Chapter

Prospects for Increasing the Dynamic Efficiency of Asynchronous Double-Feed Machines and Wind Power Generators Using Structural Methods and Solutions

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Abstract

The chapter proposes to consider the problems of control of asynchronous machines with dual power supply, as a nonlinear structure, the transfer functions of which depend on the frequency of the stator voltage and the relative slip. The authors cite the results of research confirming the high efficiency of control of asynchronous electric motors, using cross-dynamic connections on the developed torque or a signal close to it (active component of the motor stator current). The proposed correction operates in a wide range of changes in the rotation and sliding speeds of the asynchronous electric generator. This is especially important for wind turbines that need to remain efficient at different speeds. As a justification, the results of experiments, modeling and industrial application of control algorithms with positive torque coupling are presented. Research results suggest that such algorithms will improve the efficiency of wind power by 5–10%.

Keywords: asynchronous called double-feed machines (DFM), frequency regulation, dynamic positive feedbacks, active stator current, rotor current, signal spectrum, parrying of step and harmonic moments

1. Introduction

The squirrel cage induction motors (SCIM), widely used in industry and power engineering, are distinguished primarily by their high reliability and low cost. Asynchronous electric drive (AED) of mechanisms in which they are used, as a rule, do not require a significant range of speed and torque control, high control accuracy and fast transients. Even in drives with rather expensive frequency and voltage converters (FC), it is not easy to solve the problems of SCIM control. Research of control systems of such drives continues at the present time.

At the same time, in a number of units, wound rotor induction motors (WRIM) are widely used. The design of these motors allows connecting additional active resistances to the rotor and adjusting the ratio of active and reactive power. In this case, the stator and rotor currents, the rotation speed and the developed torque change at a constant rotation speed of the magnetic field. At the same time, the design of the engine becomes somewhat more complicated, and accordingly, its cost increases (slightly). It was this ability to regulate speed and torque that made WRIM the main electric motors in a number of mechanisms in the 60s and 70s before the widespread introduction of available FC. In a number of countries (for example, in Russia and the CIS), such drives are still used in hoisting and transport mechanisms. At the same time, the problems with the dynamics of the drive remain, in general, the same as for the SCIM.

The ability to adjust the WRIM operating mode from the rotor side not only in motor, but also in generator modes ensured the use of WRIM in the power industry, in those generating sets in which the rotation speed of driving machines cannot be sufficiently stable. At the same time, asynchronous machines with a phase rotor were called double-feed machines (DFM). Since the water flow rate in hydropower generators cannot be constant and it cannot be controlled by mechanical means with an accuracy of more than 1%, a voltage source is included in the rotor of the machine, which corrects the voltage parameters on the stator of the machine connected to the power grid.

In recent years, asynchronous dual-feed machines have become widely used in wind energy, which over the past few decades has emerged in a number of countries in a separate energy sector that successfully competes with traditional energy sources. DFM in wind turbines allow to generate electricity with the required parameters at different wind speeds, supplying energy directly to the network through the stator windings (**Figure 1**) [1].

At the same time, the problems with the regulation of the DFM, as an asynchronous electric machine, are fully manifested. They play a significant role in reducing the efficiency of wind turbines. A whole range of problems should be noted.

Problem analysis. The generally accepted mathematics for describing processes in AC electric machines plays a significant role. When describing the work of DFM [1, 2], vector equations and dependencies, traditional for AC machines, are used with a large number of assumptions and simplifications. One of the main ones is the neglect of the components of higher harmonics in the rotor and stator currents and voltages in the DFM. The DFM equations, like the equations describing all asynchronous and synchronous motors, do not take into account changes in the

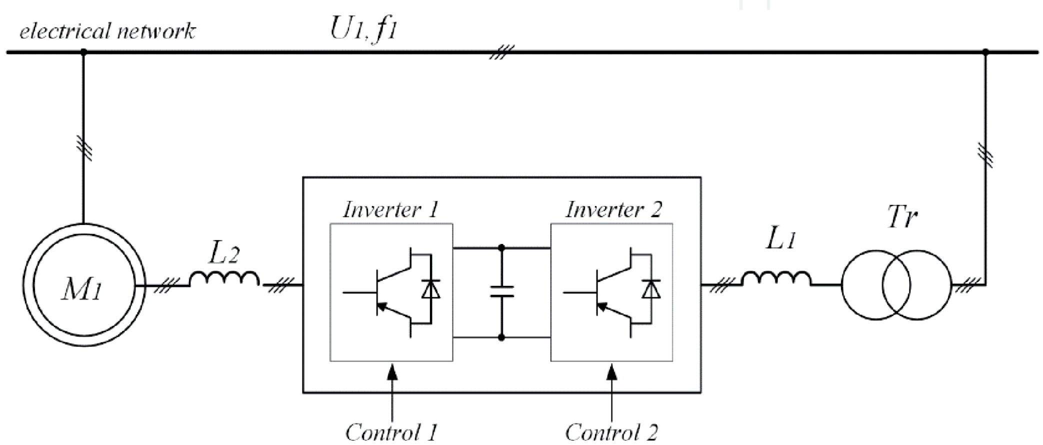


Figure 1.
Connection diagram DFM.

frequency of voltages and currents at all. Naturally, these vector equations take into account transient processes in a very simplified way [2]:

Consider an example of such a description [1]:

$$\begin{cases} U_1 = R_1 i_1 + \dfrac{d\Psi_1}{dt} + j\omega_k \Psi_1; \\ U_2 = R_2 i_2 + \dfrac{d\Psi_2}{dt} + j\left(\omega_k - p\omega\right)\Psi_2; \\ \Psi_1 = L_1 i_1 + L_m i_2; \\ \Psi_2 = L_2 i_2 + L_m i_1; \end{cases} \tag{1}$$

where U_1, U_2 – stator and rotor voltage vectors; Ψ_1, Ψ_2, i_1, i_2 – vectors of flux linkages of stator and rotor currents; R_1, L_1, R_2, L_2 – active resistances and inductance of stator and rotor; L_m – main inductance of the magnetizing circuit; ω_k – angular velocity of rotation of the coordinate system; ω – angular speed of rotation of the rotor; p – number of pole pairs of the machine.

Eq. (1) are obtained from the equations of an alternating current electric machine under the assumption that the processes of changing currents and voltages in the DFM are sinusoidal signals of constant frequency. If we assume the change in this frequency, which occurs when regulating the speed and torque of the DFM, the original equations become so complicated that it will be impossible to analyze them and select an effective correction based on them.

These methods of describing asynchronous electric drives with vector equations lead to a number of limitations in control devices. For example, an increase in the stator magnetic flux (ratio U\f) leads to a violation of stability and an increase in stator currents at low loads [3–6], therefore control algorithms in many inverters limit this parameter, reducing the possibility of accelerating transient processes.

Another problem is the dependence of the drive dynamics on the stator voltage frequency [7–10]. Vector equations describing asynchronous electric drives do not allow to reliably describe these processes and suggest effective correction.

Figure 2 shows the results of experiments with an asynchronous drive with vector control, closed by a speed signal with surges of a torque load. The processes of

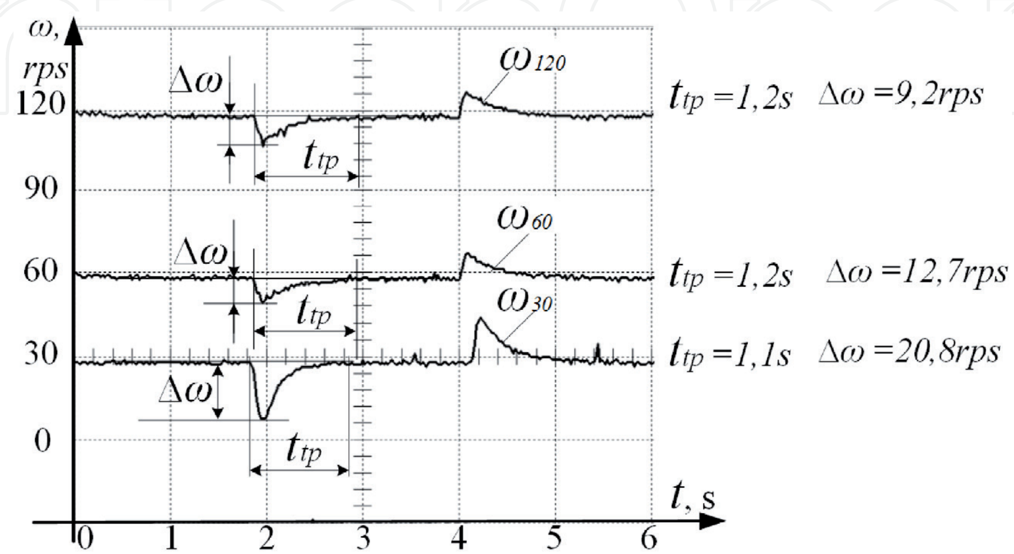


Figure 2.
Diagrams of the speed change when parrying a stepped torque at different speeds of rotation in a drive with vector control.

parrying a torque load are different at different speeds of rotation and frequencies of stator voltage and are strongly "tightened". At even higher speeds, the stability of the drive [7–9, 11, 12] is impaired.

It should be noted that the traditional means and methods of regulation of asynchronous electric drives with frequency control (PID speed or torque controllers) with vector control or direct torque control work very poorly precisely when parrying "step" or harmonic torque loads. This is shown in articles [7–10, 13].

In DFM wind turbines, the wind works exactly as a moment load. In this case, the wind parameters are not stationary and difficult to predict.

There are many works devoted to the study of the parameters of wind flows, one of the time dependences is shown in **Figure 3**. As a rule, several ranges of speed variation can be distinguished in the wind speed - slow and faster.

The frequency of rapid variations in wind speed is from to too high for its effective "tracking" by powerful and large-sized electric drives of wind turbines [14–17]. Electric generators and wind turbines in general have significant inertia – tens and hundreds of seconds due to their very large dimensions.

The control systems of these installations should work as follows. DFM, as a generator, must convert mechanical wind energy, determined by the average wind speed, into electrical energy. And, as an electric drive, it must correct and smooth out wind gusts so that they do not "distort" the frequency and amplitude of the stator voltage. To solve this problem in the DFM must be the inverter connected to the rotor circuit. It can adjust the frequency and amplitude of the stator voltage precisely. At the same time, a change in the voltage in the rotor has a complex effect on the DFM, causing "its" transient processes.

In DFM, most often, rather traditional algorithms for asynchronous electric drives are used to optimize stationary modes - depending on the wind speed, the structure of the drive changes - the torque or speed of the motor is controlled by loops with a PID controller. At the same time, during the change in the wind speed, the restoration of the parameters of the DFM operation mode - the torque, the speed of rotation and, accordingly, the frequency of the stator voltage - occurs rather slowly, and in order not to violate the compliance with the requirements of the parameters of the stator voltage – frequency and amplitude, most often,

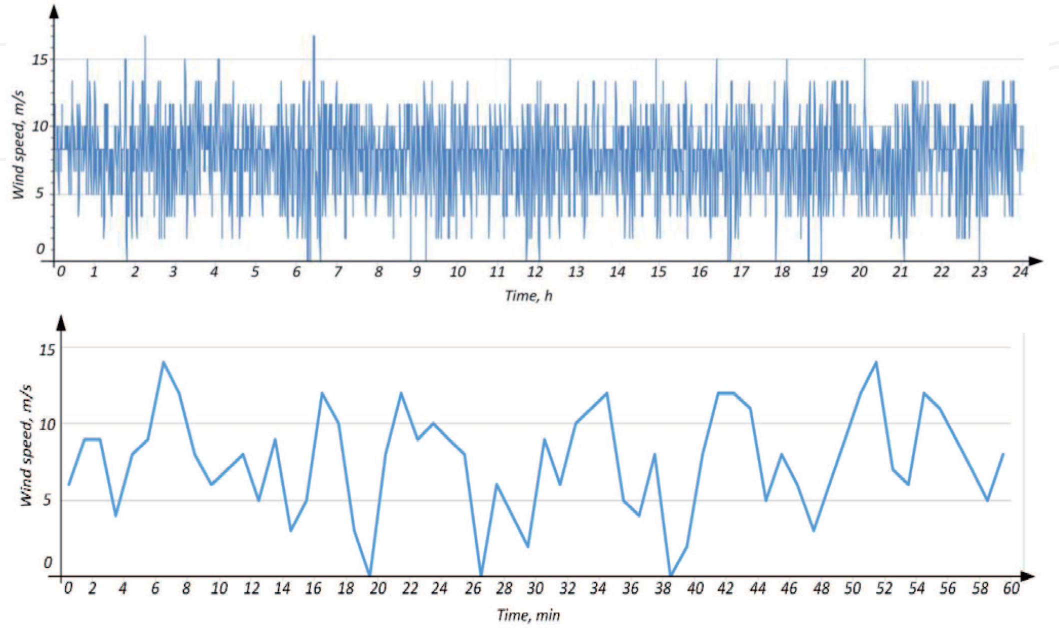


Figure 3.
Example of a graph of the change in wind speed.

energy transfer is blocked and the entire wind turbine is stopped. That is, the use of optimization methods is limited to modes of uniform power generation, i.e. they can be used only when the wind turbine is in a stationary state, with small and slow changes in the parameters of wind flows. In case of transient processes or in emergency situations, the methods are not applicable.

The reason that DFMs are disconnected from the grid during transient modes is the inability of the regulation system to track these changes in wind speed with minimal transients. The shutdown and protection devices receive considerable attention from developers and researchers. At the same time, the purpose of the protection devices is to preserve the operability of the equipment with “non-mode” parameters of the wind and power grid, and to reduce the time of inoperability of wind power units. But in all these devices, little attention is paid to the dynamics of installations in operating states. The modes and settings of the regulators remain standard, which means that they are quite ineffective in terms of dynamics. All this also reduces the efficiency of wind turbines to critically low values. At the same time, the “dynamic potential” of asynchronous electric drives is far from being exhausted and is not used in most drives because most often it is not required. But not in the case of wind turbines.

The authors carried out research on the dynamics of asynchronous electric drives with frequency control, which are of undoubted interest for wind power. The research consisted of the development of theoretical provisions, bench experiments, simulation and application of industrial units in electric drives.

2. Theoretical provisions

Vector equations were replaced by continuous ones in a certain area of the multidimensional space formed by variable coordinates of the electric drive - rotation speed and mechanical moment and independent functions - stator voltage frequency and relative slip. As a result, a nonlinear transfer function was obtained that connects the developed mechanical torque and absolute slip - the difference between the stator voltage frequency and the engine speed. The formula for this function includes, as variables, the frequency of the stator voltage and the relative slip. The formula can be called the nonlinear transfer function or the dynamic Kloss formula. In articles [18–26] the conclusion of the proposed nonlinear transfer function is given in sufficient detail, the result is as follows:

$$W(p) = \frac{2M_k\left(T_2' p + 1\right)S_k}{\omega_1\left[\left(1 + T_2' p\right)^2 S_k^2 + \beta^2\right]} \tag{2}$$

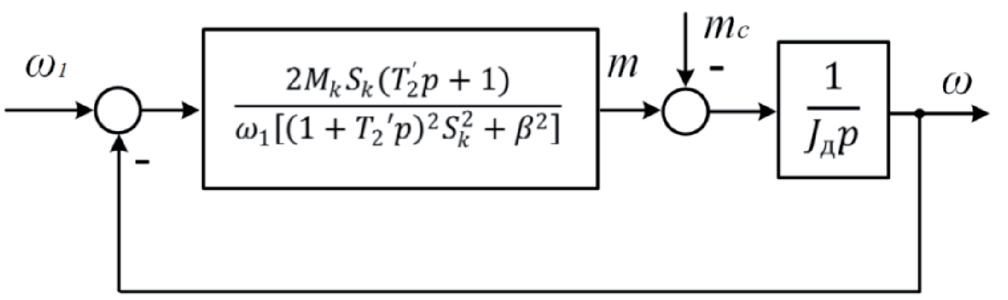


Figure 4.
Block diagram of the working section of the mechanical characteristics of an alternating current machine.

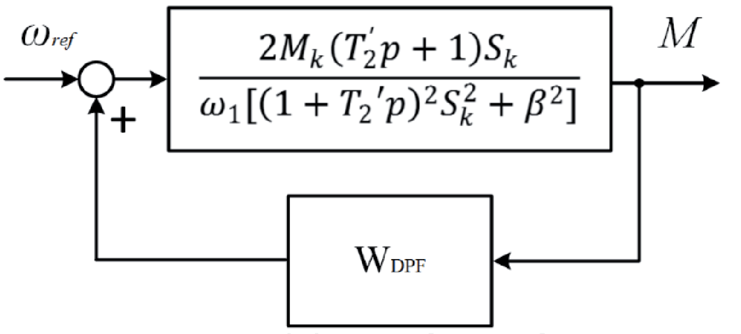


Figure 5.
Block diagram of the corrected electric drive.

where, ω_1 is the stator voltage frequency, β is the relative slip, depending on the drive load.

This transfer function corresponds to the block diagram shown in **Figure 4**.

In works [18–27] it is shown how it is possible to linearize the specified transfer function, that is, to exclude the dependence of the transfer function and the dynamics of the asynchronous drive on the frequency of the stator voltage and slip by positive feedback on the developed torque. The structural diagram will take the form (**Figure 5**).

The transfer function of the correcting link, which is necessary in positive feedback to maintain the stability of the drive, is as follows:

$$W_{DPF} = \frac{\omega_1 \beta^2}{2M_k S_k \left(T_2' p + 1\right)} \tag{3}$$

Equivalent transfer function of the drive with this connection will take the form:

$$W_{eqv} = \frac{2M_k S_k \left(T_2' p + 1\right)}{\omega_1 \left[\left(1 + T_2' p\right)^2 S_k^2\right]} = \frac{2M_k}{\omega_1 S_k \left(1 + T_2' p\right)} \tag{4}$$

The resulting transfer function of an asynchronous electric motor with parameters depending on the frequency of the stator voltage and slip is an "incorrect" expression from the point of view of the exact mathematics of functional transformations (Laplace transforms). But Eqs. (2) and (3) can describe the dynamics of transient processes with small frequency changes and slip (which change little the value of W (p) with significantly smaller errors than vector equations, which are accurate not only at a constant frequency, but also with the mandatory sinusoidality of currents and voltages in the stator and rotor of an induction motor [11, 15, 23–25, 28–30].

The method using nonlinear transfer functions turns out to be more accurate than the generally accepted apparatus of vector equations. Especially important for the DFM wind turbine is the fact that the efficiency of the choice of correction is also significantly higher for the processes of parrying moment disturbances in asynchronous electric drives with frequency control [21, 22, 27, 28, 31–33].

Thus, the proposed positive dynamic connection by the torque of the engine or its analogue significantly reduces the time of the transient parrying processes and their maximum values. Experiments investigating the response of the drive to load surges with various methods of WRIM control have fully confirmed this.

This made it possible to formulate a hypothesis that the identification of an induction motor with a frequency converter by a nonlinear transfer function is more accurate than vector equations, which is confirmed by the choice of a more effective correction selected for this transfer function.

It should be noted that experiments with parrying the moment disturbance at a constant frequency of the stator voltage with minimal transients in the speed of rotation of the engine and in the torque is the most desirable process for the DFM of wind turbines.

In this case, the corrected drive will ensure the “bringing” of all variable coordinates of the DFM to the required “zone, where the rotor frequency converter will equalize the frequency of the stator voltage to the specified value with high accuracy.

In asynchronous electric drives using mass-produced frequency converters, it is quite problematic to introduce a positive torque connection. As experiments have shown [8–10, 18–27], it can be replaced by a connection according to the active component of the stator current, which is measured by almost all known frequency converters widely used in industry.

In powerful and not cheap drives of wind power systems, it is advisable to install sensors for direct measurement of the mechanical moment and speed sensors, and magnetic flux sensors in the DFM. In this case, the complexity and uniqueness of each high-power wind turbine allows the application of solutions with a high cost, but at the same time with high efficiency.

As mentioned above, analytical expressions describing asynchronous electric drives have significant errors. Therefore, decisive importance in assessing the correctness and effectiveness should be given to experimental research.

3. Bench experiments

The test bench (**Figure 6**), On which the research was carried out, contains - a load asynchronous squirrel-cage motor (M1) and a working electric motor with a phase rotor (M2) operating on one shaft, frequency converters (FC1, FC2) that control motors, rotor current sensors of the working electric motor, and a common shaft speed sensor (BR1) and a periodic reference signal generator (SG1).

The order of experiments is formulated according to the transfer function of the electric drive (2)-(4).

The signal supplied to the input of the frequency converter U2 of the working WRIM drives the drive to a certain speed of rotation (and the corresponding frequency of the stator voltage). This determines the parameters of the transfer function, depending on the frequency of the stator voltage.

The signal generator SG sends a periodic signal of a certain frequency to the input of the frequency converter U1 of the load SCIM, which creates a load torque with an amplitude of 10% of the nominal value, which determines the range of variation of the transfer function parameter, which depends on slip – formula (2). The same input receives a step signal at the level of 100% of the nominal mechanical torque.

The purpose of the experiment is to provide evidence of the effectiveness of the drive control method. The control system of the drive must ensure maximum parrying of any moment disturbance, that is, the better the drive maintains the rotation speed (the less it deviates from the set speed), the more efficient its control.

Various operating modes of electric drives were investigated.

For studies of the DFM of wind power plants, the reactions of control systems to moment loads are of greatest interest.

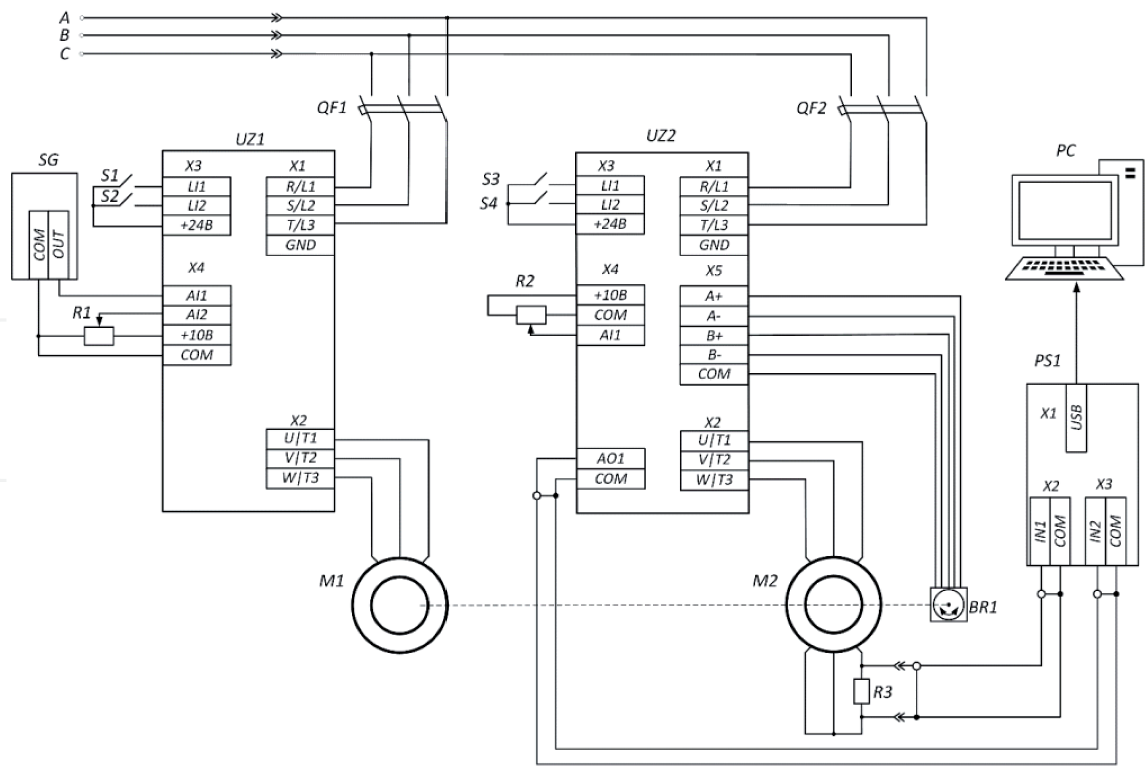


Figure 6.
Electrical circuit of the experimental stand.

Figure 7 shows the diagrams of changes in the speed of rotation of the engine with a “step” load with various control methods - open scalar control, vector control with speed feedback, and in a drive with torque (current) coupling. Transient time and maximum speed deviation for stepped load torque – minimum in an electric drive with DPF.

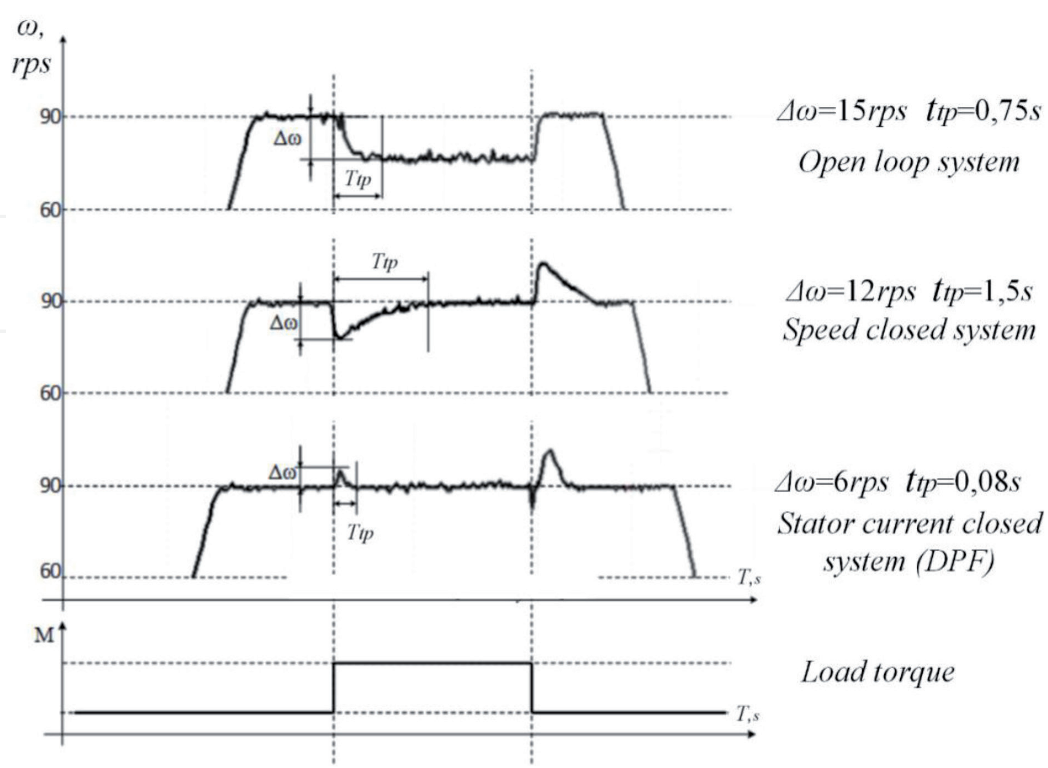


Figure 7.
Drive response to “step” load surge

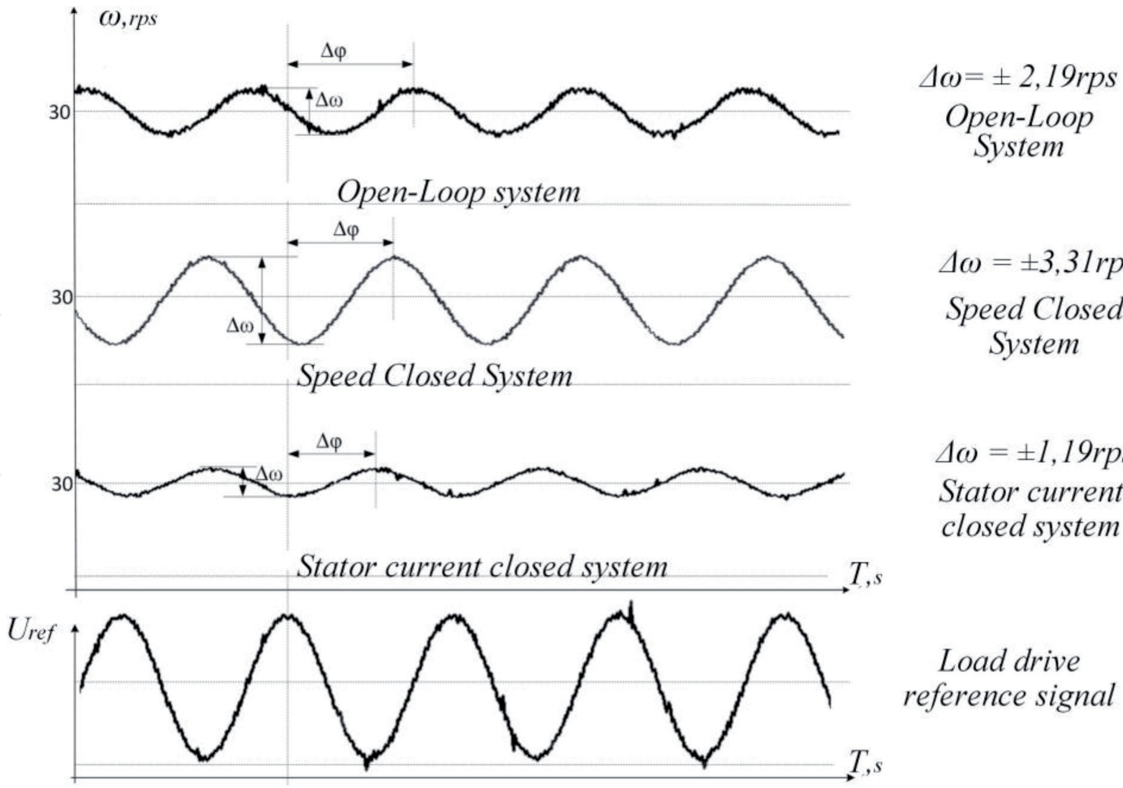


Figure 8.
Drive response to harmonically varying load torque.

In **Figure 8** diagrams obtained in the course of experiments with variable load - harmonic change in torque with a frequency of 1 Hz, — in the example, the amplitude of change is 10% of the nominal torque value.

The amplitude of deviations from the set speed for a periodic disturbing torque with a frequency of 1 Hz in an electric drive with DPF is also the smallest.

Advantages of a drive with positive torque coupling (or its close analogue - active stator current) are obvious.

4. Analysis of the efficiency of asynchronous drives in the rotor current spectrum

In a number of modes, according to the speed diagrams, it is rather difficult to assess the degree of advantage of this or that control method for asynchronous electric drives.

A technique for assessing the dynamics of the drive by the frequency of the rotor current is proposed and developed, which is of undoubted interest for DFM. Experiments have shown that this estimate is much more convincing than the analysis of velocity diagrams.

Since the frequency of the rotor current is precisely determined by the slip in the motor, the rotor current spectra characterize the control efficiency of the drive. This technique is discussed in detail in [18–21, 23–27, 34].

Figures 9–11 shows diagrams and spectra of the rotor currents with load surges with different control methods: DPF drive (**Figure 9**), open-loop scalar drive (**Figure 10**), closed loop scalar drive (**Figure 11**). Particular attention should be paid to the nature of the stator current when using a dynamic positive connection for the motor torque (for the active stator current).

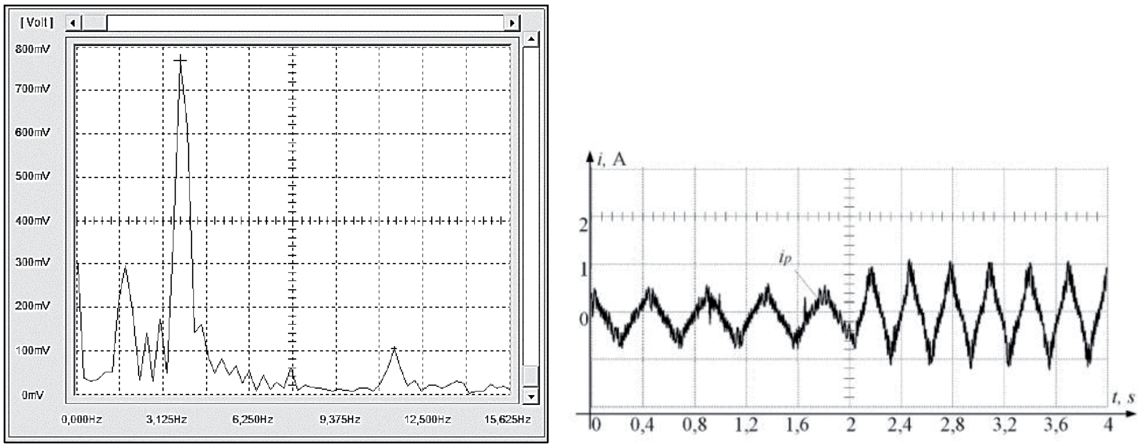


Figure 9.
Diagram and spectrum of the rotor current for scalar control with positive feedback.

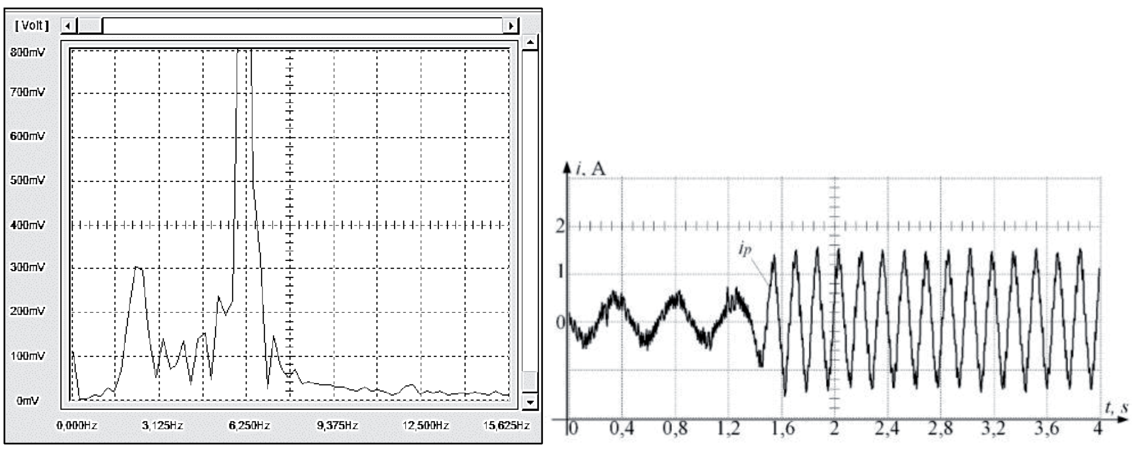


Figure 10.
Diagram and spectrum of the rotor current with vector control.

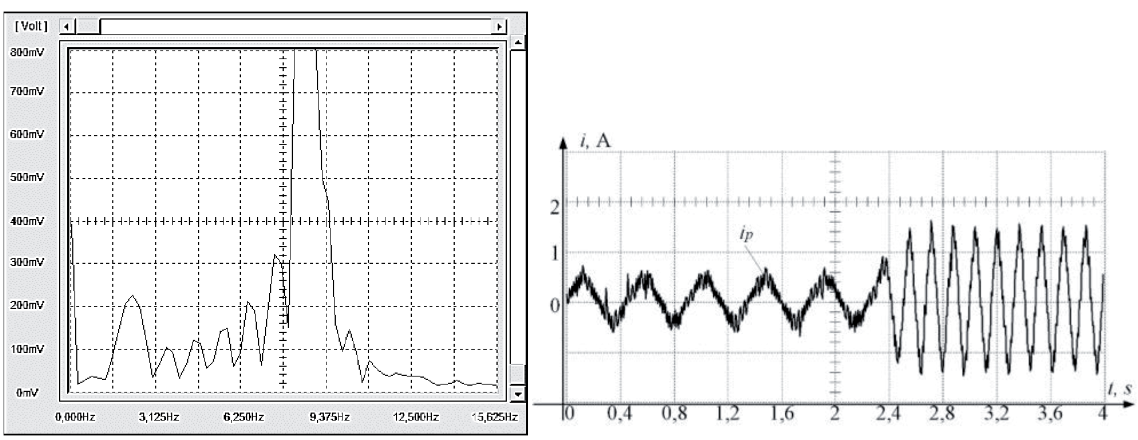


Figure 11.
Diagram and spectrum of the rotor current for scalar control.

Experiments with load surges have unambiguously shown a significant advantage of this scheme.

Basic frequencies of the rotor current.

- no load –1,7 Hz in an asynchronous drive with scalar control,
- 2,1 Hz in an asynchronous drive with a vector control and.

- −1,7 Hz in an asynchronous drive with a positive torque coupling.
- both with load- 4,75 Hz in an asynchronous drive with scalar control,
- 8,75 Hz in an asynchronous drive with a vector control and.
- −3,5 Hz in an asynchronous drive with a positive torque coupling.

That is, an electric drive with a dynamic positive connection in terms of the torque developed by the drive (or an analogue of this signal - the active component of the stator current) requires significantly less slip to create the required torque than in drives with scalar or vector, speed-closed controls. (Position P1).

Detailed drive experiments with this feedback have shown the nature of this efficiency. Since the transfer function (2) depends on the frequency of the stator voltage, the experiments were carried out at several different speeds of rotation of the engine and, accordingly, these frequencies.

The experiments were carried out at five operating speeds (31,42 rps, 62,83 rps, 94,25 rps, 125,67 rps, 157,08 rps) which corresponds to the frequencies of the stator voltage - 10 Hz, 20 Hz, 30 Hz, 40 Hz, 50 Hz. Diagrams of processes in speed, rotor currents and their spectra are shown in **Figures 12–14**. In all cases, under load, rotor current distortions and the third harmonic are observed, compared with the main one in the rotor current spectra.

It is known from the theory of automatic control that odd harmonics in periodic signals of a closed automatic control system (ACS) arise in the presence of symmetric static nonlinearities. In AED, such a static nonlinearity is the magnetization curve of the stator and rotor. This nonlinearity is characterized by saturation regions in which an increase in the magnetic field strength proportional to the current does not lead to a significant increase in magnetic induction.

This testifies to the saturation of the magnetic structure of the motor, which occurs only under load and ensures high efficiency of torque generation under load with a smaller mismatch between the synchronous speed and the rotor speed. It can

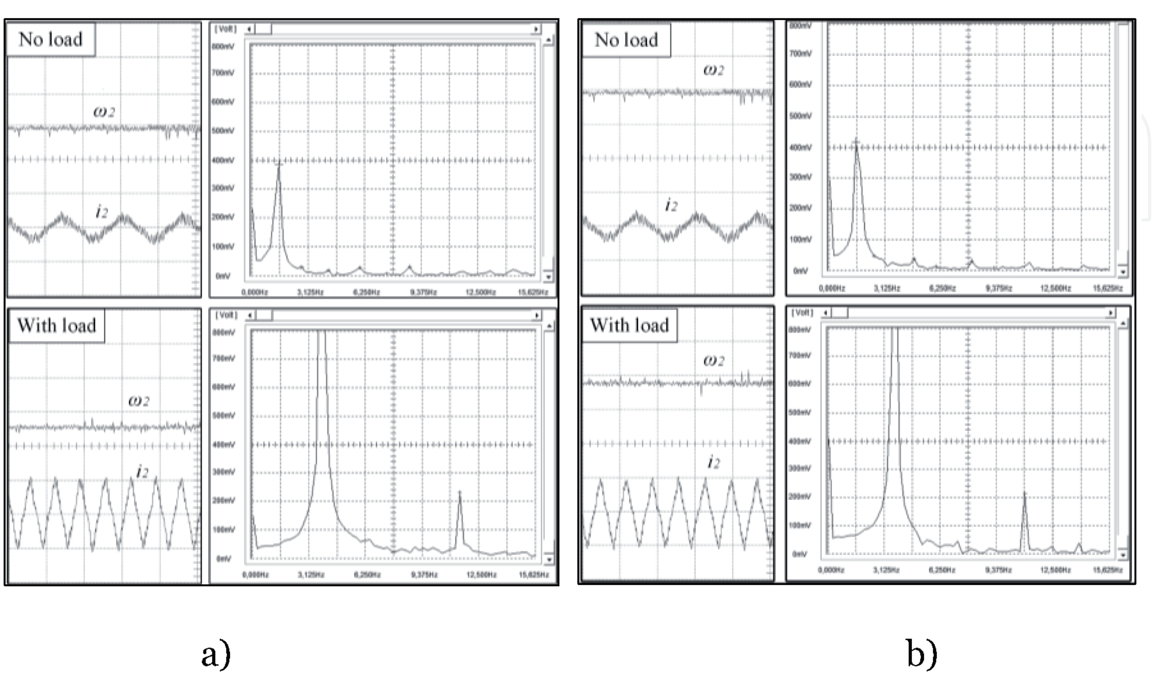
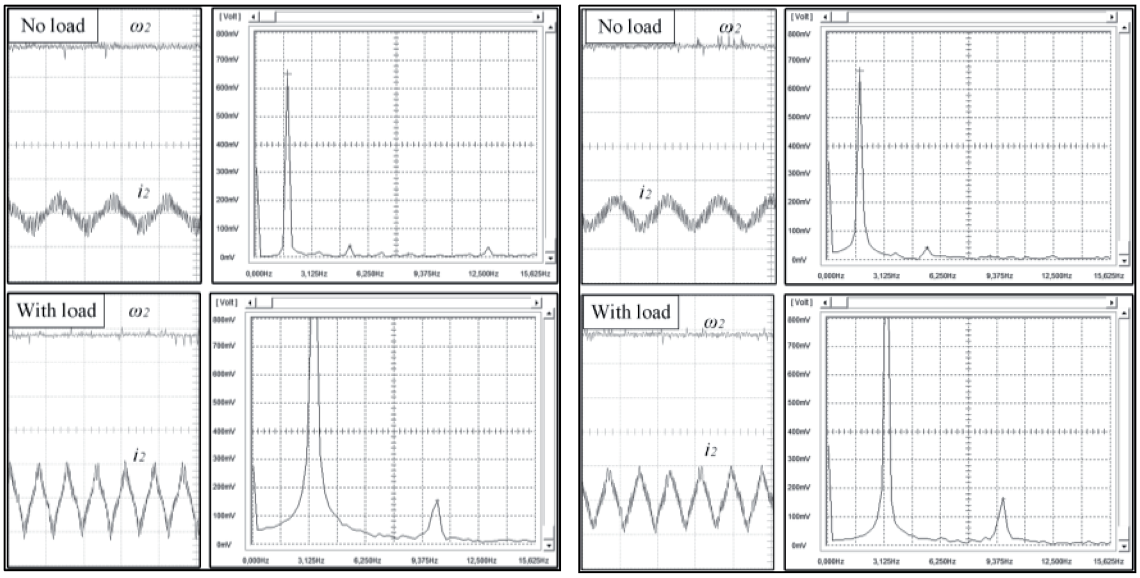


Figure 12.
The frequency of the stator voltage is 10 Hz (a) and 20 Hz (b).



a) b)

Figure 13.
The frequency of the stator voltage is 30 Hz (a) and 40 Hz (b).

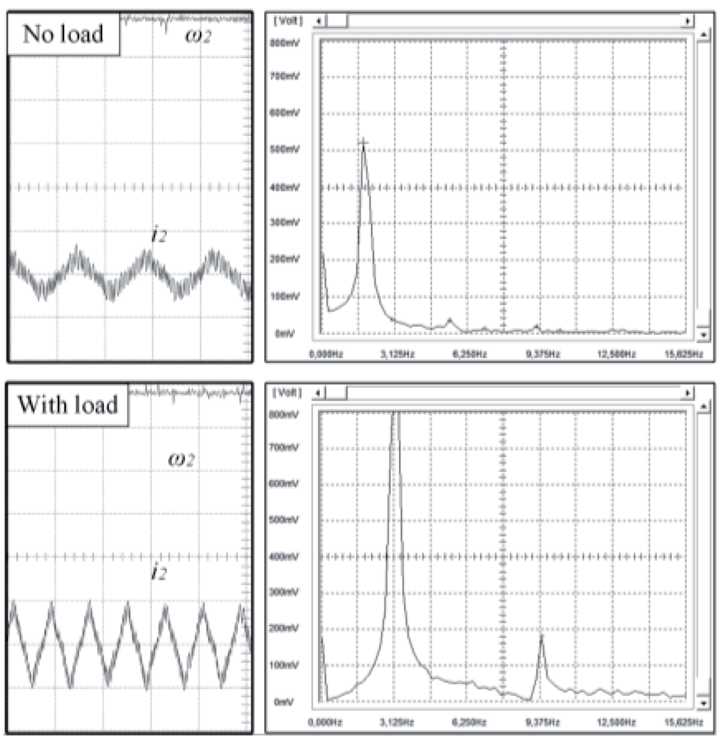


Figure 14.
The frequency of the stator voltage is 50 Hz.

be assumed that sections 1 (**Figure 15**) of the rotor current, characterized by rapid rise and fall, correspond to precisely these sections of the saturation.

With changes in load, the frequencies of the 1st and 3rd harmonics also changed, but the ratio of frequencies did not practically change. The distribution of frequencies and amplitudes of the rotor current depending on different frequencies of the supply voltage is presented in **Table 1**.

Experiments have shown two very important results of a positive torque relationship.

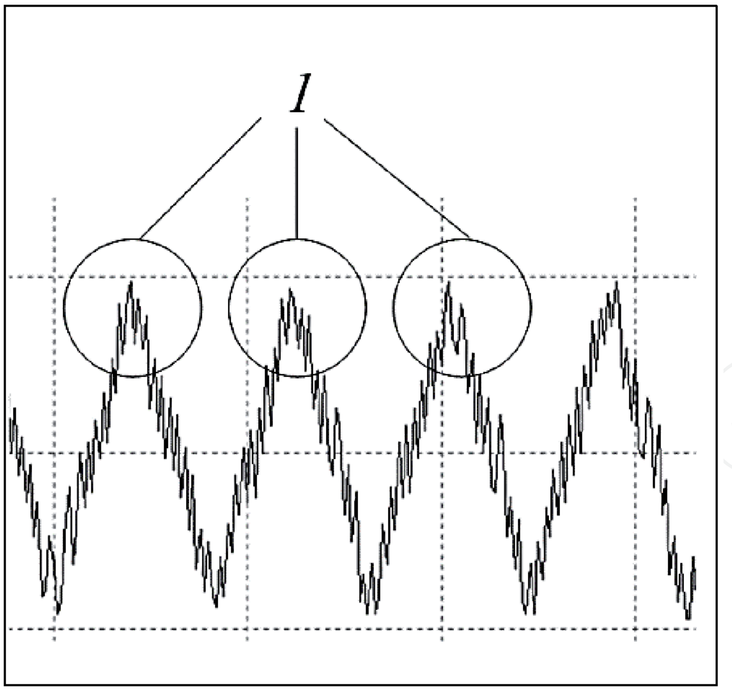


Figure 15.
Saturation sections characteristic.

ω_1, Hz	No load				With load			
	1st harm.		3rd harm.		1st harm.		3rd harm	
	f, Hz	*A*, V	*f*, Hz	*A*, V	*f*, Hz	*A*, V	*f*, Hz	*A*, V
10	1,5	0,39	4,25	0,019	3,75	1,24	11,5	0,23
20	1,5	0,42	4,75	0,037	3,75	1,32	11	0,21
30	1,75	0,65	5,25	0,039	3,5	1,0	10,25	0,15
40	1,75	0,66	5,5	0,042	3,25	1,35	9,75	0,16
50	1,75	0,52	5.5	0,036	3.25	0,96	9,5	0,18

Table 1.
*Numerical values of the frequencies and amplitudes of the prevailing harmonics of rotor currents in experiments to parry the load at different speeds of rotation (**Figures 12–14**).*

1. These experiments show that the proposed corrections force the magnetic flux under load - that is, they make it possible to obtain the maximum stator magnetic flux - the maximum possible drive efficiency and at the same time the drive maintains the stability of the processes in all modes.

2. According to the frequency of the rotor current without load and under load, it follows that at all speeds of rotation, the parrying of the load occurs at the same absolute slip - 3 Hz, i.e. an initially non-linear asynchronous electric drive is linearized by this connection more accurately than by vector control with a PID speed controller (**Figure 11**).

In general, the experiments carried out with the stand shown in **Figure 6** showed that an electric drive with a torque correction (or an active component of the stator current) has advantages in the dynamics of almost all possible modes - parrying load surges – stepwise and periodic.

5. Modeling

Simulations have also confirmed the effectiveness of the dynamics of corrective link actuators. So in the model (**Figure 16**) with load surges, the parrying efficiency in schemes with DPF is much higher. This is proved by both the processes in speed (**Figures 17–19(a)**) and the rotor current spectra (**Figures 17–19(c)** and **Table 2**).

Figures 17–19 shows diagrams of simulated drive acceleration processes from zero to speed corresponding to the frequencies of the stator voltage 10, 20, 30, 40, 50 Hz. Load surges are modeled at steady-state speeds. The diagrams of the speed (diagram a), of the mechanical torque, developed by the motor (diagram b) and the rotor current (diagram c) are displayed. It is obvious that in all modes the frequency of the rotor current in the drive model closed in speed (**Figure 17**) is significantly higher than in a drive with stator current feedback (**Figure 19**).

The values of the fundamental frequencies of the rotor current in the models of the electric drive with different control algorithms is presented in **Table 2**.

In these diagrams, the processes in the speeds of rotation do not differ significantly, but the processes in the rotor currents have significantly different frequencies, which shows the high efficiency of the proposed method for evaluating the

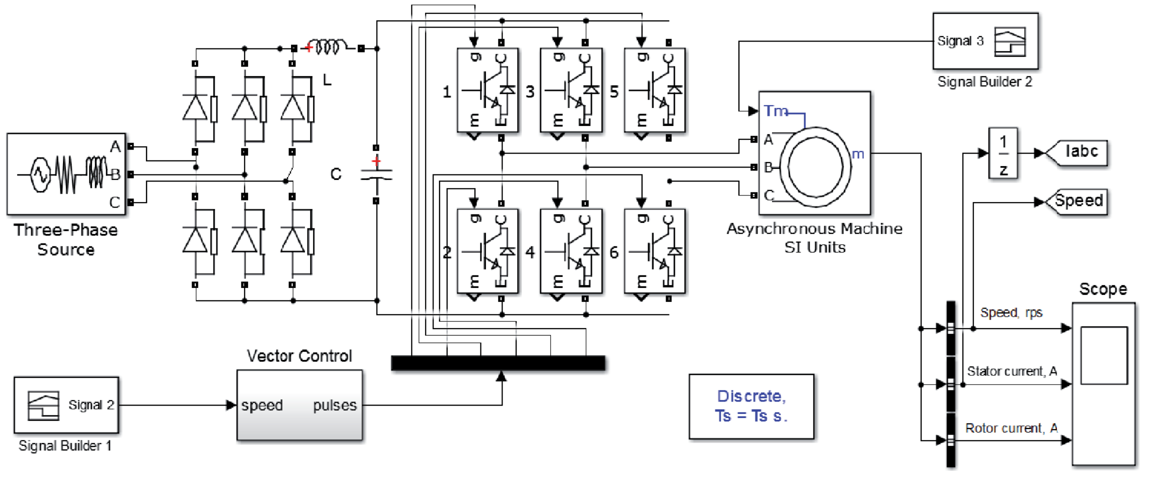


Figure 16.
Model of an asynchronous electric drive with vector control in Matlab Simulink.

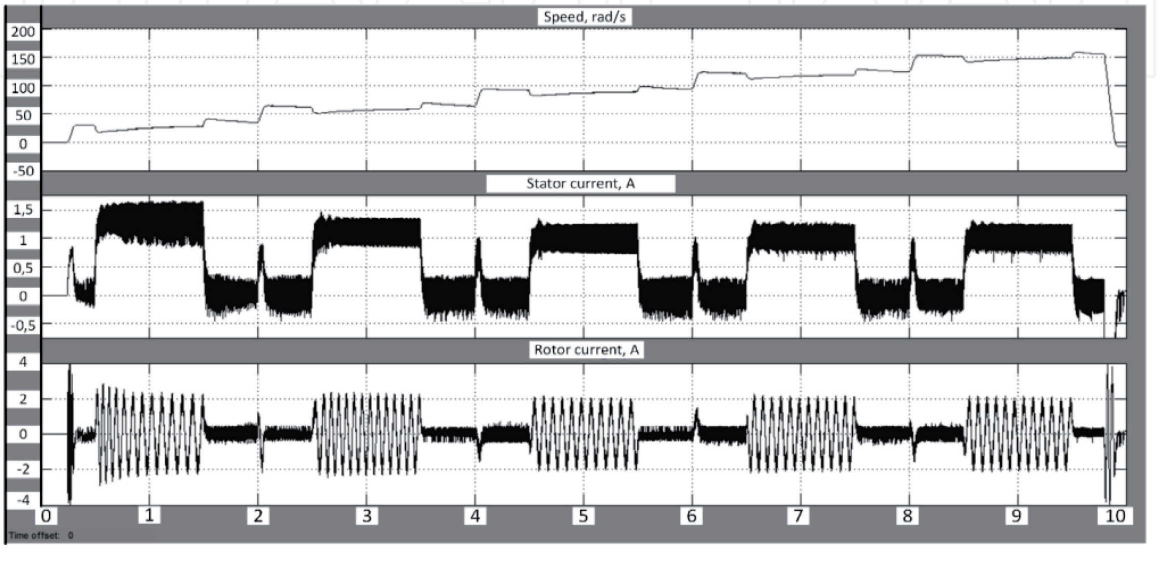


Figure 17.
Processes in a vector control drive model.

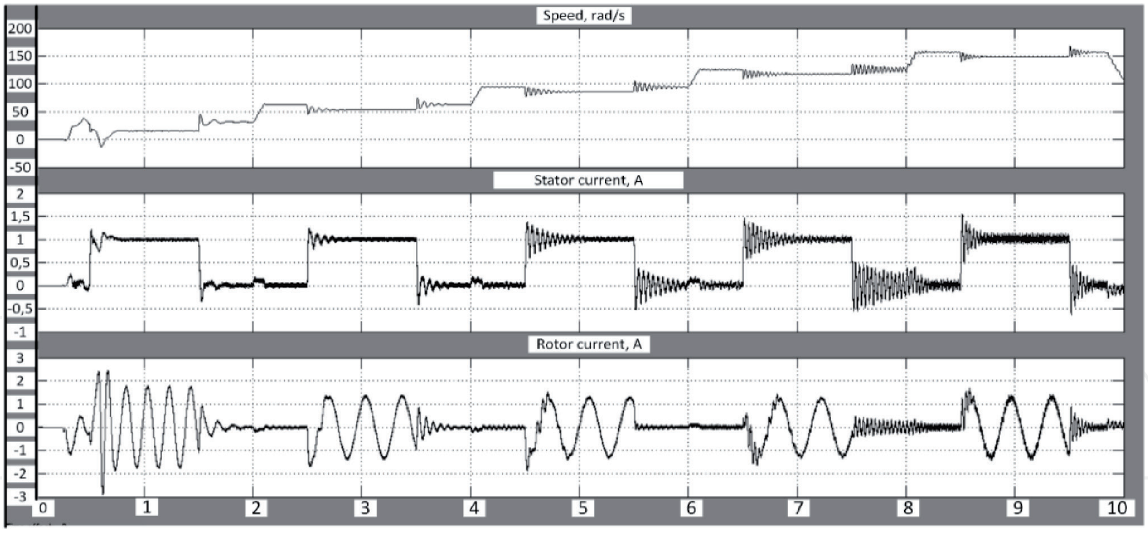


Figure 18.
Processes in a scalar drive model.

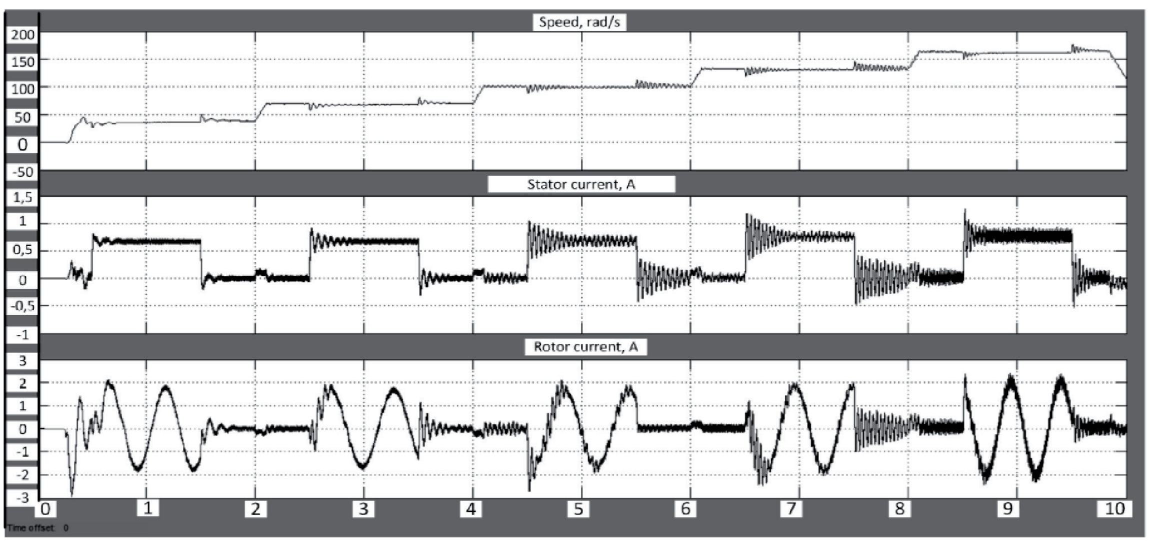


Figure 19.
Processes in the drive model with torque feedback (active stator current).

Control algorithm	Fundamental frequency, Hz				
	10	**20**	**30**	**40**	**50**
SC	5,12	2,98	2,66	2,56	2,66
SVC	10,64	12,81	10,62	11,63	11,63
SC with DPF	1,90	1,71	1,71	1,75	2,06

Table 2.
The fundamental frequencies of the rotor currents of the processes in the model shown in **Figures 17–19**.

method of controlling asynchronous electric machines by rotor currents. It should be expected that the method will be useful in milking machines of wind power plants.

6. Implementation in production mechanisms

The correction was introduced into the electric drives of the transport line, which were experiencing moment loads. According to the conditions of the technology, transient processes during the "capture" of the transported workpieces had to be minimized. At the same time, it was important to leave asynchronous drives of mechanisms, without transferring these mechanisms to expensive precision drives. Also, several control methods were tested, according to transient processes, shown in **Figures 20–22**. A clear advantage in the quality of working out disturbances - behind a drive with torque coupling (active component of the stator current).

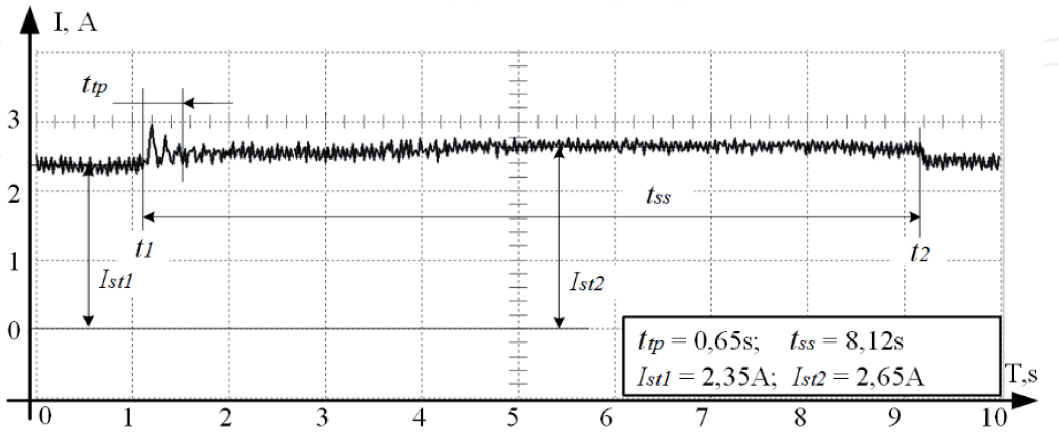


Figure 20.
Scalar controlled electric drive (SC).

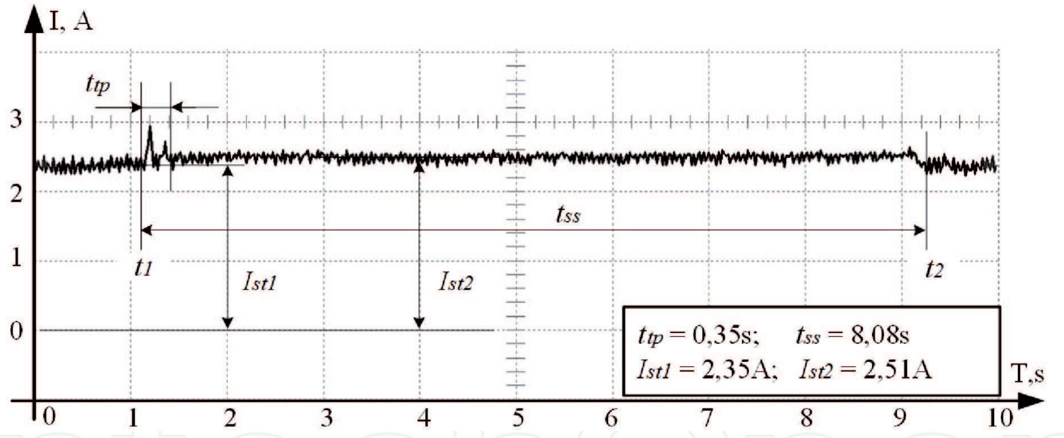


Figure 21.
Vector controlled electric drive (SVC).

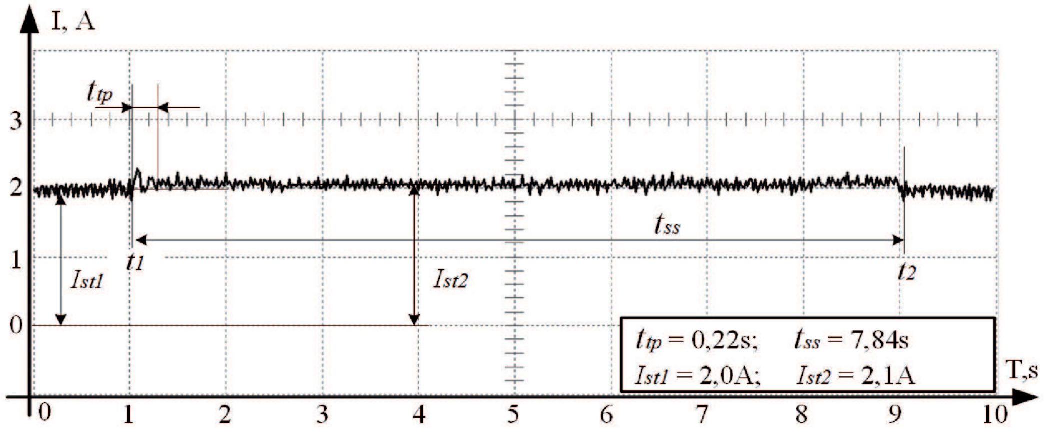


Figure 22.
Stator current feedback electric drive (DPF).

Under production conditions, it was possible to achieve a significant reduction in currents in all modes and times of the transient process.

7. The discussion of the results

According to the simplified vector equations of the DFM during transient processes in the drive, it is quite simple to correct the frequency of the stator voltage by changes in the voltage supplied to the DFM rotor within small limits. As follows from the vector equations, it is sufficient to take into account changes in the rotation speed of the DFM. However, in reality, a wind power plant is a multi-connected structure with complex mutually influencing transient processes that are caused by dynamic gusts of wind and transients in the wind turbines themselves. Vector equations that greatly simplify the description of these complexes do not allow obtaining an effective control structure in transient processes.

The identification of processes in asynchronous electric motors with a wound rotor by a nonlinear transfer function proposed in previous studies describes the processes in SCIM, WRIM and DFM much more accurately and efficiently.

Multidimensional transfer functions will make it possible to describe transient processes in such complex control systems as DFM or induction motors with a wound rotor and effective methods of their correction.

Numerous experiments have shown that cross-connections compensate for the influence of these factors - the influence of variable loads, different frequencies of stator voltage (in this case, it is invariable) is much more effective than other known control methods.

In addition to transient processes, transfer functions will make it possible to describe reactions to variable disturbing factors - periodic reference signals and moment disturbances are described in the works, and in this case, these are the effects of wind and regulation from the rotor.

The dynamic drive will fend off gusts of wind and keep the rotor speed in the range without significant dips, and the stator frequency loop will perform precise control as now. The network mismatch time will decrease and the wind utilization rate will increase. Thus, the DPF correction improves the overloading capacity of the asynchronous machine, and with a dynamic load this improvement is more active than with a static load, which makes the application of this solution in TIR even more effective.

8. Conclusion

Experiments and simulations have shown that in a system with DFM, cross-links in torque and speed also linearize the DFM electric drive system, as in asynchronous electric drives with moment disturbances, providing minimal transient processes that do not interfere with the operation of the system when the wind changes. It should be expected that an asynchronous electric drive with linearizing couplings, effectively working with moment disturbances, will also be effective in wind turbines.

Thus, it can be assumed that the correction has significant prospects when it is used in electric drives based on DFM in wind turbines.

Thus, the advantage of the method of controlling asynchronous electric motors with dynamic torque coupling, confirmed in all experiments and simulations, suggests that for machines with double power supply, a similar algorithm for controlling a frequency converter from the rotor side of the machine will improve their dynamic characteristics and the final efficiency by 5–10% with minimal capital investment.

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References

[1] Lyapin Anatoly Sergeevich. "Structural model, model study of the dynamics of an electric drive with a double-feed machine and direct torque control" Scientific and Technical Bulletin of Information Technologies, Mechanics and Optics, no. 4 (80), 2012, pp. 60-64.

[2] Lyapin A.S. Model study of the double fed machine with current control. Scientific and Technical Journal of Information Technologies, Mechanics and Optics, 2016, vol. 16, no. 4, pp. 731-737. doi: 10.17586/2226-1494-2016-16-4-731-737

[3] Pat. No. 2336624 Russian Federation, IPC H02P 27/06. Direct Motor Speed Controller / V.L. Kodkin, E.R. Khaybakov. - No. 2006106477/09; Claimed. 02.03.2006; Publ. 02.03.2006, Bul. № 29. – 11p.

[4] Malcher, M.A. Problems of introduction of frequency regulation in the mining industry / M.A. Malcher, A.S. Anikin // Mining equipment and electromechanics. - 2011. - №4.

[5] PROBLEMS OF IMPLEMENTATION OF FREQUENCY CONTROL IN MINING INDUSTRY / V.L. Kodkin, A.S. Anikin, M.A. Malcher // Bulletin of the South Ural State University Series: Energy. - Vol. 18. - No.37.–2012.– P.67-71.

[6] FREQUENCY CONTROL OF ASYNCHRONOUS ELECTRIC DRIVES IN TRANSPORT Kodkin V.L., Anikin A.S. In the collection: 2015 International Siberian Conference on Control and Communications, SIBCON 2015 - Proceedings 2015. C. 7146978. WOS:000380571600016 DOI : 10.1109/SIBCON.2015.7146978

[7] EFFECTIVE FREQUENCY CONTROL FOR INDUCTION ELECTRIC DRIVES UNDER OVERLOADING Kodkin V.L., Anikin A.S., Shmarin Y.A. Russian Electrical Engineering. 2014. 85. No. 10. P. 641-644. DOI : 10.3103/S1068371214100101

[8] Experimental research of asynchronous electric drive with positive dynamic feedback on stator current Kodkin V.L., Anikin A.S., Baldenkov A.A. 2017 International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM) - Proceedings 2017 DOI: 10.1109/ICIEAM.2017.8076179

[9] Dynamic Load Disturbance Correction for Alternative Current Electric Drives V.L. Kodkin, A.S. Anikin, Y.A. Shmarin 2nd International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM); South Ural State University Chelyabinsk - Proceedings 2016 DOI: 10.1109/SIBCON.2015.7146978

[10] Spectral Analysis of Rotor Currents in Frequency-controlled Electric Drives Kodkin V.L., Anikin A.S., Baldenkov A.A. 2nd International Conference on Automation, Mechanical and Electrical Engineering (AMEE 2017) - Proceedings 2017 DOI: doi:10.2991/amee-17.2017.26

[11] Popov, V. M. [Hyperstability of Dynamic Systems], Springer-Verlag, Berlin (1973)

[12] Kodkin. V.L. Methods of optimizing the speed and accuracy of optical complex guidance systems based on equivalence of automatic control system domain of attraction and unconditional stability of their equivalent circuits/ V.L. Kodkin// Proceedings of SPIE - The International Society for Optical Engineering. – 2016

[13] Pat. No. 2412526 Russian Federation, IPC H02P 23/00. The device for frequency control of

an asynchronous electric drive / V.L. Kodkin, A.S. Anikin. - No. 2010108563/07; Claimed. 09/03/2010; Publ. 20.02.2011, Bul. № 5-12 p.

[14] Pat. №155 351 Russian Federation, IPC F03D 7/04, F03D 1/00, F03D 3/00. Adaptive combined device for regulating the rotor speed of the wind power plant / E.V. Solomin, A.S. Anikin., E.A. Sirotkin, E.E. Solomin, A.A. Sirotkin, S.V. Kozlov - No. 2014154564/06; Claimed. 12/31/2014; Publ. 10/10/2015 Bul. № 28-5 p.

[15] Vorob'ev, N.N. Theory of series. //4 ed., Revised. And additional. - Moscow: Science, 1979, – 408 p.

[16] Meshcheryakov VN, and Bezdenezhnykh DV. "Flux linkage observer for a double feed machine controlled by stator and rotor circuits" Vestnik Voronezh State Technical University, vol. 6, no. 11, 2010, pp. 170-173.

[17] Mazalov Andrey Andreevich. "Adaptive wind turbine with a double-feed AC machine" Izvestia of the Southern Federal University. Engineering Sciences, vol. 126, no. 1, 2012, pp. 26-33.

[18] Kodkin, V.L The dynamics identification of asynchronous electric drives via frequency response / V.L. Kodkin, A.S. Anikin, A.A. Baldenkov //International Journal of Power Electronics and Drive Systems.–2019.– Vol. 10 No. 1.– P.66-73

[19] Kodkin, V. Families of Frequency Characteristics, as a Basis for the Identification of Asynchronous Electric Drives / V. Kodkin, A. Anikin, A. Baldenkov //2018 International Russian Automation Conference (RusAutoCon).–2018

[20] Usoltsev, A.A. Vector control of asynchronous motors. Tutorial. - Spb .: ITMO, 2002-120 p. http://servomotors.ru/documentation/frequency_control_of_asynchronous_motors/chastupr.pdf

[21] Kodkin, V.L Analysis of Stability of Electric Drives as Non-linear Systems According to Popov Criterion Adjusted to Amplitude and Phase Frequency Characteristics of Its Elements, A.S. Anikin, A.A. Baldenkov //2nd International Conference on Applied Mathematics, Simulation and Modelling (AMSM 2017) - Proceedings 2017 P.7-14, DOI: 10.12783/dtetr/amsm2017/14810

[22] Kodkin, V.L The analysis of the quality of the frequency control of induction motor carried out on the basis of the processes in the rotor circuit / V.L. Kodkin, A.S. Anikin, A.A. Baldenkov //Journal of Physics: Conference Series.–2018.–Vol. 944(1)

[23] Kodkin, V. Stabilization of the stator and rotor flux linkage of the induction motor in the asynchronous electric drives with frequency regulation / V. Kodkin, A. Anikin, A. Baldenkov //International Journal of Power Electronics and Drive Systems.– 2020.– Vol. 11 No. 1.– P.213-219 DOI: http://doi.org/10.11591/ijpeds.v11.i1.pp213-219

[24] Kodkin, V. Structural correction of nonlinear dynamics of frequency-controlled induction motor drives / V. Kodkin, A. Anikin, A. Baldenkov //International Journal of Power Electronics and Drive Systems.–2020.– Vol. 11 No. 1.– P.220-227 DOI: http://doi.org/10.11591/ijpeds.v11.i1.pp220-227

[25] Kodkin, V. Experimental study of the VFD's speed stabilization (retention) efficiency under torque disturbances / V. Kodkin, A. Anikin, //International Journal of Power Electronics and Drive Systems.– 2021.– Vol. 12 No. 1

[26] Kodkin, V. The experimental identification method of the dynamic efficiency for frequency regulation algorithms of AEDs / V. Kodkin, A.

Anikin, //International Journal of Power Electronics and Drive Systems.– 2021.– Vol. 12 No. 1

[27] Boguslavsky Ilya Zelikovich, Danilevich Yanush Bronislavovich, Popov Viktor Vasilievich, and Rogachevsky Vladimir Samuilovich. "Features of the calculation of electromagnetic loads for machines with double power supply taking into account saturation and higher harmonics" SPbPU Scientific and Technical Bulletin. Natural and engineering sciences, no. 1 (166), 2013, pp. 67-73.

[28] Yahya Ahmed Alamri, Nik Rumzi Nik Idris, Ibrahim Mohd. Alsofyani, Tole Sutikno Improved Stator Flux Estimation for Direct Torque Control of Induction Motor Drives // International Journal of Power Electronics and Drive System (IJPEDS), Vol. 7, No. 4, December 2016, pp. 1049~1060 https://www.iaescore.com/journals/index.php/IJPEDS/article/view/5822/5589

[29] Bonar D.D., Khoury M.J. Real Infinite Series / The Mathematical Association of America, 2006. — 274 p.

[30] Loday-Richaud M. Divergent Series, Summability and Resurgence II. Simple and Multiple Summability / Springer International Publishing, 2016. — 272 p.

[31] Srinivas Gangishetti, Tarakalyani Sandipamu Different Control Schemes for Sensor Less Vector Control of Induction Motor // International Journal of Power Electronics and Drive System (IJPEDS), Vol. 8, No. 2, June 2017, pp. 712~721. https://www.iaescore.com/journals/index.php /IJPEDS/article/view/6757/6394

[32] Md. Rashedul Islam, Md. Maruful Islam, Md. Kamal Hossain, Pintu Kumar Sadhu Performance Analysis of a DTC and SVM Based Field-Orientation Control Induction Motor Drive // International Journal of Power Electronics and Drive System (IJPEDS), Vol. 5, No. 3, February 2015, pp. 336~343 https://www.iaescore.com/journals/index.php/IJPEDS/article/view/5068/4681

[33] Kodkin, V.L Performance identification of the asynchronous electric drives by the spectrum of rotor currents / V.L. Kodkin, A.S. Anikin, A.A. Baldenkov //International Journal of Power Electronics and Drive Systems.–2019.–Vol. 10 No. 1.– P.211-218 DOI: http://doi.org/10.11591/ijpeds.v10.i1.pp211-218

[34] Pat. No. 2599529 Russian Federation, IPC H02P 25/02. The device for frequency control of an asynchronous electric drive / V.L. Kodkin, A.S. Anikin., Ya.A. Shmarin, A.A. Baldenkov - № 2014151549/07; Claimed. 11/17/2015; Publ. 10.10.2016, Bul. № 28-12 p.