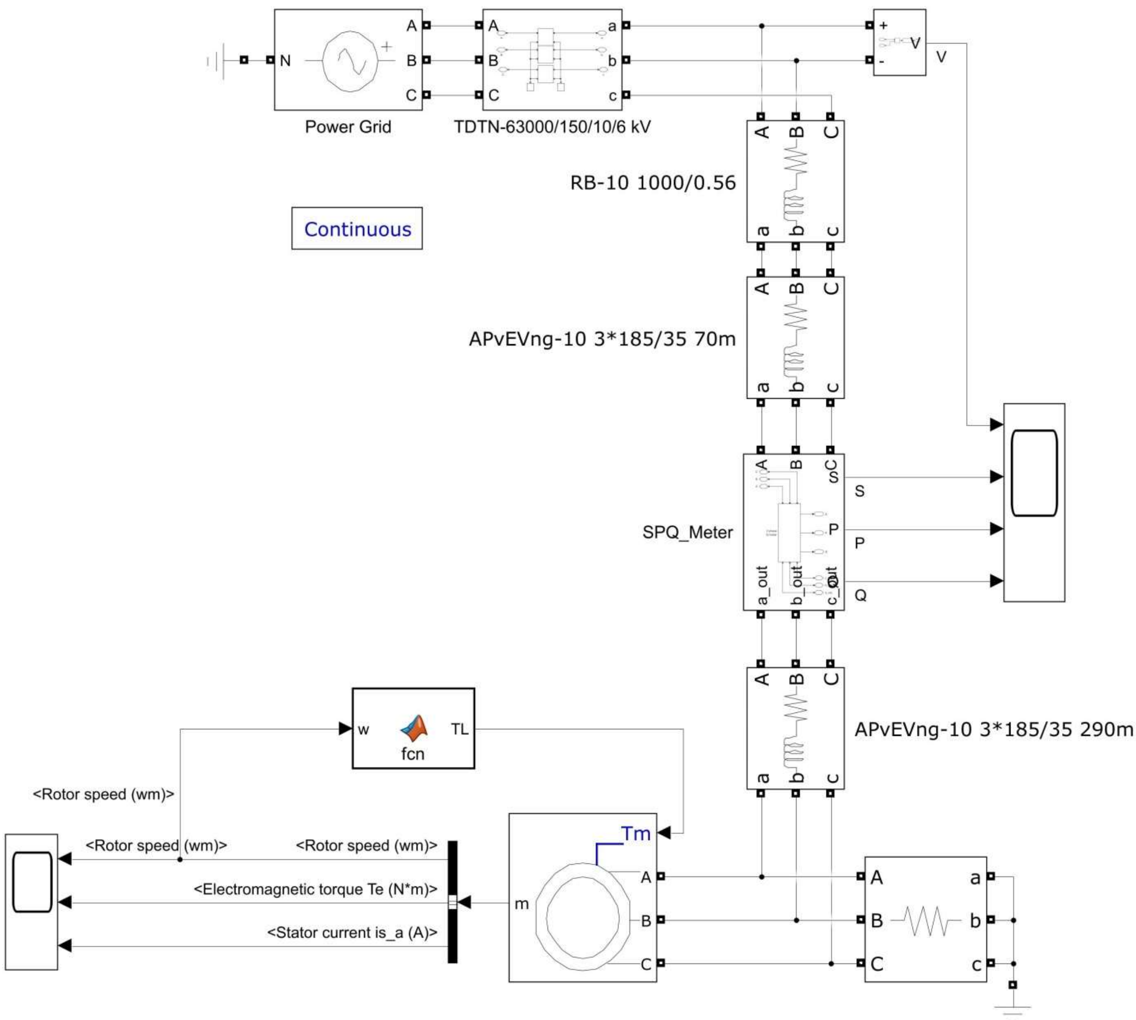

Fig. 1. Simulation model of the distribution network of a sintering plant with direct start of an asynchronous electric drive

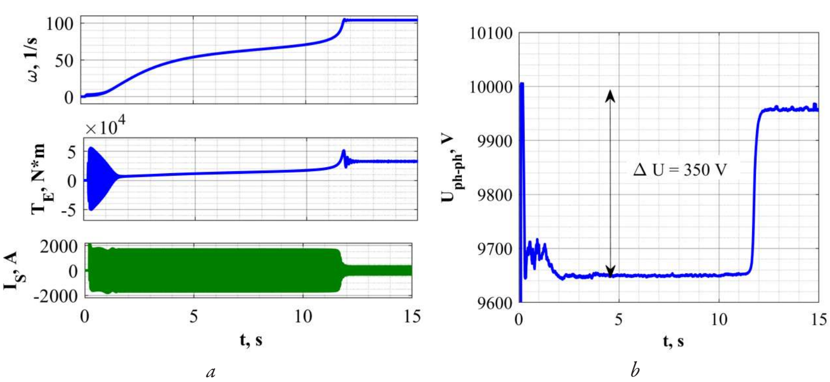

Fig. 2. Graphs of transient processes of direct start of an asynchronous motor of an exhauster in the distribution network of a sintering factory: *a* – angular velocity, electromagnetic moment, stator current of an asynchronous motor; *b* – linear voltage of the distribution network

3.2. Research on the quality of electricity in the distribution network during controlled start-up of an asynchronous electric drive

To study the quality of electricity in the distribution network of a sintering factory with controlled start-up of an asynchronous electric drive, a thyristor voltage regulator TVR and a measurement subsystem Measurer were added to the previously created simulation model, Fig. 1, 3.

In modern theoretical electrical engineering, only the concepts of the instantaneous power of an electric circuit, which is defined as the product of instantaneous voltage values [25, 26]

$$s(t)=u(t)\cdot i(t), \quad (1)$$

and the active power of an electric circuit, which is defined as the average value of the total power for the measurement period [26]

$$P=\frac{1}{T}\int_0^T u(t)\cdot i(t)\mathrm{d}t, \quad (2)$$

where $u(t)$, $i(t)$ – the instantaneous values of the voltage and current of the electric circuit.

For further implementation, the following method of determining the components of the total power was adopted. The active power of the circuit is determined by equation (2). The total power of the circuit can be defined as the product of the effective values of the current and voltage for the same measurement period by the formula

$$S=\overline{U}\cdot\overline{I}, \quad (3)$$

where $\overline{U}$, $\overline{I}$ – the effective values of the voltage and current of the electric circuit.

The inactive components of energy can be calculated according to the expression

$$T=\sqrt{S^2-P^2}, \quad (4)$$

where S, P – the total power and active power of the electric circuit.

For sinusoidal circuits, the inactive component of power coincides with the reactive power.

As an integration interval for calculating the average values, the period of the power supply network voltage $T = 1/f$, s is used.

Fig. 4 shows a simulation model of the subsystem for calculating the quality of electricity indicators of a three-phase network, which implements the calculation of the total power and its components according to formulas (2)–(4).

In addition to the components of the full power, the Measurer subsystem measures the harmonic distortion factor THD of the phase voltage (output THD_U), and the relative effective values of the higher harmonics of the phase voltage of orders 5, 7, 11, 13 (output UH-5-13).

The sign of the inactive power is determined by the sign of the reactive power of the first harmonic of the phase voltage.

The results of the simulation of the controlled start of the exhaust fan electric drive taking into account the influence of the distribution network of the sintering plant are illustrated by the following diagrams, Fig. 5–7.

Fig. 5 shows the diagrams of electromechanical transient processes during the smooth start of the exhaust fan electric drive using a thyristor voltage regulator.

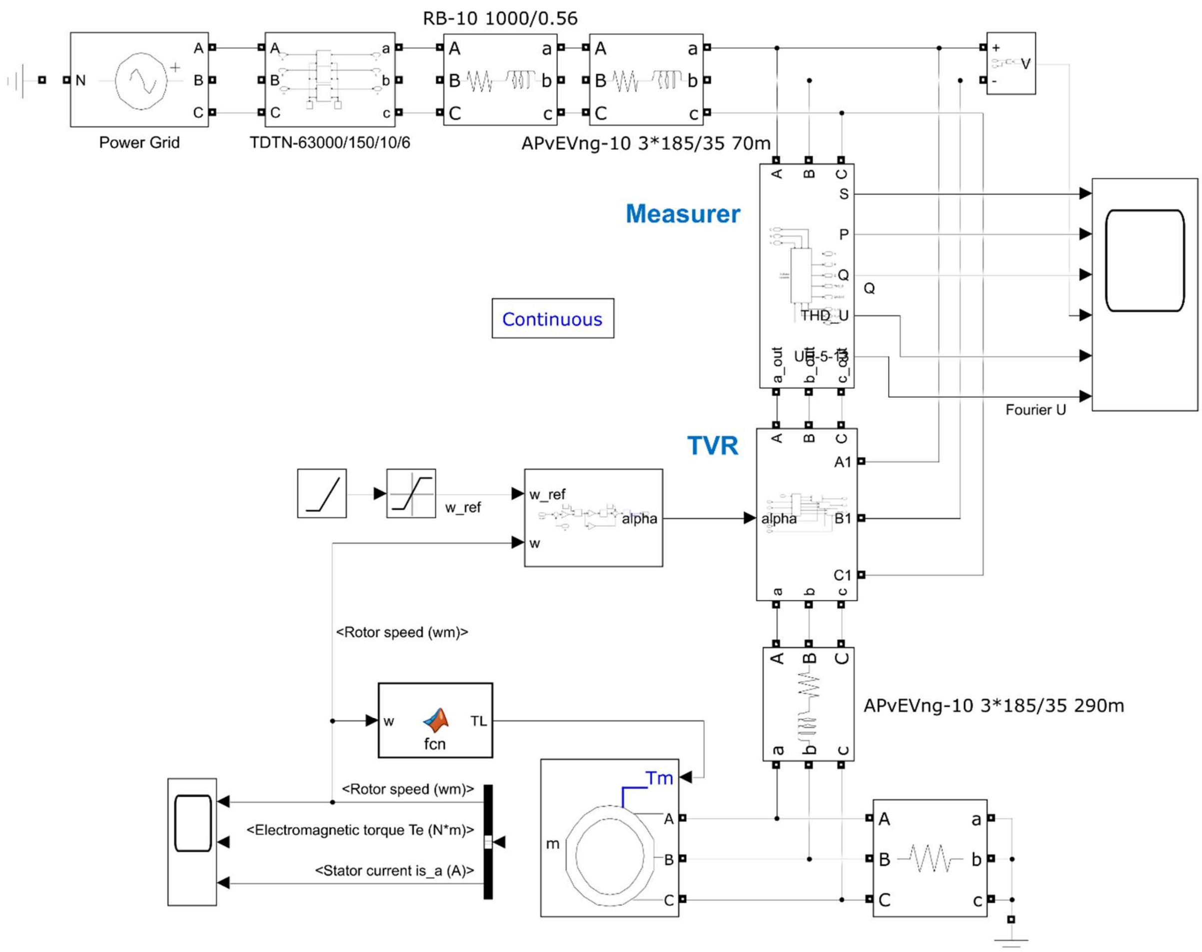

Fig. 3. Simulation model of the distribution network of a sintering factory with controlled start of an asynchronous electric drive of an exhauster

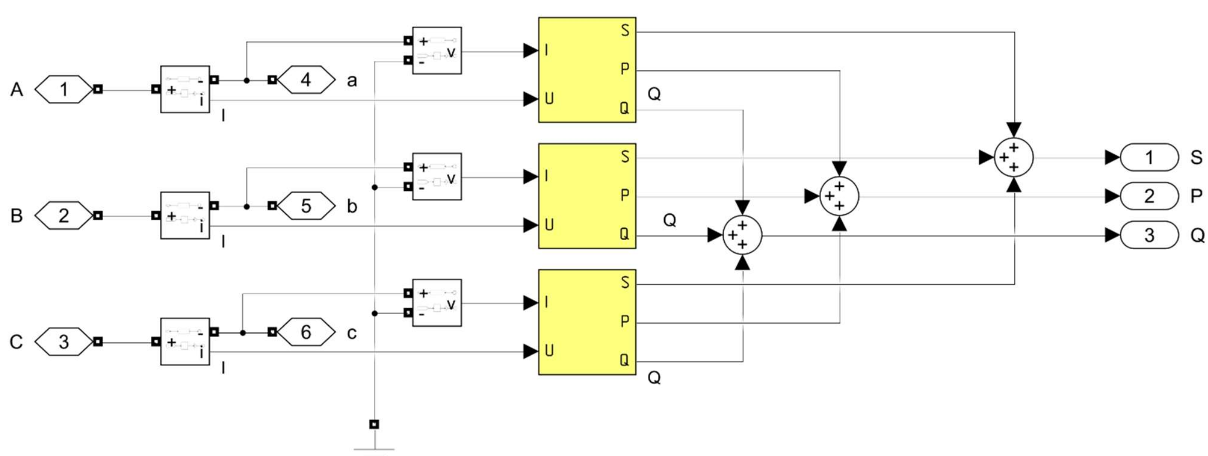

Fig. 4. Simulation model of the Measurer subsystem for determining the power quality indicators of a three-phase network

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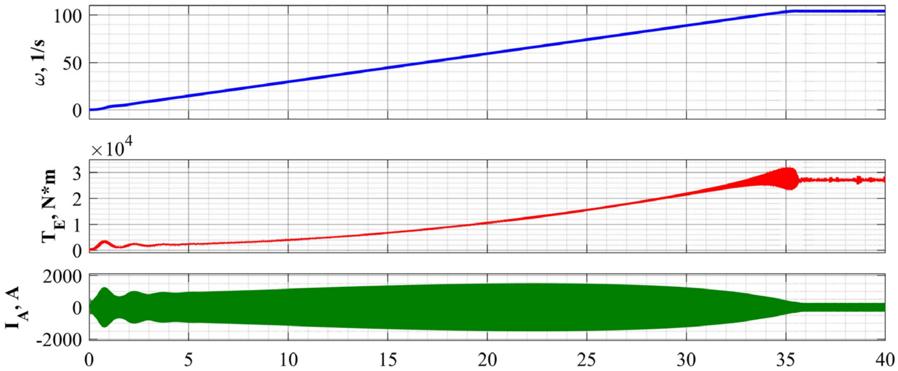

Fig. 5. Transient processes of soft start of the exhaust fan electric drive with a thyristor voltage regulator

The obtained modeling results coincide with the general theoretical ideas about the operation of the asynchronous electric drive, and the numerical characteristics correspond to the technical data of the drive motor, Table 1, which confirms the adequacy of the simulation model.

Fig. 6 shows the diagrams of the components of the full power and some characteristics of the quality of electricity of the sintering factory distribution network.

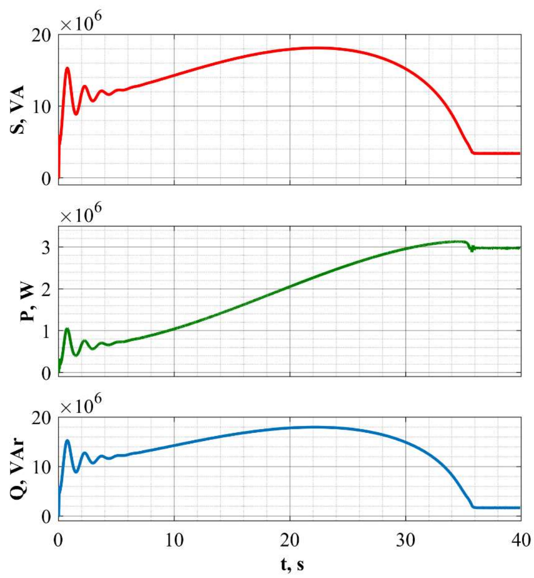

Fig. 6. Diagrams of total power consumption and its components during smooth start-up of the exhaust fan drive using a thyristor voltage regulator

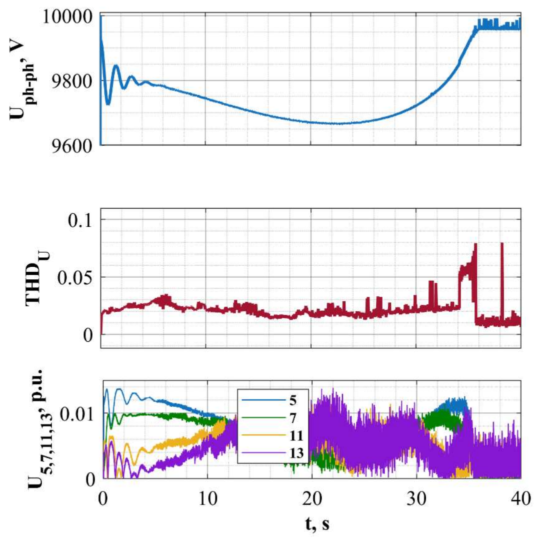

Fig. 7. Diagrams of the quality of electricity distribution network of the sintering factory during the soft start of the exhaust fan drive using a thyristor voltage regulator

Fig. 7 shows diagrams of the main voltage quality indicators in the distribution network of the sintering factory during controlled start-up of the exhaust fan drive: linear voltage, harmonic distortion factor of voltage and effective values of higher harmonic voltages.

Based on the results of the calculations, the following conclusion can be drawn. Despite the limitation of the starting current during the soft start, the consumption of reactive power remains quite high, which leads to a significant (about 4%) decrease in the voltage in the supply network, Fig. 7. The soft start of the exhaust fan drive with a thyristor voltage regulator is accompanied by harmonic distortions of the network voltage, Fig. 7. With the considered configuration of the distribution network, the harmonic distortion coefficient is at the level of 2–2.5%, and in the critical slip region it reaches a value of 6%. The most influential are harmonics of order 5 and 7, but in the critical slip region the higher harmonic of order 13 reaches a comparable value.

3.3. Justification of the feasibility of using active power quality control devices

Thyristor voltage regulators as the basis of soft starters have become widespread in industry to ensure smooth start-up of powerful asynchronous electric drives. The main functional purpose of these technical solutions is to reduce starting currents, which helps to minimize wear of electromechanical and technological equipment, reduce electrical loads on the distribution network. At the same time, the use of the phase principle of voltage regulation in traditional soft starters leads to significant deviations in power quality indicators. These shortcomings are increasingly limiting the possibilities of their use in the context of strengthening regulatory requirements for energy efficiency and compliance with international standards for the quality of power supply.

The functioning of a thyristor voltage regulator is based on the principle of cutting off a fragment of a sinusoidal signal, which makes it possible to regulate the average voltage at the terminals of the electric motor. In starting modes, the power factor reaches critically low levels (0.2–0.5). This leads to the formation of significant reactive power consumption and is accompanied by the following: increased energy losses in the power supply system and deterioration of overall energy efficiency, the risk of financial sanctions by the electricity supplier for exceeding the norms of reactive energy consumption, increased voltage drop in the network infrastructure, which complicates the operation of related equipment.

The phase voltage control principle is a source of nonlinear distortions of currents and voltages in the distribution network. The current consumed by the soft starter is characterized by a non-sinusoidal shape with a broadband harmonic spectrum. The highest amplitudes are characteristic of odd lower-order harmonics – 5th, 7th, 11th, 13th, which cause destabilization of the functioning of sensitive electronic systems (for example, programmable logic controllers, computing complexes), create thermal overload of neutral conductors, transformer equipment and electric motors, reducing their operational life, and can provoke resonant processes in networks with capacitor installations;

Active power quality assurance systems with various schemes are widely used in industry to compensate for the above-mentioned negative phenomena in real time. Active power filters are able to provide almost completely active nature of the load, affect high-frequency harmonic distortions of currents and voltages. This allows maintaining the power factor at 0.95–1.0 throughout the full start-up cycle and stable operation, reducing financial losses associated with reactive energy consumption, reducing active power losses and stabilizing voltage in the distribution network, improving the voltage shape for all connected consumers, and increasing the reliability of automation and control systems.

Modern STATCOM-class power quality assurance systems are able to perform rapid voltage regulation and compensate for supply voltage asymmetry.

Despite the need for initial capital investments, the implementation of active devices demonstrates a quick payback due to reduced electrical energy losses, the absence of penalties, more efficient utilization of existing infrastructure, minimizing downtime and extending the operational life of equipment.

The technical combination of soft starters based on TRN with active power quality management systems, in particular power filters, is a sound engineering and economically justified solution. The feasibility of using such an integrated approach is determined by three key aspects: reducing reactive power consumption, minimizing harmonic distortions of voltage and current, and ensuring increased resistance to short-term voltage drops.

Thus, the operation of soft starters with thyristor voltage regulators without using means to compensate for their impact on power quality in modern conditions is a technically risky and economically impractical strategy. The integration of active power quality assurance systems transforms such systems into full-fledged, energy-efficient and responsible components of a modern industrial power grid, ensuring a high power factor, a minimum level of harmonic distortion, and increased resistance to network disturbances.

3.4. Limitations and directions of research development

The practical significance of the obtained results is to determine the required range of reactive power compensation in the process of controlled start-up of an asynchronous electric drive taking into account the configuration of the distribution network. This will allow to increase the accuracy of determining the parameters of the power active filter intended for operation as part of a thyristor voltage regulator, to reduce capital costs for the production of a power active filter.

The limitation of the research is the absence of regression dependencies of the level of consumed reactive power and voltage drop at the distribution network node on the load power and start-up duration.

The prospects for further research are related to the choice of a rational scheme of a power active filter, the creation of systems for automatic stabilization of the level of consumed reactive power or the voltage level at the distribution network node.

4. Conclusions

1. The design of the enterprise's distribution network and the parameters of its equipment significantly affect the parameters of the equivalent circuit of the electric drive. This necessitates the creation of a detailed simulation model of the electric drive taking into account the equipment of the distribution network. A simulation model of the distribution network of a real sintering factory of a metallurgical enterprise with an asynchronous electric drive of the exhauster 9000-11-5 with a capacity of 3500 kW is considered. The implementation of a detailed simulation model of the exhauster electric drive in the scheme of the shop distribution network is performed in the MATLAB/Simulink environment using the Simscape Electrical library. Using simulation modeling of the direct start of the exhauster electric drive, it was established that the duration of the start-up process is about 12 s, which is almost 3 s longer than when starting from an ideal voltage source. The voltage drop in the distribution network node is about 9% of the nominal voltage ($\Delta U \approx 350$ V).

2. To study the quality of electricity in the shop distribution network during the controlled start of a powerful asynchronous electric drive, the developed simulation model of the distribution network was supplemented with a simulation model of a thyristor voltage regulator. An own algorithm for calculating the full power and its components under conditions of a complex non-sinusoidal form of voltages and currents was proposed. This algorithm is also implemented in the simulation model of the controlled start of an asynchronous electric drive.

According to the results of the simulation modeling of the controlled start, the following conclusions can be drawn. Despite the limitation of the starting current during the soft start process, the consumption of reactive power remains quite high, which leads to a fairly significant (up to 4%) voltage drop in the supply network. The soft start of the exhaust fan drive with a thyristor voltage regulator is accompanied by harmonic distortions of the mains voltage. In the considered configuration of the distribution network, the harmonic distortion factor is at the level of 2–2.5%, and in the critical slip region it reaches a value of 6%. The most influential are the harmonics of order 5 and 7, but in the critical slip region the higher harmonic of order 13 reaches a comparable value. The results can be explained from the point of view of the physics of electromagnetic transients in the induction motor, as well as from the point of view of how semiconductor voltage regulators work. The high current load during start-up occurs because at high slip the rotor resistance is still very low. Soft start with phase control limits this current, but makes the shape non-sinusoidal and shifts the harmonic components, hence the resulting effect: deterioration of the apparent power factor plus generation of higher harmonics in the network. Torque/voltage fluctuations are mainly caused by electromechanical dynamics of transients, especially when passing through the critical slip region.

3. The feasibility of using active power quality control devices as part of starters with thyristor voltage regulators is theoretically substantiated. Substantiation of the appropriate design of a power active filter was not considered within the scope of this work and is a direction of further research.

Theoretically obtained results complement the quantitative relationships between the initial parameters, network configuration and power quality indicators. In practice, this creates a basis for optimal design and selection of starters for powerful electric drives, taking into account their impact on the network, as well as for recalculation or refinement of calculations of compensating device parameters.

Conflict of interest

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

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Data availability

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.

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Authors' contributions

Oleksiy Gromovyy**:* Conceptualization, Formal analysis; ***Arailym Smail: Data curation, Formal analysis; ***Karshiga Smagulova:*** Funding acquisition, Investigation; ***Mirkomil Melikuziev**:* Resources, Software; ***Mila Baranovska:*** Supervision; ***Andrii Romanets***: Methodology, Project administration, Software, Data curation; ***Ihor Novitsky:*** Validation; ***Anna Humeniuk:*** Visualization; ***Ilya Kolysnychenko:*** Writing – original draft, Resources; ***Dmytro Bilukhin:*** Resources, Writing – review and editing.

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