Chapter

Nonlinear Dynamics of Asynchronous Electric Drive: Engineering Interpretation and Correction Techniques

Vladimir L. Kodkin, Alexandr S. Anikin and Alexandr A. Baldenkov

Abstract

The results of theoretical and practical research studies most widely used in the industry of variable frequency drives (VFD) are presented in this manuscript. Such objects are characterized by dynamic nonlinearities that are difficult to take into account in the mathematical description for the development of control algorithms. Accounting for these nonlinearities leads to equations that are very problematic to solve. Therefore, the equations of the mathematical model on which the vector control system is based are compiled with the assumption of the sinusoidality of the processes occurring in the control object. Comparative results of the analysis of dynamic of VFD with two types of sensorless control, vector and scalar, show the problems that these assumptions lead to.. For identification of nonlinearities, dynamic formulas of transfer functions of torque generator in VFD are proposed, taking into account slip and stator voltage frequency The nonlinear transfer functions obtained in this work made it possible to substantiate structural solutions that linearize the VFD and substantially increase their efficiency. The use of dynamic feedback on the stator current allowed to significantly increase the dynamics and efficiency of a more stable scalar control.

Keywords: electric motors, asynchronous electric motors, nonlinear control systems, rotor and stator currents, spectral composition, stability criterion, linearization of a nonlinear system, mathematical modeling, nonlinear transfer functions

1. Introduction

1.1 About asynchronous electric drives

Asynchronous electric motors (AEM) are the most common electromechanical converters in the industry. Invented more than 150 years ago, they very quickly became integral elements in all technical systems due to their manufacturability, low price, good weight, and size characteristics. At the same time, for more than

100 years, they have been used in mechanisms with virtually no control over the speed of rotation or the mechanical moment developed. Only in the 1980s of the twentieth century, that is, 100 years after the invention, with the start of production of powerful controlled semiconductor switches, it became possible to effectively control the stator frequency and, along with it, almost any AED coordinates. There was a very interesting situation. The principles of frequency control were developed at the beginning of the twentieth century, but not having a wide practical application, they largely remained a theory. Developed in the 1970s, the principles of "transvector" control were immediately recognized as "reducing" the AED to a DC drive, that is, practically to a linear stationary system. The use of AED with frequency converters in a wide practice has encountered a number of problems. It turned out that AEDs are a substantially nonlinear link and the existing control methods (scalar control (SC), space vector control (SVC)) do not remedy this situation too much. At present, the following situation is "generally accepted": scalar control preserves the nonlinearity of the AED, but is not intended for dynamic mechanisms and does not require dynamic analysis, and vector control reduces the AED to a DC drive; therefore, complex nonlinear methods are not applied to anything. Everything is complicated by the fact that both linear and nonlinear equations of electromechanical complexes are only an approximation to real technical systems.

1.2 About mathematical models and linear stationary systems

Reality is more complicated than any mathematical model. At the same time, strict solutions exist only in the area of linear stationary systems (LSS), which are described by linear differential equations with constant coefficients in the "left" part of the equations—the one that describes the control object itself—in our case, the electric drive. For such systems, you can highlight a number of important features:

- LSS equations have strict solutions, the qualities of which - stability, static and dynamic errors and the time of transient processes do not depend on the "right" part of the equations, which, as a rule, describe external perturbations or job signals.

- The most important of the estimates is the assessment of sustainability which is made by sufficiently accurate, for example, criteria Nyquist.

- Systems and individual blocks are identified by transfer functions and frequency characteristics strictly defined by differential equations.

- If in the "right" part of the equation, that is, at any input of the system, there is a harmonic signal of a certain frequency, then all blocks will have harmonic input and output signals of only this frequency, different in amplitude about the phase.

Naturally, real electric drives can be identified by LSS with only very large approximations. In direct-current drives with independent excitation, these approximations are insignificant; they mostly relate to mechanical structures with stiffness and gaps. In asynchronous electric drives, the reduction to LSS is associated with much larger errors. The equations of a generalized AC motor, even with significant assumptions, can be reduced to linear equations with variable coefficients or to nonlinear control systems. For engineering calculations, the differences between these systems are very conditional. If variable coefficients depend on the same coordinates of the electric drive (rotational speed, stator current, etc.), the system with variable coefficients should be considered rather nonlinear. Moreover, for a system with variable coefficients, transfer functions, stability criteria, and dynamic characteristics will not be as accurate and strict as for LSS.

Engineers need to solve the problem of whether to use rigorous calculation methods, reducing the actual system of the electric drive to LSS, very far from the original one, or describe the electric drive with a closer nonlinear system and use much less rigorous methods of calculation in its analysis. This work is aimed at finding a compromise of identification and calculation methods for asynchronous electric drives.

2. Problem statement

2.1 Asynchronous electric drives and linear stationary systems

Linear stationary systems, which we will further call simply linear, have one big advantage over reality. These equations have exact solutions. But nonlinear equations are either very difficult to solve or not at all. But this is not the biggest problem in the interaction of linear and nonlinear systems. Linear cybernetic systems, and electric drives in particular, have processes whose quality—stability, transient time, and the magnitude of the static and dynamic errors of the drive—do not depend on the input "master" signals and on external influences and disturbances, since they are determined only by parameters of the control system itself. Thus, such system is predictable. To identify it, it is not necessary to test it with signals of different magnitudes and rates; it should not allow unexpected operating modes and all the more emergency ones. In addition, it is quite simply adjusted by regulators and feedbacks. For nonlinear control systems, all these are just dreams and desires. Systems behave differently at different speeds and under different loads, stable at nominal speed, and they become oscillatory at low speeds, etc. But probably the biggest problem is that they cannot be adjusted by the usual methods—PI and PID regulators behave completely unpredictable. Paraphrasing the classic, one can say: "All linear systems are the same, and nonlinear ones are each nonlinear in their own way." From the foregoing, it is clear that any engineer would prefer to deal with linear control systems and electric drives, or at least with the systems closer to linear with those tasks and disturbances that this system is experiencing. Nonlinear components can be very different—inevitable "imperfections," restrictions, dead zones, backlashes, etc. But there are also "fundamental" nonlinearities in electric drives; this is the *moment formation*—the operation of multiplying two variable functions—current and magnetic flux. In asynchronous motors, these are periodic functions; as a result, this drive even has a mechanical characteristic that is strictly nonlinear. It is obvious and follows from the Kloss formula and the equivalent scheme, in which there is an element, dependent on slip. Those nonlinearities of asynchronous electric drives are known, but adjusting them with simple means (*IR*, compensation) does not work. The electric drives becomes ineffective. To overcome this, a special "vector" control is applied, which also turns out to lead to new nonlinearities and problems, including unexpected ones. In this way, to bring an automatic system closer to a linear one is to make it predictable, adjustable, reliable, and efficient. In the proposed paper, some methods of such an approximation are given. We called them linearization methods. Usually, this term is called the simplification of the original nonlinear equations of the system. But we left this term unchanged. In our opinion, this term reflects too well the goals and results of this work to replace it with another.

In modern high-tech industrial mechanisms, electric actuators play a very important role. The quality of technical complexes and their competitiveness depend on their ability to "fend off" disturbances, for example, change in air temperature, “dips” and “surge” of power voltage, wear of mechanical parts, and, most importantly, external loads.

AC drives with asynchronous and synchronous electric motors have significantly better “robustness” properties, the latter, as a rule, differing from brushless DC motor only by the control method. But control problems are the reason why AC drives are still rarely used in complex technological mechanisms. These problems are connected with essentially nonlinear equations, which describe the processes of formation of a mechanical torque in an asynchronous electric motor. Neglecting them leads to the fact that the simplified formulas do not at all reflect the processes occurring in AC drives. Accounting for these nonlinearities leads to equations that are very difficult to solve. Even for assessing sustainability, it is difficult to choose the appropriate mathematical apparatus. This state of affairs requires the creation of a new engineering calculation method and the synthesis of AED control system.

Engineering calculation is a solution that determines the technical and economic development; it is limited not only by the conditions of the task itself. It is necessary to solve it so that the result could be effective and useful. These are significant limitations that theoretical science sometimes does not have.

In this regard, when developing new electric drives based on an asynchronous motor and frequency converter (FC), great attention should be paid to the methodology of experimental studies. The authors have been working on these problems for about 15 years.

The first few years were devoted to theoretical studies, namely, the analysis of the dynamics (primarily stability) of systems with variable carrying signals [1].

A major project was the project of introducing frequency-controlled drives to self-propelled wagons for the mining industry in 2008–2010 [2, 3]. As a result of the modernized control algorithm introduction, it was possible to increase the loading capacity of the car by 1.5 times.

In subsequent years, numerous experimental studies were carried out, the results of which are reflected in publications [4–8] and patents [9–11], introduced in industry and energy. The algorithms of sensorless correction with frequency control were significantly refined, the existing algorithms were investigated in detail, and the problems of these algorithms were identified. This work was carried out in collaboration with representatives of *Schneider Electric* in Russia, who provided equipment for the experiments. The authors thank the company. In this regard, the starting materials for research were experiments. Their goal was to clarify the advantages of vector control over scalar ones and find a convenient way to identify the dynamics of such drives. However, the results of the experiments forced to significantly adjust the research plan.

2.2 On the existing control methodologies and assumptions

A lot of books have been written about the problems of AED vector control. The original structures of the model built into the regulator contain many mathematical inaccuracies. To assess these inaccuracies, we consider the block diagram of a current-controlled drive, given in the monograph by Usoltsev (**Figure 1**).

The desired linearization occurs, if several conditions are met:

1. Exactly coincides the rotor rotation speed and the rotation speed of the vectors of the stator current. In fact, in the sensorless circuit, this condition cannot always be satisfied, especially in dynamic modes. As a result, the connection between the model and the motor becomes a very complex link with floating frequency characteristics; as a result the control inevitably falls apart.

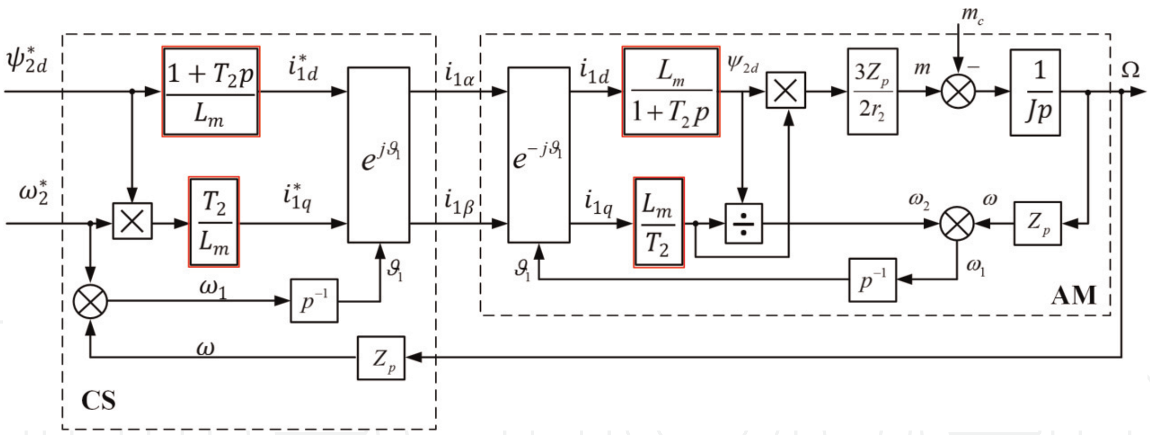


Figure 1.
Block diagram of space vector control.

2. The transfer functions of the rotor circuit and its models must be exactly the same. This is also not always the case. Moreover, the structure of the model does not take into account the initial conditions, which are determined by external disturbances. Therefore, processes at zero initial conditions (drive acceleration) usually occur "correctly" but react to the external load much worse and in accordance with other dynamic characteristics.

3. The basic equations of the processes for the vector control of the stator current projections are obtained by representing the operator image of the product of functions by the product of a function by the reference image of another factor, that is, Parseval's integral is simplified significantly, but the errors of this simplification are not specified in any work.

4. All equations allow sinusoidal processes: currents, EMF, and voltages. Really, after all, "vector control" controls the current or voltage vector, and what if the signals are not harmonic? Who controls other harmonics? What are the projections of other harmonics? The question is rhetorical.

5. In the calculations it is assumed that the rotor flow does not change, which of course does not correspond to reality. But the price of this assumption is also not known.

6. And the last question. In the scheme there is no link reflecting the dynamics of the converter itself, that is, systems with a switch, delay links, and filters. This link can be very conditionally considered an inertia-free link.

To evaluate all these errors, especially to show the modes in which they will be significant, no engineering technique is trying to do. Moreover, "as time passes," the assumptions are forgotten, and on the basis of these "new" ideas, vector control is constructed, which inverse operators "linearize" the drive, turning it into a similarity to a DC drive. These algorithms fundamentally contain errors, which are especially pronounced in dynamic modes and in the countering of external torque perturbations. In this case, as mentioned above, in the dynamic links of a real electric motor appear initial conditions, which cannot be in the links opposite to the dynamic links of the electric motor. These links become different. In conventional control schemes, external disturbances lead to a shift in the equilibrium state. In the scheme with direct linearization (**Figure 1**), it destroys that. The same is true for other assumptions. Analytically it is very difficult to take into account their influence. Therefore, an engineering technique is proposed that combines a qualitative analysis of the equations, transfer functions, and frequency characteristics with modeling and experiments. In contrast to the usual starting and braking modes at one average speed, the conditions for them are formed, taking into account all the above features, namely, at different frequencies, load surges, and accelerations.

Thus, the nonlinearity of the equations of AED is well known and does not cause doubts. But there are no techniques that would allow to evaluate the effect of these unaccounted nonlinearities on the drive final characteristics. One can only assume a violation of stability under complex torque loads and complex reference signals. Since nonlinearity is preserved for all known most widely used control methods (scalar, vector, direct torque control), it is advisable to identify the dynamics of adjustable electric drives with detailed modeling and experiments in a variety of modes: start-up brakes and modes of different torque loads. So, vector control, in order to reduce AED to DC systems, tries to linearize AD with nonlinear transformations. With these inaccuracies nonlinearity only increases.

2.3 Problems of AED practice

As mentioned above, the research was based on experiments and modeling. A model diagram is shown in **Figure 2**. The electric drive was subsequently accelerated to speeds of 30, 60, 90, 120, and 150 rad/s corresponding to the frequencies of the supply voltage of 10 – 20 – 30 – 40 – 50 Hz, and a load was drawn at each speed of rotation (**Figure 3**). The load was set by stepwise action equal to the nominal value of the motor torque. The oscilloscope displays the speed, electromagnetic torque, and other necessary variables of the drive.

A stand was made for experiments (**Figure 4**). It consists of two asynchronous motors (M1, with a squirrel-cage rotor; M2, with a wound rotor) with a rated power of 370 W, synchronous speed of rotation 1500 rpm, nominal speed of rotation of 1370 rpm, and rated voltage of 380 V, controlled by two FC ATV32 (UZ1) and ATV71 (UZ2) by *Schneider Electric*. Interconnected motor shafts are connected to a speed sensor (encoder), information from which is transmitted to the FC UZ2. Used in the stand frequency converters belong to the middle technical-economic class. They have a relatively low cost, which allows them to be widely used at enterprises

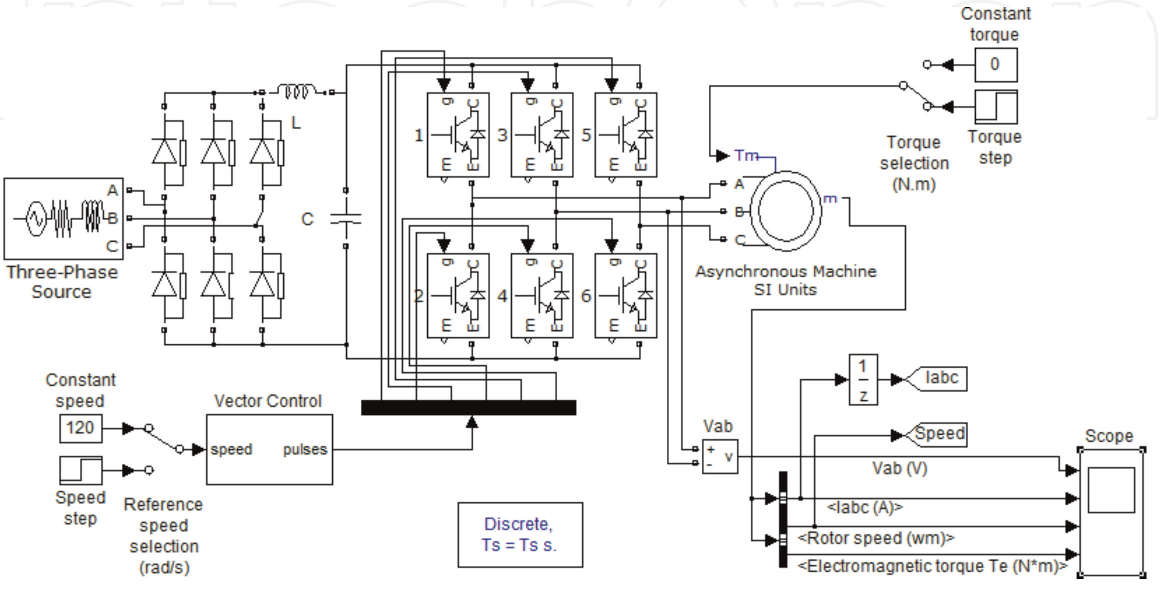


Figure 2.
Diagram of AED model.

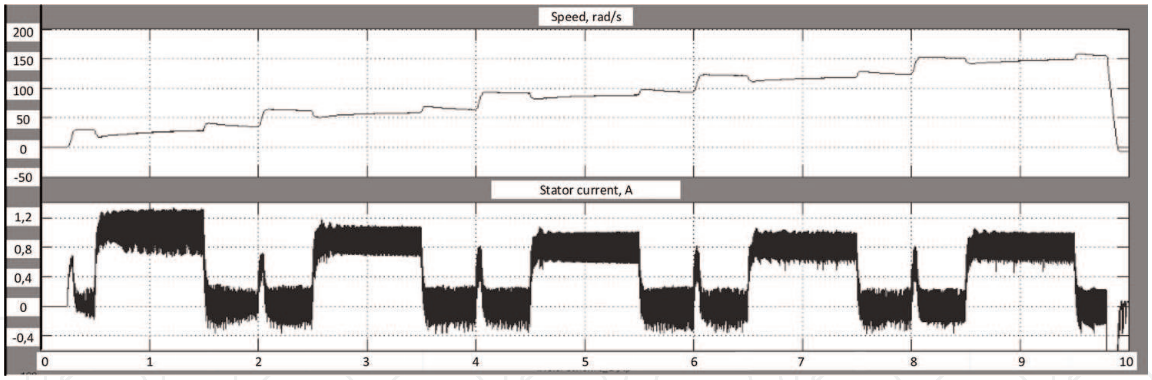


Figure 3.
Modeling processes in an asynchronous electric drive.

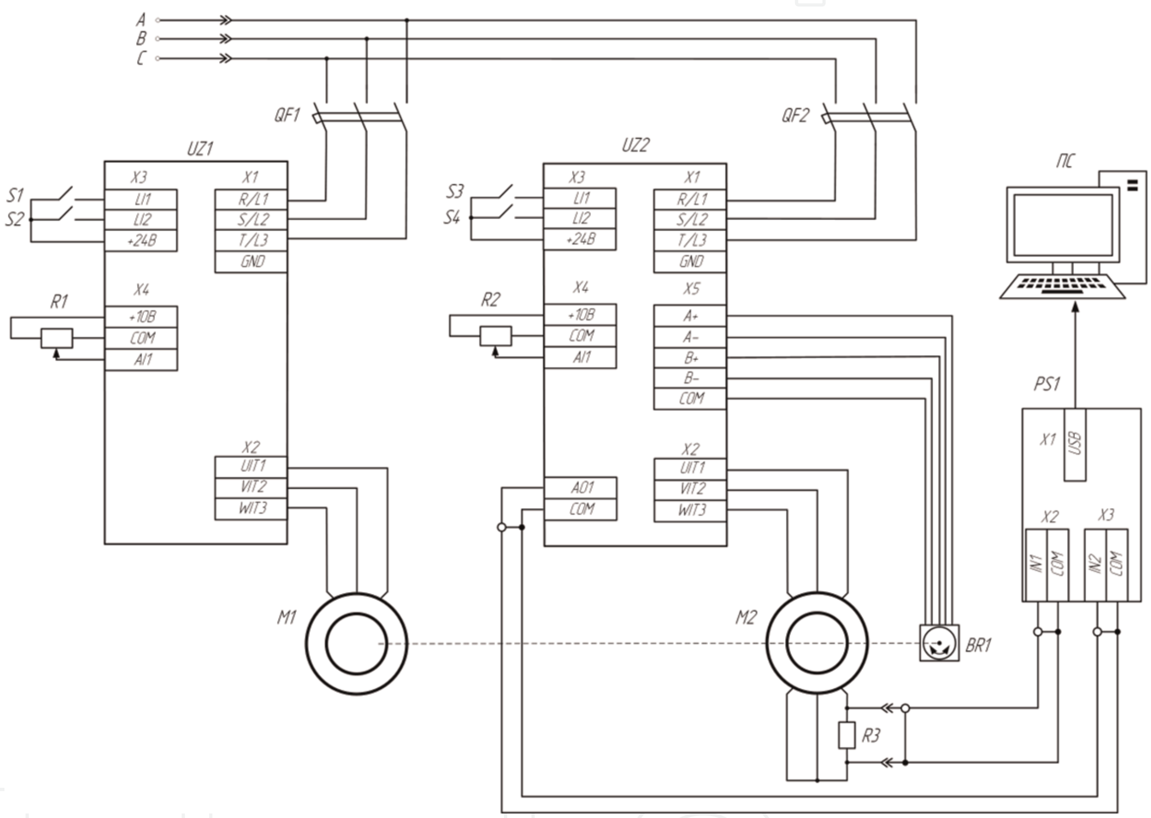


Figure 4.
Schematic circuit of the stand for the study of the dynamic characteristics of the drive.

of various levels (including small businesses), and at the same time, they have a broad functionality, including all standard, well-developed control algorithms, which makes them universal in terms of application in various technical systems.

The first results of the experiments were the operation of the drive with load surges. These results were poorly explained from the point of view of the absolute advantages of vector control and the proximity of this drive to DC drives. The parallel movement of the mechanical characteristics under the frequency control of the drive should lead to the same absolute speed drops with the same loading torques. Instead, the "dip" speeds turned out to be different both in absolute and relative values, both for scalar and vector control. If different processes were expected for scalar control, the results for the vector were unexpected (**Figures 5** and **6**). The dynamics of acceleration processes up to speeds of 10, 20 rad/s, and so on in a scalar control are somewhat different, as in the vector one. In case of load surges, the processes differ both in dynamics (transient time) and in static speed dip. Moreover, at speeds of 60 rad/s (i.e., at a frequency of 10 Hz) and below, both

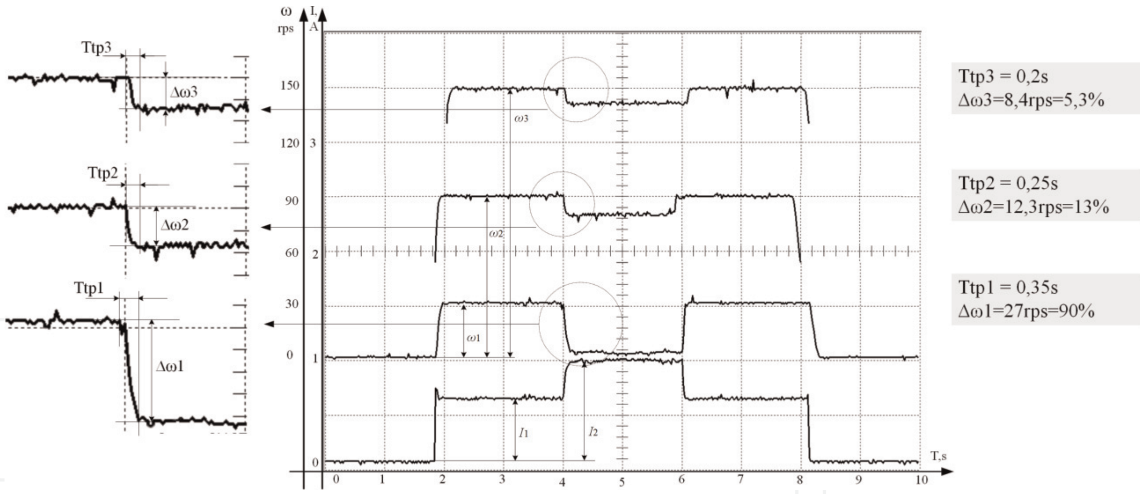


Figure 5.
Step loading response of AED with scalar control (ω1 = 30 rad/s; ω2 = 90 rad/s; ω3 = 150 rad/s).

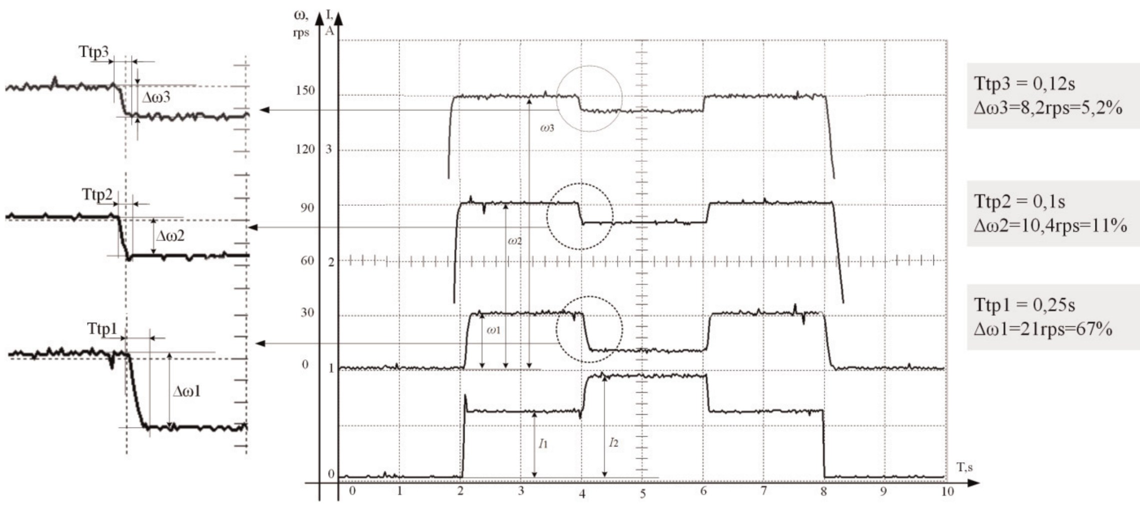


Figure 6.
Step loading response of AED with vector control (ω1 = 30 rad/s; ω2 = 90 rad/s; ω3 = 150 rad/s).

scalar and vector controls behave almost exactly the same. It should be noted that in the drive equations, there are no prerequisites for this state of affairs.

It should be noted that maintaining the speed under shock torque perturbations is one of the most difficult tasks of automated electric drives. Even DC motors, closed in speed or angular position, with very good control characteristics cannot avoid significant dynamic failures and complex speed recovery processes during load gain. But the processes of working out such loads are the most important characteristics of complex control systems.

When the speed sensor is installed and the PI regulator is turned on, the processes in the drive with vector control also do not match the expected ones. In the AED with the PI speed regulator, the two-time changes in the regulator parameters do not completely change the process (**Figure 7**). Attention should be paid to the duration of the process, which is substantially longer than the process time in an open-ended drive. Similar results were obtained in the simulation.

Experiments with periodically varying loads were carried out using a similar technique. Since various properties of the drive are evident at different frequencies of the stator voltage, the drive under study accelerates to different speeds, corresponding to the frequencies of the stator voltage—10, 20, 30, 40, and 50 Hz, respectively. A constant reference signal was summed up with a periodic sinusoidal signal with varying amplitude and frequency. This sum signal was fed to the analog

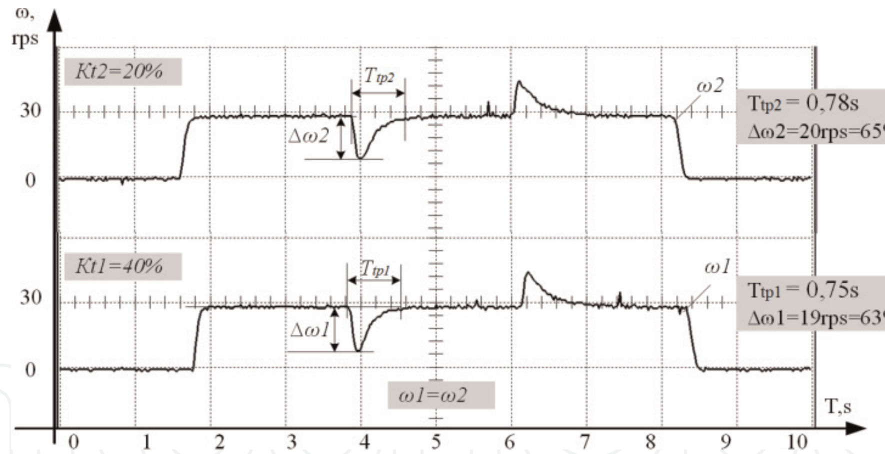


Figure 7.
Step loading response of AED with vector control with speed feedback (ω1 = ω2 = 30 rad/s; PI-regulator settings: K_t1 = 40%; K_t2 = 20%).

inputs of the FC of the test drive (**Figure 8**). In this case, the higher the amplitude of the oscillation, the more effective the drive. The same sine-wave reference signals were applied to the input of the load drive converter (**Figure 9**). The ability of the drive to maintain a given speed was investigated. The efficiency of the drive is higher in the case in which the amplitude of the speed oscillations is lower.

As follows from **Table 1**, the drive efficiency with vector control is not the best, including and with speed feedback. These results required a different theoretical approach to the problem.

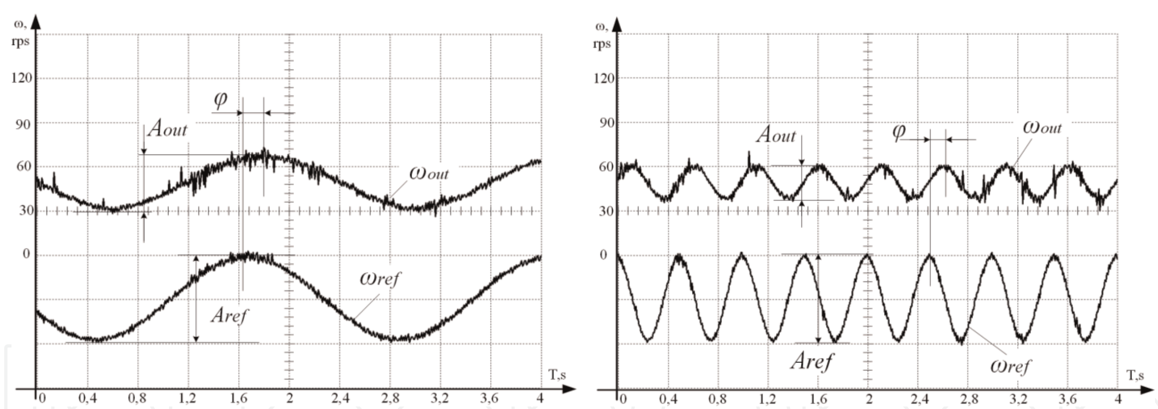


Figure 8.
Speed diagrams with harmonic (sinusoidal) speed reference signal.

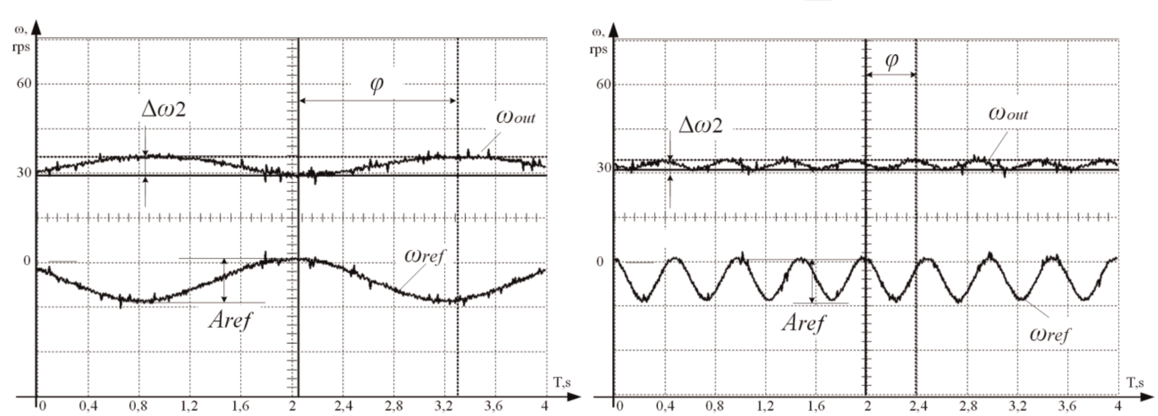


Figure 9.
Speed diagrams for harmonic torque perturbation testing.

Drive control system	Test the periodic reference signal		Test of periodic torque perturbation	
	Δω, rad/s	Δφ, el. deg.	Δω, rad/s	Δφ, el. deg.
Open system (scalar control)	±5.0	87	±2.38	245
Open system (vector control)	±5.03	84	±2.19	270
Speed feedback system	±4.99	84	±3.31	230

Table 1.
Results of experiments for periodic signals.

2.4 Instability systems AED with vector control

Dynamic properties of the electric drive are best evaluated by frequency characteristics. For their registration, we carried out the experiments in which a constant reference signal and a periodic sinusoidal signal with varying amplitude and frequency were fed to the analog inputs of the FC. The effective value of the stator current was selected as an output signal. This signal is selected as the most reliable of the signals computed by the inverter, since the models for calculating the speed and torque of the motor are not known. Most often, the stator current signals are close to harmonic and indicate a "correct" system response to input signals (**Figure 10**).

At certain values of the amplitude (A) and frequency (f), "disruptions" of control characterized by a mismatch between the frequency of the input signal and

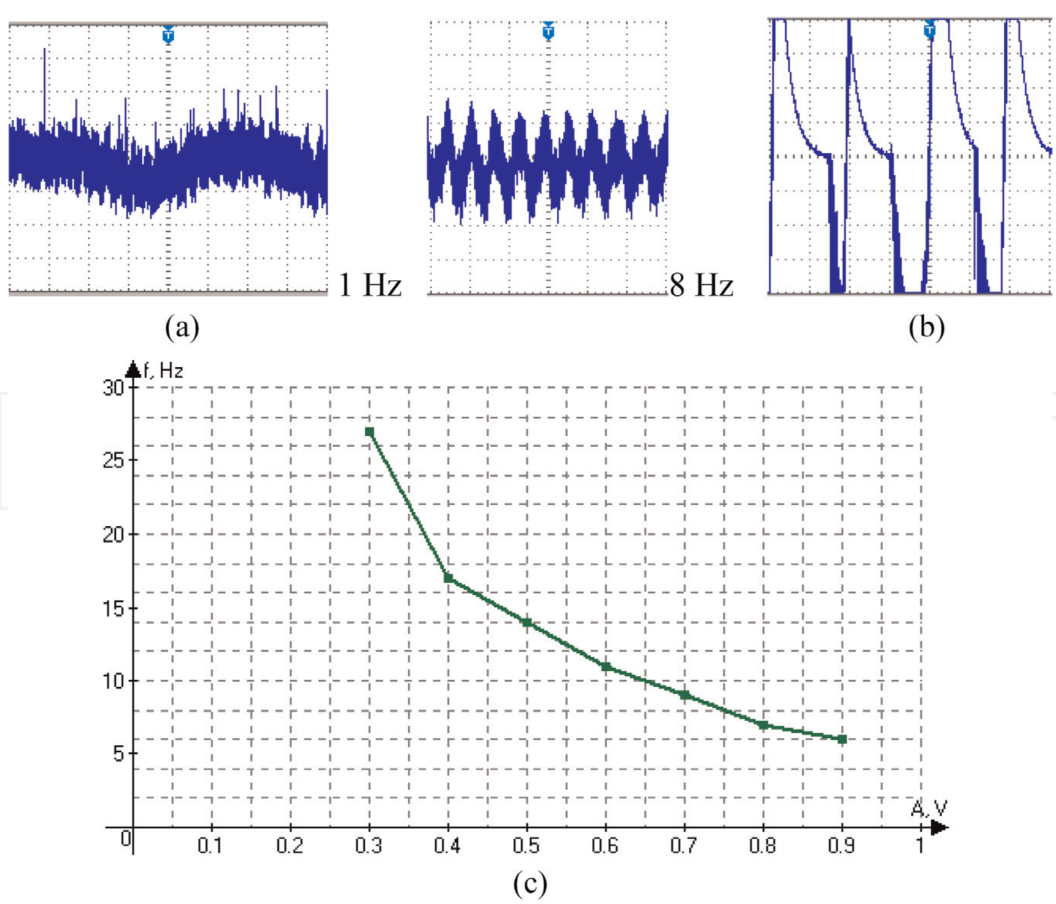


Figure 10.
The stator current diagrams during the development of variable tasks 1 and 8 Hz (a), during the "control failure" (b) and the dependence of the reference signal frequency on the speed on the same signal amplitude, at which the "breakdown" of control in the FC occurs (c).

the frequency of the output signal occurred. The process of disruption is also accompanied by a significant increase in current. The point of control failures did not change when the parameters of the controller built into the inverter were changed, the mechanical part of the electric drive changed, and the load changed. It was found that the frequency of disruptions depends only on the amplitude of the input signal. The dependence of the disruption frequency on the amplitude is determined experimentally. It can be assumed that the cause of failures is the disregard of the initial conditions by the motor model; the parameters of the sine wave determine these conditions.

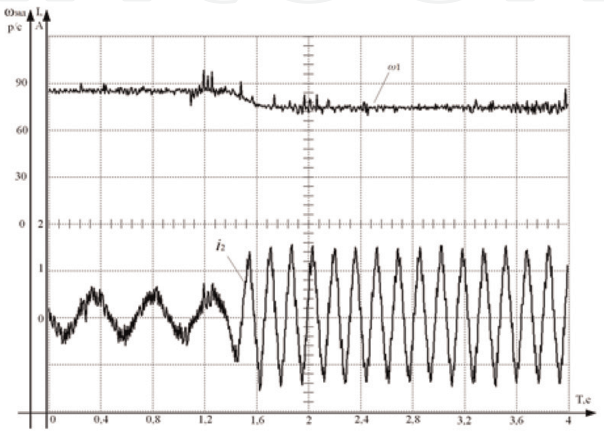
It should be noted that in AED studies with later models of converters (*ATV71* and *ATV32*) with open vector control, these failures are not present, but they occur under other conditions. It is important to note that the possibility of such control failures under certain external conditions is not mentioned at all by any documents. And the dangers of resonance processes in mechanisms with such drives are very high and can have very serious consequences.

2.5 Performance identification of the asynchronous electric drives by the spectrum of rotor currents

As mentioned above, an asynchronous electric drive is a nonlinear control system, moreover, "on a carrier" harmonic signal. The equations describing it, most often, are reduced to vector interpretations of all signals—rotor and stator currents, EMF, voltages, etc. Both vector and scalar controls are constructed using these equations. At the same time, everyone is well aware that the real variables of the coordinates and signals contain the harmonics of other frequencies, the presence of which "collapses" most of the provisions of these theories. For example, widely used transformations of coordinates in d and q will not make sense if the current signals contain harmonics of frequencies other than the main one.

It remains to find out the "share" of high (or other) harmonics in the signals of an asynchronous electric drive. During the experiments, it was decided to analyze the spectra of rotor currents in asynchronous electric drives with different control methods—scalar (**Figure 11**), vector sensorless (**Figure 12**), and vector speed feedback (**Figure 13**). These experiments are described in detail in a number of articles. This paper presents the results of modeling and experiments and new comments on these results.

As noted in [6, 8] in the case of vector control, especially when the speed loop is closed, the proportion of other harmonics, as compared with the main one, is



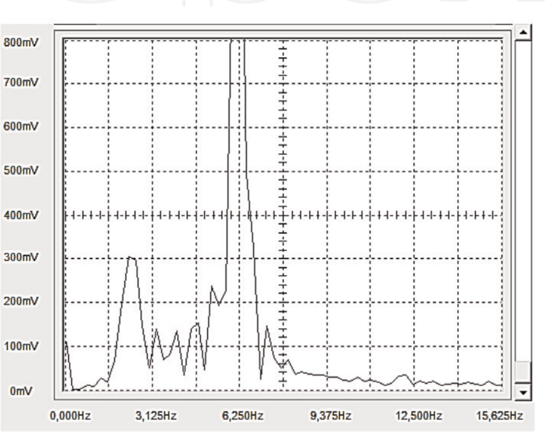


Figure 11.
The diagram of the speed and current of the rotor of an asynchronous drive with vector control. Spectrum of the rotor current signal.

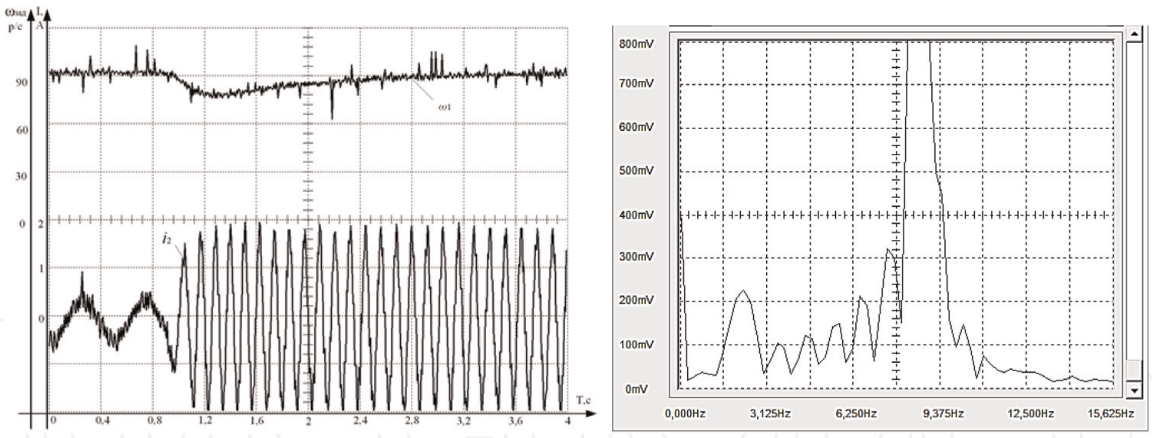


Figure 12.
The diagram of the speed and current of the rotor of an asynchronous drive with closed-loop vector control. Spectrum of the rotor current signal.

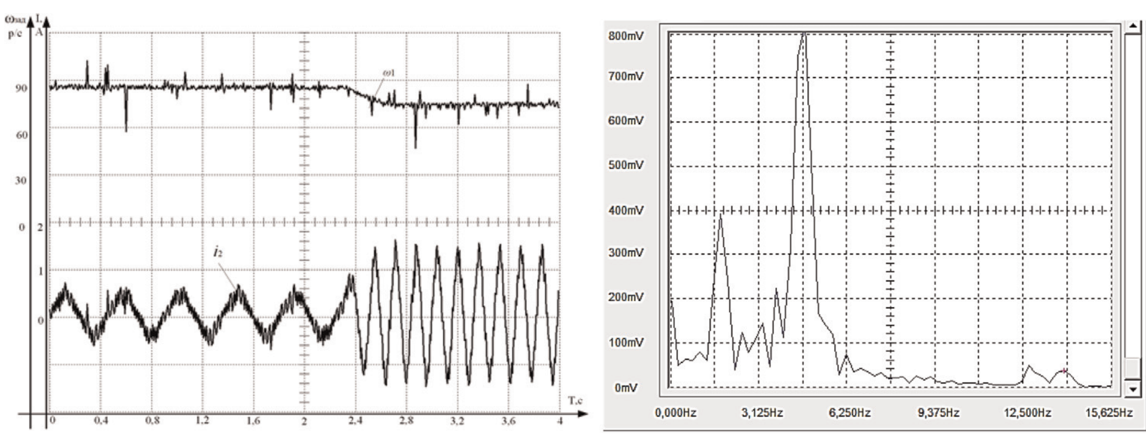


Figure 13.
Diagram of the speed and current of the rotor of an asynchronous drive with scalar control. Spectrum of the rotor current signal.

significantly higher than with scalar control. At the same time, the frequencies of rotor currents with the same load are the highest for a system with a speed loop. Since, in an asynchronous electric drive, the mechanical moment is formed when the rotor rotates at the speed of rotation of the electromagnetic field, it is natural to evaluate the efficiency of the formation of the moment by this error rate or, as it is called in the electric drive, by slip. The greater the slip for the formation of the moment, the less effective way of its formation is applied. As it is known, the frequency of the rotor current in an asynchronous electric drive is rigidly connected with the slip. Experiments show that with vector control the efficiency of the formation of the moment, at least in the converters of the frequency of the middle technical-economic class, is lower than with scalar control. This is also confirmed by the simulation of asynchronous electric drive systems (**Figures 14** and **15**).

The frequency of the rotor current under load (at a speed of 90 rps) with vector control is 10.6 Hz, scalar without feedback—2.72 Hz.

Analysis of the spectra of rotor currents convincingly shows that the formation of the necessary torque in a vector-controlled electric drive, even when the speed loop is closed, is not the most effective; the reason for this is probably the presence of significant harmonics at a frequency of 3–8 Hz (**Figures 12** and **13**). **Table 2** shows the experimental values of the main frequencies of the rotor currents, which cast doubt on the generally accepted opinion about the high efficiency of the formation of the torque in vector control.

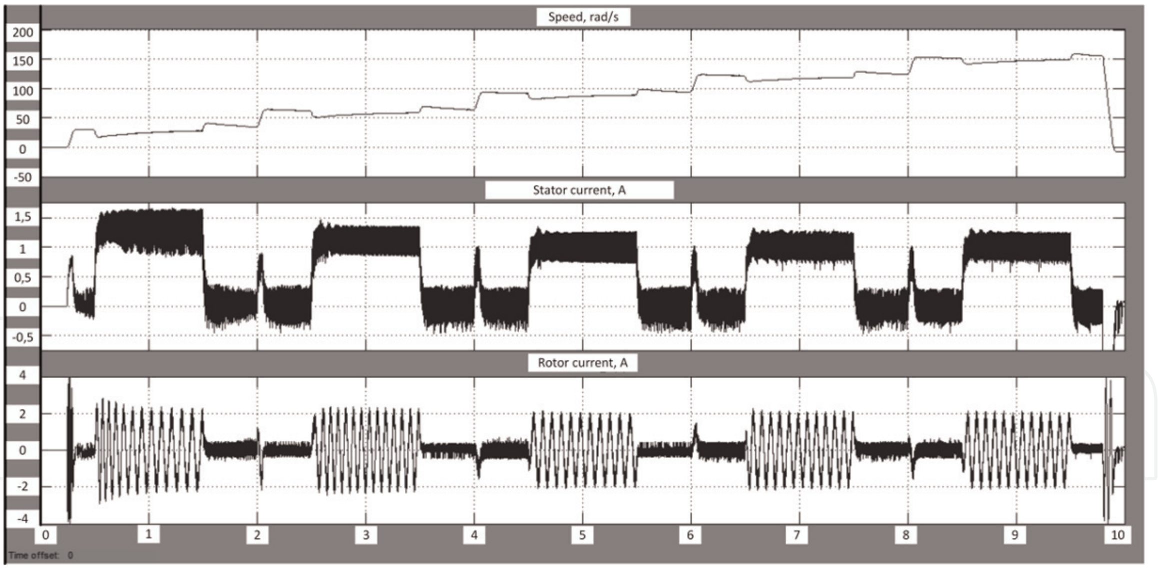


Figure 14.
Modeling processes in an asynchronous electric drive with vector control system.

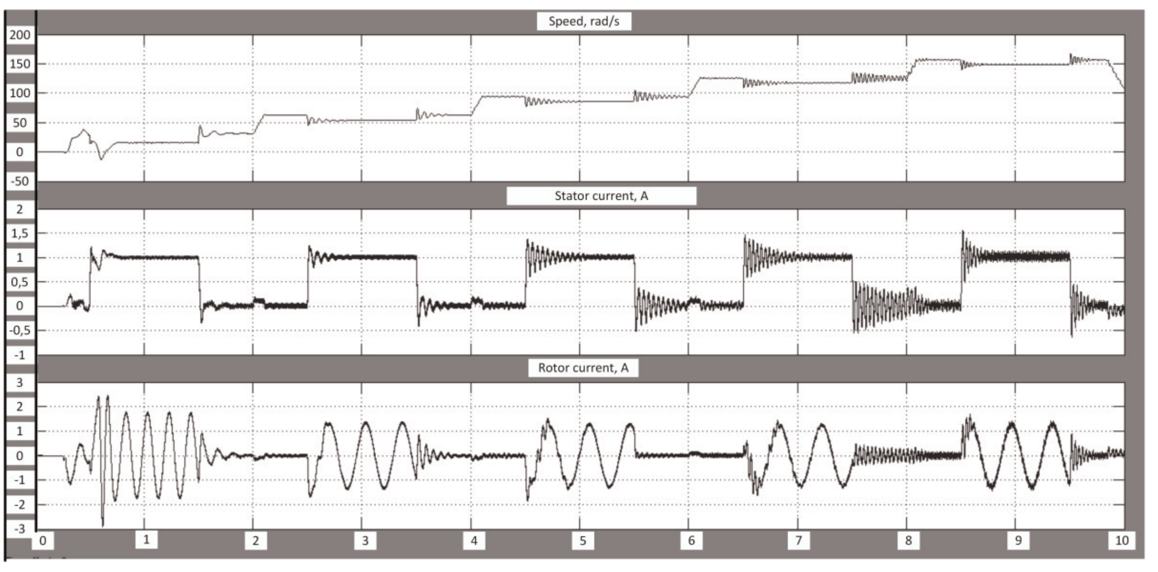


Figure 15.
Modeling processes in an asynchronous electric drive with scalar control.

Control system	No-load	Under load
Vector control	2.1 Hz	6.25 Hz
Vector speed feedback control	2.1 Hz	8.75 Hz
Scalar control without feedback	1.69 Hz	4.75 Hz

Table 2.
Frequency of the fundamental harmonic for various control algorithms.

Another conclusion from these experiments is that the components of the signals of other harmonics are very significant, which makes the errors of the generalized equations, expansions on the d and q axes, and other transformations very essential. Since nonlinear operations are carried out in vector control in models of a control unit of frequency converters, these errors increase, as evidenced by higher frequencies of rotor currents under identical loads compared to scalar control.

Thus, multiple nonlinear operations are the reason for the appearance of non-fundamental harmonics in the electric motor currents and, as a result, the inefficiency of control methods.

2.6 AED nonlinearity is the main cause of "complex" dynamics

The main nonlinear operation in the drive is the multiplication operation, which is very difficult to transfer to the Laplace transform domain and frequency transformations. In AC drives, the multiplication operation is performed, usually with harmonic or close to them variables. It is very important to consider that multiplying the original harmonic signal by a harmonic signal with a "carrier" frequency shifts the frequency of the original signal to the carrier frequency. In AED, this multiplication occurs twice.

The system can thus be represented as a symmetrical three-phase system with modulating and demodulating links (**Figure 16**).

As a result of the transformations, the transfer function of the torque shaping circuit will take the form

$$W_{ft} = \frac{3}{2} ReW(p + jf) \tag{1}$$

for $W(p) = \frac{1}{(T_\Sigma p+1)}$:

$$W_{ft} = \frac{3}{2} \frac{T_\Sigma p + 1}{(T_\Sigma p + 1)^2 + (T_\Sigma f)^2} \tag{2}$$

High-frequency signals obtained as a result of modulation and demodulation form a symmetrical system upon addition and do not form a high-frequency component in the electromagnetic and mechanical torques, and the shift from the carrier frequency remains in the low-frequency components. This shift in the frequency response of the dynamic link characterizing the electromagnetic processes —in the stator and rotor under frequency control—is variable and largely affects the dynamics of the drive.

From this transfer function, it can be assumed how these transfer functions, which vary with frequency ω and slip β, "work" in vector and scalar controls.

With vector control, the modulating units are energized, the amplitude and phase of which are "modeled" in the control unit so as to linearize this transfer function, and such linearization potentially contains many errors. If there is no-load measurement (β) in the inverter, then the linearization procedure will be the same for any loads, which naturally leads to regulation errors that we observe in experiments.

With scalar control and the effect of IR and S compensations, local positive feedback is included in the structure. If this connection is "hard," it breaks the

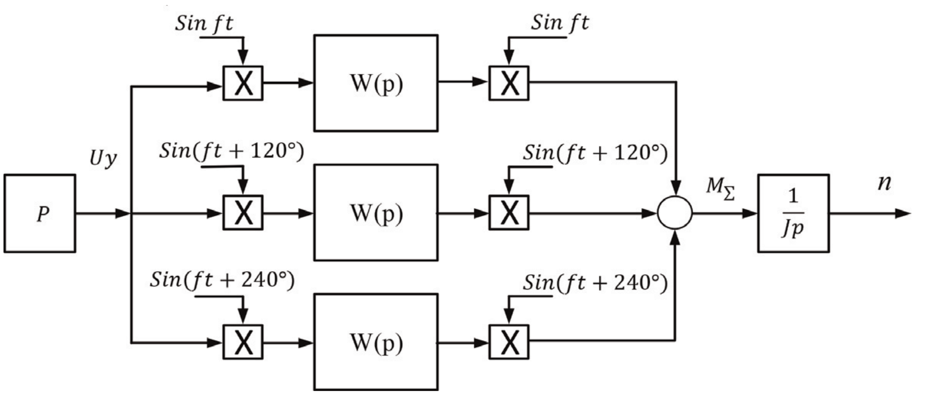


Figure 16.
Structural scheme for the analysis of nonlinearities of AED.

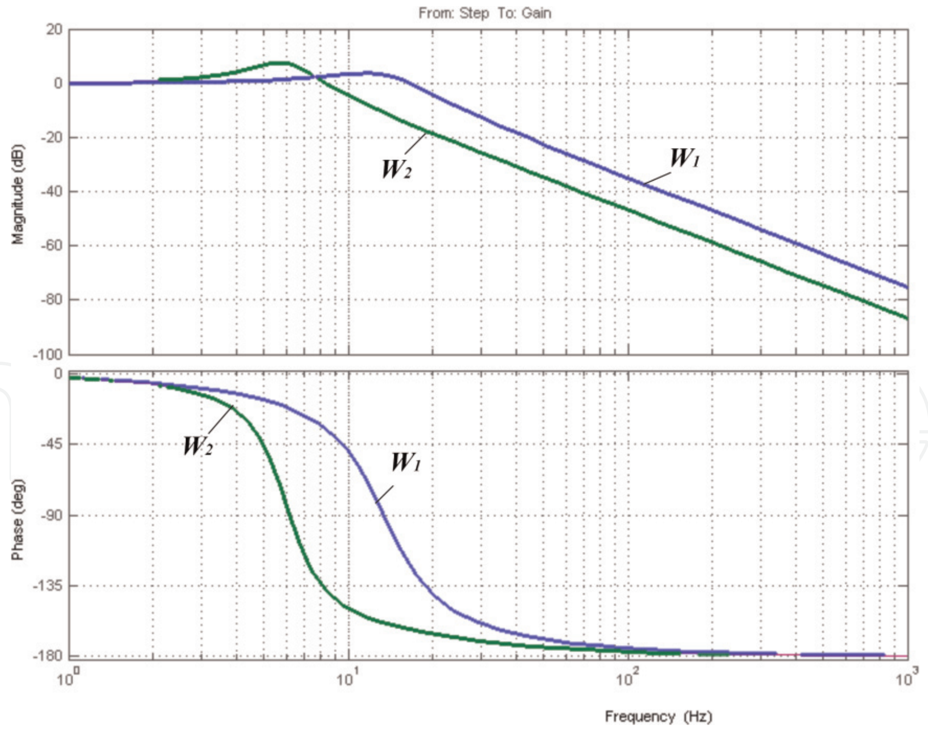


Figure 17.
Amplitude and phase frequency characteristics of the AED at different frequencies of the supply voltage (W1 (f1 = 50 Hz), W2 (f2 = 5 Hz)).

stability in a system "prone" to oscillation, as can be seen from the frequency characteristics of the structure.

The possibilities of effective correction will be discussed below.

Formulas (1) and (2) describe families of frequency characteristics of asynchronous electric drives and explain the differences in drive dynamics at different speeds and complexity when closing the speed loop, described above. It should be noted that the representation of the torque shaping loop in the drive of the AC drive by a family of frequency characteristics, each of which corresponds to its carrier frequency, is not quite a strict solution, but other methods are even more complicated and also contain errors. **Figure 17** shows the frequency characteristics of the structure corresponding to the scheme shown in **Figure 16** at frequencies of 5 and 50 Hz. The differences are very significant, as well as the problematic synthesis of the control system, which should stabilize the acceleration process from 15.7 to 157.08 rad/s with changes in the frequency characteristic of the torque-forming unit.

The above results lead to the need to form a method for identifying AED dynamics.

Another mathematical operation that allows to obtain transfer functions of such a structure can be a multidimensional Laplace transform with transitions to one variable using the method described in [12, 13]. The transfer function of the equivalent link after two multiplication operations is as follows, which is very similar to the formula (2).

All this allows to proceed to the following mathematical transformations.

3. Identification of AED dynamics by frequency characteristics

3.1 Modeling of processes in AED

Both process modeling (**Figure 3**) and experimental research (**Figures 5–9**) show that at different speeds and with different loads on the drive, the processes are qualitatively different. Therefore, they should be described by different frequency characteristics. The task that should be solved first of all is the formation of the frequency characteristics of the asynchronous drive for each specific mode.

3.1.1 The proposed solution

The basis for choosing the method for calculating the dynamic mechanical characteristic, propose in the same monograph by Usoltsev ([14], p. 135).

The resulting formula connects the electromagnetic torque with the critical slip and the current slip; all of these values depend on the frequency of the stator voltage:

$$m = \frac{2M_k}{(1 + T_2'p)\left[\frac{S_k}{\beta}(1 + T_2'p)\right] + \frac{\beta}{S_k}}, \tag{3}$$

where $T_2' = \frac{L_k}{R_2}$ is the rotary time constant and $\beta = \frac{\omega_2}{\omega_1}$ is the relative slip.

Usoltsev calls this formula a dynamic mechanical characteristic and simplifies it to a first-order dynamic link that cannot be described by the processes presented in **Figure 3**.

The refinement of the linearization conditions allows us to obtain a different formula for the dynamic link connecting the torque developed by the induction motor with the rotational speed (Kloss dynamic formula), while some of the coefficients of the formula depend on the frequency of the supply voltage and slip:

$$m = \frac{2M_k(T_2'p + 1)}{(1 + T_2'p)^2 \frac{S_k}{\beta} + \frac{\beta}{S_k}} \tag{4}$$

Then, the equation of the connecting torque (m), the relative slip (β), and the motor parameters (T'_2, M_k, S_k) will take the form:

$$m = \frac{2M_k(T_2'p + 1)S_k\beta}{(1 + T_2'p)^2 S_k^2 + \beta^2}, \tag{5}$$

and the transfer function connecting the absolute slip and the torque will take the form:

$$\mathrm{W(p)} = \frac{2\mathrm{M_k}(\mathrm{T_2'p} + 1)\mathrm{S_k}}{\omega_1\left[(1 + \mathrm{T_2'p})^2\mathrm{S_k^2} + \beta^2\right]} \tag{6}$$

where ω_1 is the frequency of the stator voltage.

The block diagram of the drive in the work area will take the form shown in **Figure 18**.

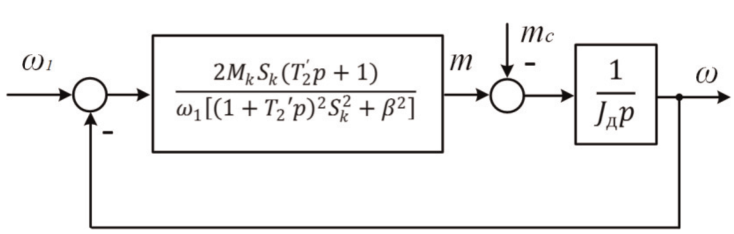


Figure 18.
Structural diagram of an asynchronous motor in the working area of mechanical characteristics.

The transfer function of the torque driver changes as the stator voltage and slip frequency changes, that is, it is essentially nonlinear.

It should be noted that at β = 0, the transfer function, as well as the structural diagram, exactly coincides with the linear transfer function and structural diagram

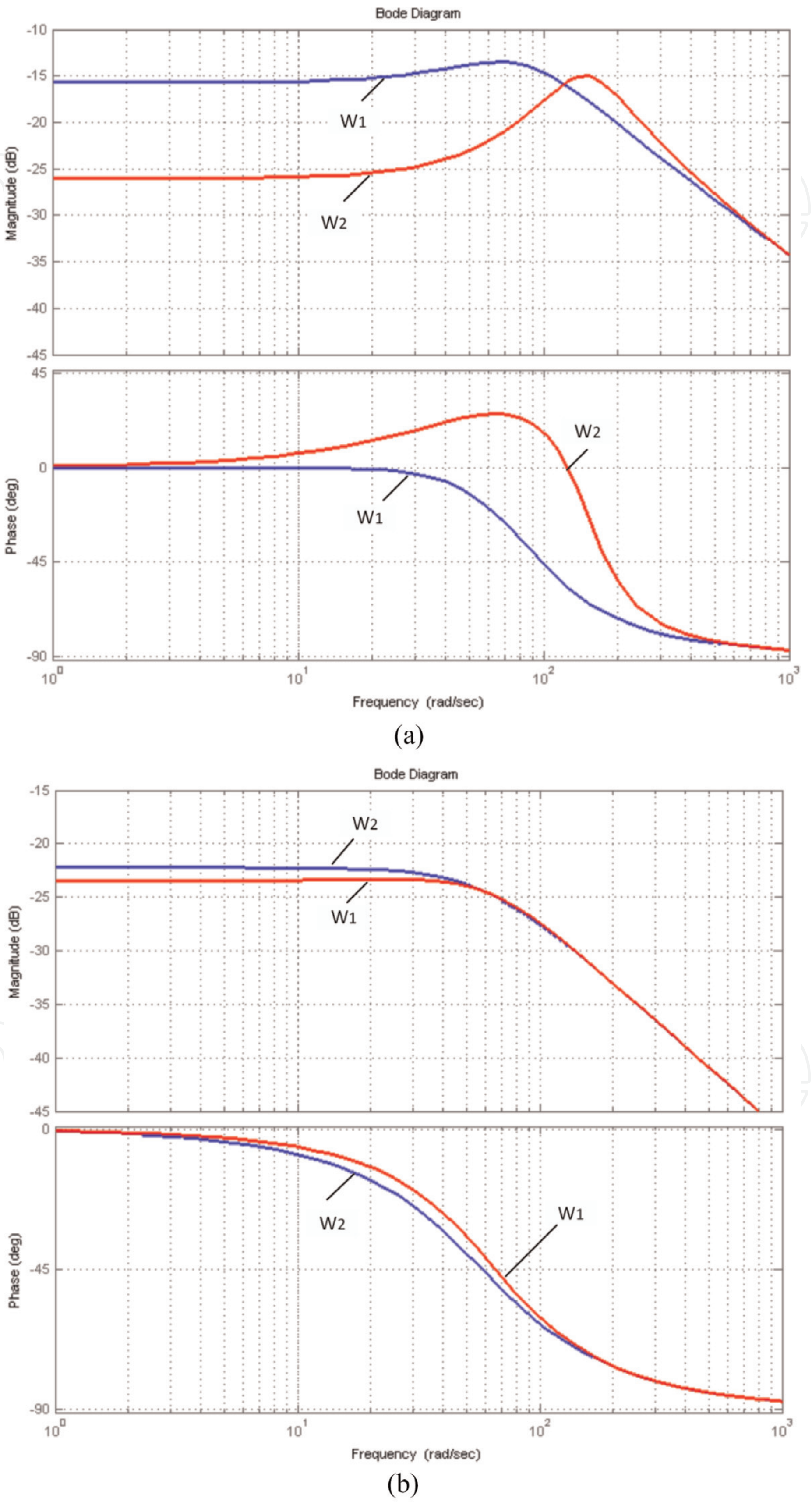


Figure 19.
Amplitude and phase frequency characteristics of the AED at different frequencies of the supply voltage (10 Hz (a) and 50 Hz (b)) and slips corresponding to small (ω_1) and nominal (ω_2) loads.

for the asynchronous drive, given in the monograph by Usoltsev [14]. In the proposed nonlinear interpretation, formula (5) and the block diagram (**Figure 18**) explain some of the problems of an asynchronous electric drive. To this end, it is proposed to consider the transfer functions and the corresponding frequency characteristics at "frozen" (fixed) but different values of the frequency of the stator voltage and slip. In this case, instead of the traditional characteristics of the control object, it will be necessary to consider "families" grouped by varying stator voltage (its frequency) or slip.

The frequency characteristics of an asynchronous electric drive with frequency control based on an asynchronous motor with a squirrel-cage induction motor used in the research stand (**Figure 4**) are shown in **Figure 19**. They are built using the *Matlab Simulink©* application.

The amplitude and phase frequency characteristics of an electric motor at a stator voltage frequency of 10 Hz and slip corresponding to small and nominal loads are shown in **Figure 19a**. **Figure 19b** shows similar characteristics for a stator voltage frequency of 50 Hz.

The given frequency characteristics well explain some of the problems of AED. When operating at low frequencies of the stator voltage, the phase shifts with changing load (and slip) change significantly, which leads to instability and inefficient operation at low speeds. It is necessary to pay attention to the change in frequency characteristics when changing the frequency of the stator voltage; this affects the acceleration processes. Thus, the nonlinearity of the transfer functions of the torque driver requires linearization to improve the efficiency of the electric drive. One of the widely used methods of linearization are various types of so-called "transvector" control. With this control, the dynamic links of the reverse dynamic links of the motor are formed in the control device. These links are adapted to different motor operation modes.

It should be noted that in a real drive, a perfect adaptation is impossible. The transfer functions incorporated in the software of the frequency converter and the real asynchronous motor may vary for several reasons (some parameters are difficult to measure, the structure of the real electric motor is much more complicated than the model, and some parameters may change during operation). Dynamic links are quite complex. This leads to the fact that the equivalent transfer functions of AED may in some modes contain resonant links that lead to control failures, high-frequency harmonics, and differences in dynamics at different speeds noted during the experiments [15, 16]. The stability analysis of such systems presents a known complexity. Moreover, the classical stability criteria for nonlinear systems do not apply to systems with dynamic nonlinearities. It is advisable to consider some of the "offshoots" of one of these criteria—Popov's criterion.

4. Analysis of stability of electric drives as nonlinear systems

4.1 Popov's criterion for nonlinear systems

Stability theory is a modern mathematical field which is probably the most widely used in the modern engineering for the last 100 years. Moreover, multiple research works on this theory were inspired or conditioned by practical problems of cybernetics and electromechanical systems. The similar mathematical field is definitely the theory of stability of nonlinear systems conceived by Romanian mathematician Popov [17]. This theory, once known as absolute stability theory and later as hyperstability theory, describes conditions of stability for automatic control systems which may reduce to the simplest structure given in **Figure 20**.

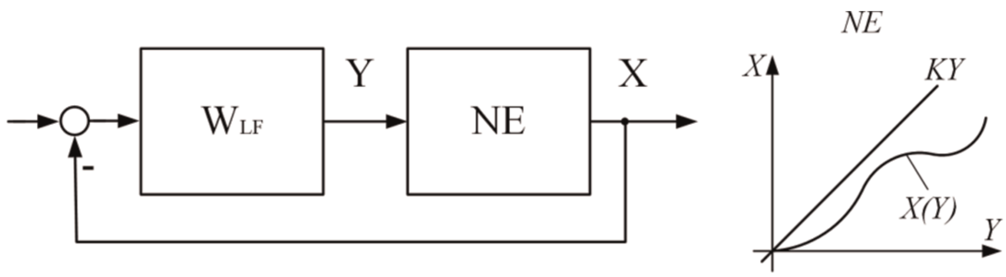


Figure 20.
Nonlinear automatic control system block diagram.

There can be distinguished linear element with frequency characteristic W_{LF} and nonlinear element (NE) that has an upper bound—static, for static nonlinearities (7), or integral (8).

$$X(Y) \leq KY \tag{7}$$

$$\int_0^t X(t)dt \leq KY \tag{8}$$

Popov obtained stability criteria by frequency characteristics of linear elements and boundary characteristics of nonlinear element. However, the practical application of the criterion for electric drives remained only limited. Plotting modified hodographs needed for the criterion was not very convenient. It was difficult to distinguish "weak" elements and suggest their adjustment. Real electric drives can hardly reduce to structures shown in **Figure 20** due to multiple cross couples, so the Nyquist criterion is still used even if results are not sufficiently accurate.

It is commonly believed that modern electric drives do not have a stability problem. All conventional systems use Pc, PI, and PID controllers as it is assumed that the whole system is close to a second-order linear system where these controllers are the most efficient. As a result, the wider application is being found by methods for building automatic systems based on stability criterion for linear systems—the Nyquist criterion.

There are several known formulations of this criterion.

1. For the closed-loop system, it is necessary and sufficient that for frequencies where a Bode magnitude plot is positive (i.e., $L(\omega) > 0$), the phase frequency characteristic of the open-loop system should not cross the axis $-180°$ or should cross it even a number of times (**Figure 21**).

In practice, most often this variant of the criterion is formulated as a limitation of a phase shift of the logarithmic frequency characteristic of the open-loop system at the cutoff frequency (i.e., at $L(\omega) = 0$) with a lower bound value ($-180°$).

Let us consider one of the most important features of the criterion—when it is used, only a certain range of frequency is taken into account, namely, the cutoff frequency of the system or some region around it. This results in a large number of practical consequences—criteria of negligibility of elasticity of servo drive gears, requirements for parameters of actuating motors and information systems, methods for separate, etc. Phase shift at the cutoff frequency may be used for assessment of stability "margin" of the control system (the difference between the phase shift and the critical value $-180°$). Along with that, results of experiments are often gravely inconsistent with a theory, but it is normally assumed that this inconsistence is within tolerable limits.

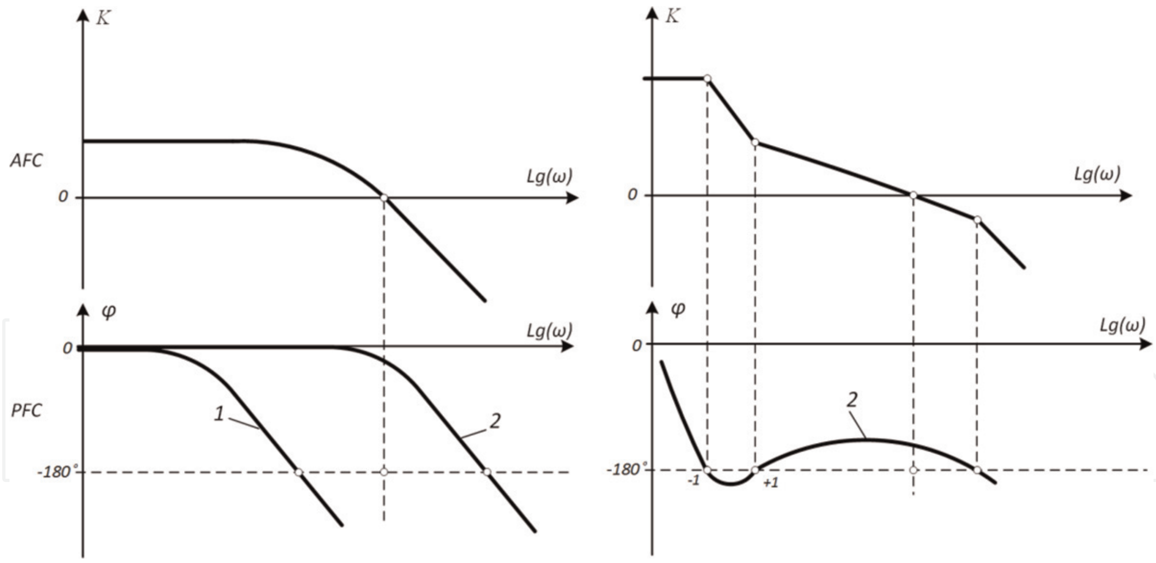


Figure 21.
Nyquist criterion by the Bode magnitude plot (1, instable system; 2, stable system).

In any case, attempts to question the very possibility of constructing electric drives, as something close to the desired linear systems, were extremely rare. Despite the fact that the presence of highly essential nonlinearities in them is not disputed by anyone. But their influence is not considered to be sufficient to abandon the usual methods of building electric drives.

The peak of research in this theory fell on the 1970s–1980s of the twentieth century and, at present, is considered irrelevant. This is due to many reasons. Let us discuss some of them more thoroughly. The first obvious reason is that many problems have already been solved over the years. The second is that due to technological progress in related areas of technology (in electronics, in engineering, especially in computing), the problem of sustainability has become "routine" for many cases. Since the characteristics of almost all elements of the systems become such that they do not affect the stability with modern requirements on accuracy and speed. However, in recent years, a class of systems has appeared, or rather "manifested," in which in the near future, a stability analysis will become extremely important. At the same time, the nonlinearity of these systems is obvious, and modern means and methods with which these nonlinearities are trying to compensate, according to many researchers, can lead not only to inefficient modes of operation but also to the emergence of critical and even emergency situations.

The authors conducted a whole range of experiments with these systems, and they concluded that it was necessary to analyze control systems from the point of view of stability and take into account their essential nonlinearities. These nonlinearities are such that linearization is quite difficult to carry out, and simplifications lead to the "emasculation" of any complexity in these tasks, while in practice all the difficulties remain. So Usoltsev [14] forcedly reduces the nonlinear asynchronous electric drive to a linear system II or even I order.

We assume that the widespread introduction of frequency control systems is a sufficient reason to return to the formulation and solution of problems of analyzing the nonlinear system stability. In our opinion, there are two main reasons for the rare use of Popov criterion in electric drives. One of them, purely technical, is that the criterion operates with frequency loci. Engineers are accustomed to working with amplitude and phase frequency characteristics, on which the influence of each link and any of its features is very clear. According to these characteristics, it is convenient to apply the Nyquist criterion and evaluate the effect on the stability of a particular link. According to the hodograph, such an analysis is possible only if this feature is singled out in a separate link. The calculation of the frequency locus of the entire system is a rather cumbersome process, and its automation makes it difficult to solve synthesis problems. The second is that in a frequency drive, it is impossible without simplification to divide the system into a purely linear link and a nonlinear structure, as is necessary in the Popov criterion. Hence, the first task is to formulate the Popov criterion in the categories of amplitude and phase frequency characteristics, to make it look like the Nyquist criterion.

4.2 Popov's sustainability criterion for systems with nonlinear dynamics

Analytically, the Popov criterion is as follows: the closed-loop automatic control system as in **Figure 20** is stable if there is a real positive q such that for linear and nonlinear elements of the system, the following condition is met:

$$\mathrm{Re}(1+j\omega q)W_{LF}+\frac{1}{K}>0 \tag{9}$$

This condition is equivalent to the following one (as K is real):

$$\mathrm{Re}\left[(1+j\omega q)W_{LF}+\frac{1}{K}\right]>0 \tag{10}$$

This condition is met if the phase shift of the combination of elements given in **Figure 22** is over (−90°).

Let us consider the elements of this diagram:

1. linear element with frequency characteristic W_{LF} of the linear part of the initial system

2. arbitrary lead element determined by q

3. instantaneous element where K is an upper bound of the nonlinear element like in the Popov criterion for the initial system

When this equivalent circuit is introduced into consideration, the Popov criterion may be formulated as follows: **nonlinear system reduced to the circuit presented in Figure 20 is stable if the phase shift of the equivalent circuit given in Figure 22 is −90° minimum, which is equivalent to positivity of the real part of the frequency characteristic of this equivalent circuit.**

This condition may be easily checked by frequency characteristics and analyzed using methods close to synthesis methods according to the Nyquist criterion. In contrast with this latter, the whole frequency range should be analyzed like in the Popov criterion, and not only the cutoff frequency like in the Nyquist criterion. The phase shift may be assessed using methods for building equivalent frequency characteristics. Here, two elements—linear and arbitrary lead—are series-connected, and the instantaneous element is paralleled. The analysis may be based on the rule of "positive limiting" of paralleled elements (**Figure 22**).

It may be assumed that this approach is also applicable for control systems where the dynamic element may be assessed by the family of frequency characteristics, that is, for all systems for which, without a serious error, it is impossible to distinguish linear dynamic element from nonlinear one having a static upper bound (**Figure 20**). Here, the condition will be analytical:

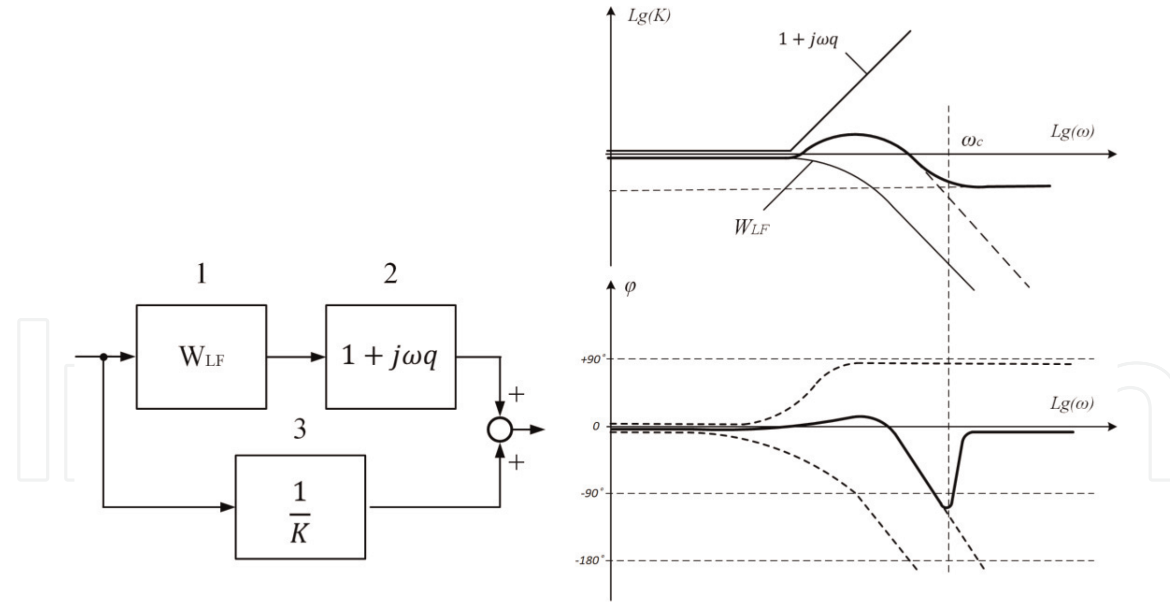


Figure 22.
Equivalent circuit of nonlinear automatic control system and its frequency responses.

$$\mathrm{Re}\left[(1+j\omega q)W_{\sim}+\frac{1}{K}\right]>0 \tag{11}$$

or according to the equivalent circuit, for the phase shift:

$$\varphi\left[(1+j\omega q)W_{\sim}+\frac{1}{K}\right]>-90° \tag{12}$$

Stability requires the positivity of a real part of the complex transfer function of the equivalent circuit (**Figure 23**) or the limitation of the phase shift of the same complex of elements at a level of −90° for all possible frequency characteristics. Phase margin may be estimated by the difference between the actual phase and −90°. Values of frequencies where the phase is below −90° allow the assessment of frequency of self-oscillations in the system.

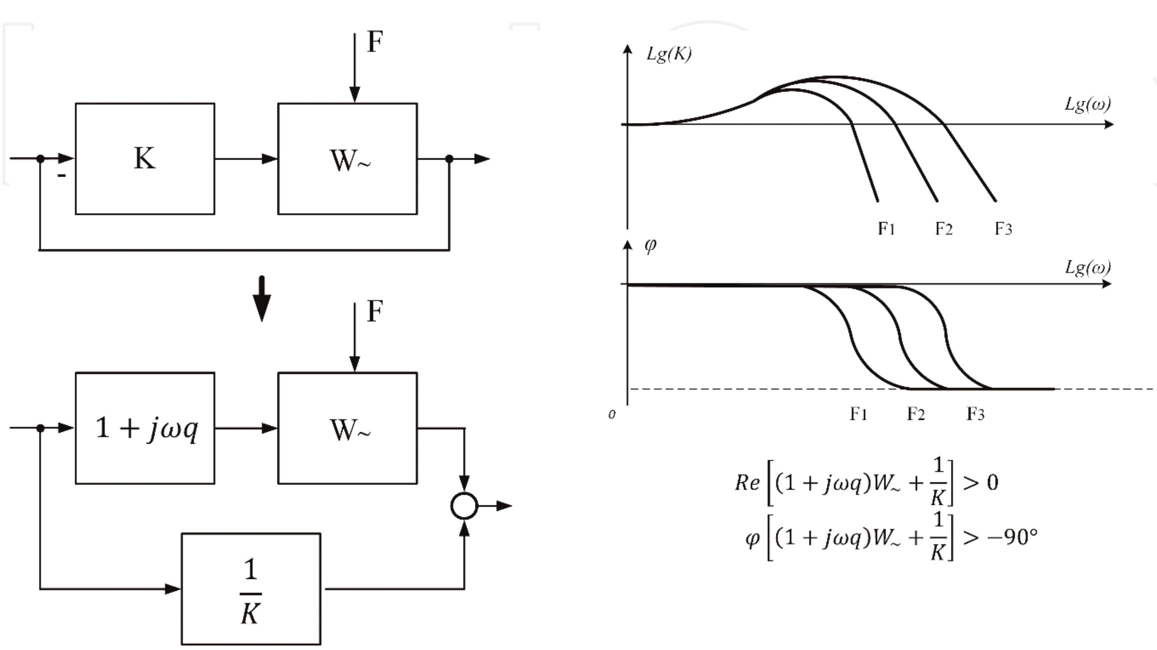


Figure 23.
Conditions of stability for control systems with dynamic nonlinear elements.

4.3 Correction for servo drive with elastic element

The difference between the suggested criterion (the suggested formulation of the Popov criterion, to be exact) and the Nyquist criterion is well seen considering the example of stability of a servo drive with a finite rigidity of gears. According to the Nyquist criterion, it is enough to "move the cutoff frequency away" from the frequency of elastic oscillations to "forget" about it. However, in practice it does not work like that. Stability testing by the means of suggested method proves it (**Figures 24** and **25**).

As can be seen from **Figures 19** and **20**, the link describing the gearbox, taking into account backlash and friction, can only be represented by a family of high-order dynamic links that will not allow an acceptable phase shift of an equivalent combination of links to satisfy the stability condition in the entire frequency range from 0 to ∞ Hz.

Effect of stabilization (or a fine stability margin) may be reached via introduction of actuating motor rate feedback which allows the adjustment of the combination of elements (**Figure 26**) and fulfillment of stability conditions for the whole system (or sufficient stability margin) (**Figure 27**). At the same time, it is necessary to pay special attention to the fact that this connection "works" in the entire frequency range—from 0 to +∞ Hz. The use of differentiating channels in PID regulators is always limited to the cutoff zone or slightly larger frequency range, because at high frequencies this channel enhances the influence of interference. And for the stability of the drive when the "shifted" frequency response of the elastic link, D-channel of regulator is not enough. Thus, the proposed interpretation of the stability criterion makes it possible to substantiate the advantages of structural correction before the generally accepted variant.

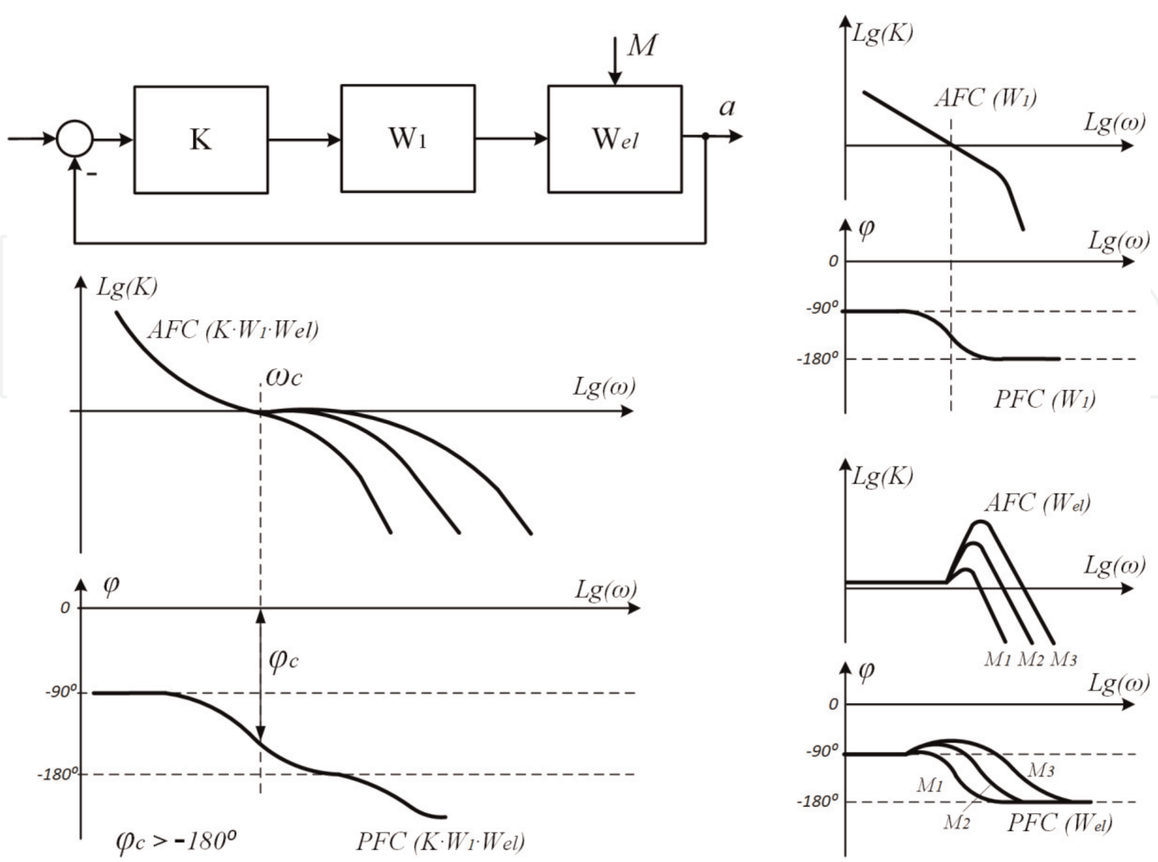


Figure 24.
Stability assessment for servo drive with elastic element according to the Nyquist criterion (satisfied).

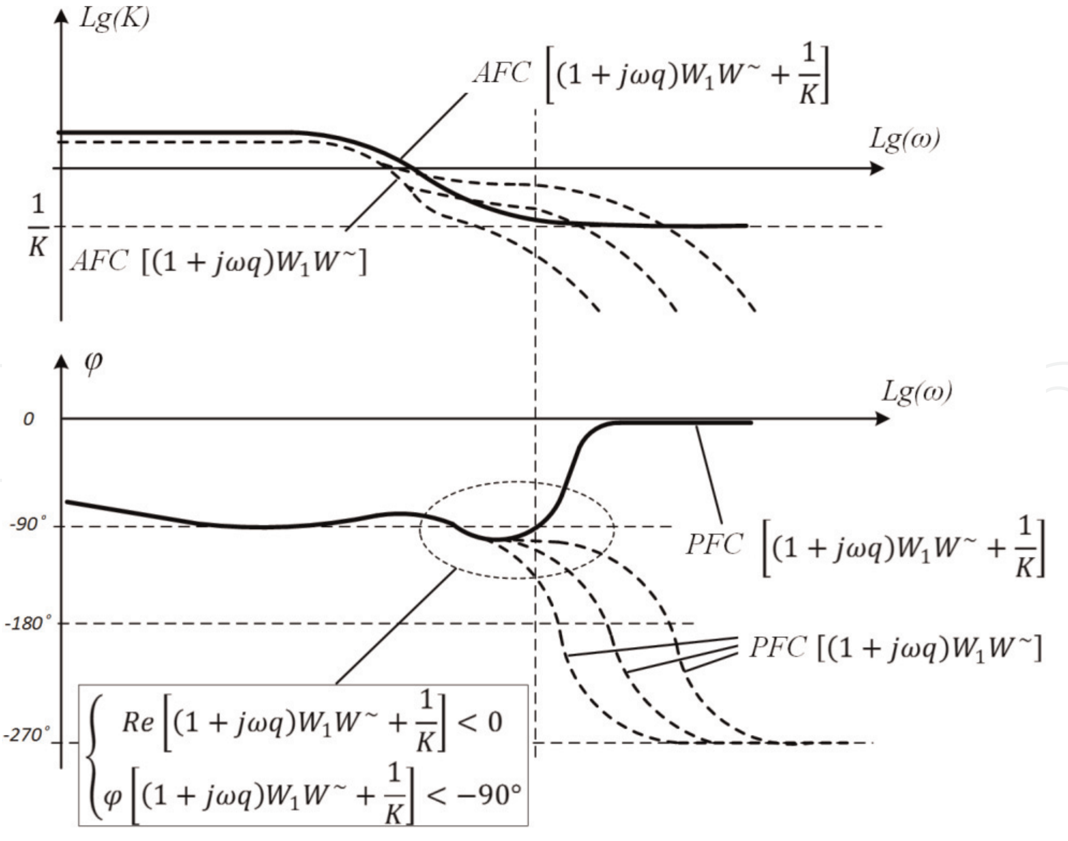


Figure 25.
Stability assessment for servo drive according to the Popov criterion (not satisfied).

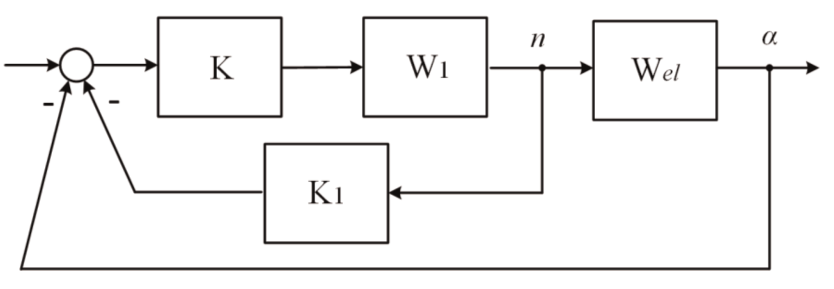


Figure 26.
Block diagram of servo drive with stabilizing rate feedback.

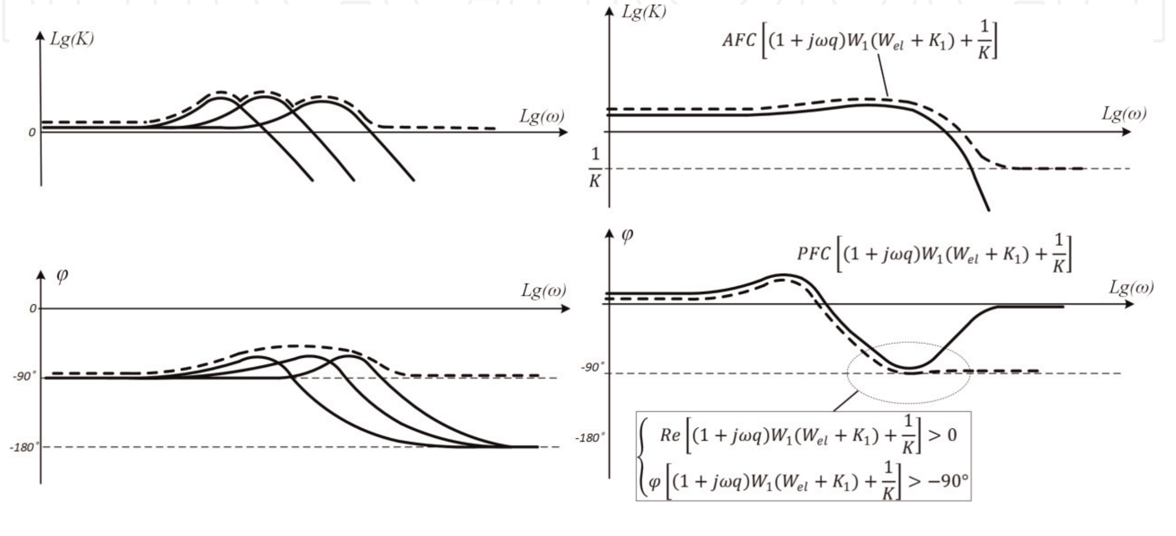


Figure 27.
Stability assessment for servo drive with stabilizing rate feedback according to the Popov criterion (satisfied).

4.4 Corrections of asynchronous electric drive

It is interesting to analyze the stability of AED, the block diagram of which contains several nonlinear dynamic links described above. As shown in **Figure 1**, vector control "linearizes" the drive converting it to a linear structure. As was shown above, this linearization is very conditional and not too accurate mathematically. However, even if we make assumptions about Laplace transformations with variable coefficients, it is impossible to avoid discrepancies in the parameters (and structure) of the model and the real motor. This will lead to the fact that their serial connection will produce a disproportionate linear link and a floating dynamic link that will be close to the resonant link. Even if we assume that this link is close to linear, for stability it is necessary to apply the stability criterion for nonlinear systems (a variant of the Popov criterion) and, therefore, to consider the entire frequency range, and not just the cutoff frequency. **Figures 28** and **29** show how applying the Nyquist criterion gives an incorrect result (and the Popov criterion is not satisfied) for a vector-controlled drive closed in speed with a PID controller. As the experiments showed, the applied algorithms are not very effective, and the hard positive feedback on the stator current breaks the stability. In works [6, 15, 18] the positive dynamic connection on current is described. Without compromising

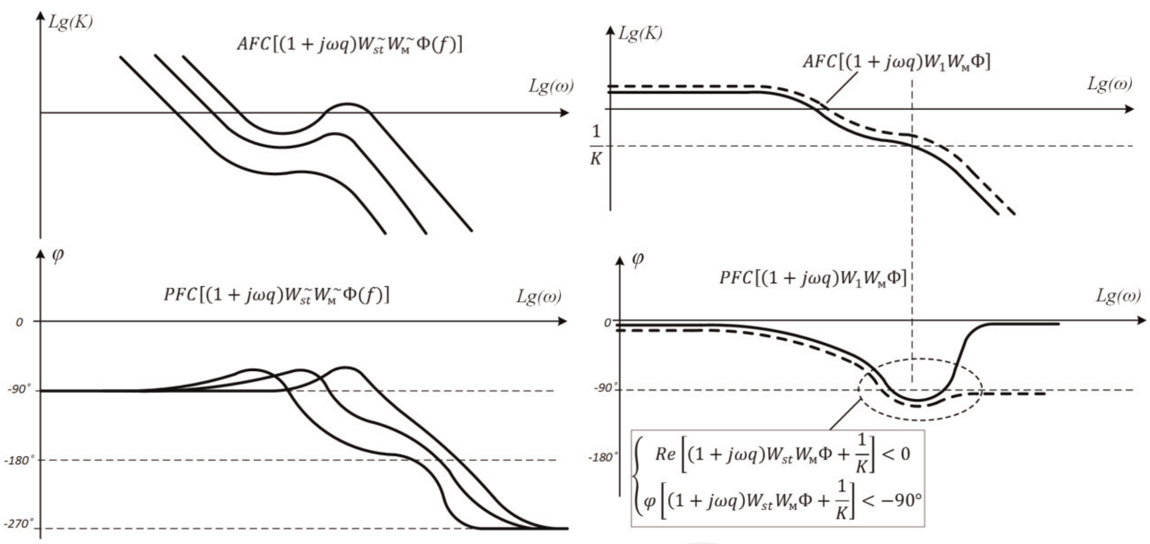


Figure 28.
Assessment of stability in the AC drive according to the Popov criterion (not satisfied).

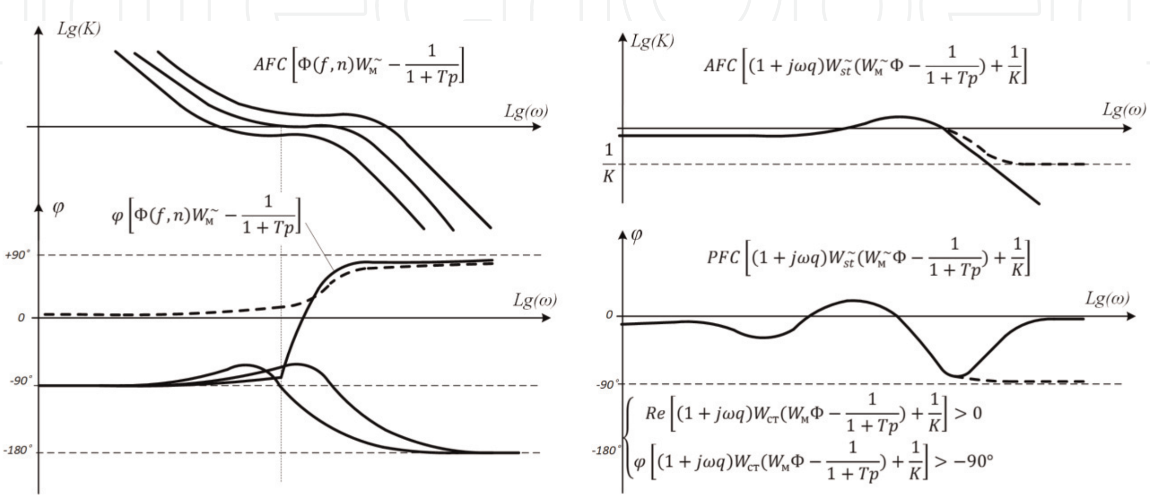


Figure 29.
Stabilization of the drive by positive feedback of the stator current with a first-order filter. Verification by Popov criterion.

stability (and in some cases improving it), this relationship provides full compensation for the load torque and not only in statics. The effect of such a relationship is described in [5, 6] and the patent [9, 11] and also confirmed by numerous experiments. The effectiveness of this connection is also confirmed by the calculation of the transfer function and frequency characteristics of the link for the formation of the torque with a positive feedback of the stator current (PDF—positive dynamic feedback).

4.5 Justification of PDF for transfer functions of AED

According to the formulas, it is possible to explain the efficiency of the positive feedback on the current of the stator of the electric motor, described in the articles [6, 15, 18]. Consider the option of applying local feedback on the electromagnetic torque in this structure. The structural diagram is shown in **Figure 30**.

In this case, the transfer function of the torque driver will take the form:

$$W_{eq} = \frac{\frac{2M_k\left(T_2'p+1\right)S_k}{\omega_1\left[(1+T_2{}'p)^2S_k^2+\beta^2\right]}}{1+\frac{2M_kS_k\left(T_2'p+1\right)W_{DF}}{\omega_1\left[(1+T_2{}'p)^2S_k^2+\beta^2\right]}} = \frac{2M_kS_k\left(T_2'p+1\right)}{\omega_1\left[(1+T_2{}'p)^2S_k^2+\beta^2\right]+2M_kS_k\left(T_2'p+1\right)W_{DF}} \tag{13}$$

Under the following conditions,

$$\omega_1\beta^2 = -2M_kS_k\left(T_2'p+1\right)W_{DF} \tag{14}$$

those, if the corrective link has the following transfer function,

$$\mathrm{W_{DF}} = -\frac{\omega_1\beta^2}{2M_kS_k\left(T_2'p+1\right)} \tag{15}$$

the transfer function of the torque driver takes the form:

$$W_{eq} = \frac{2M_kS_k\left(T_2'p+1\right)}{\omega_1\left[(1+T_2{}'p)^2S_k^2\right]} = \frac{2M_k}{\omega_1S_k(1+T_2{}'p)} \tag{16}$$

Becomes a linear link, independent of the slip (load) and fully coinciding with the transfer function given in the Usoltsev monograph for small loads [14]. Pay attention to formula (15). A dynamic link is a first-order inertia with a coefficient that ultimately depends on the frequency of the stator voltage and on the absolute

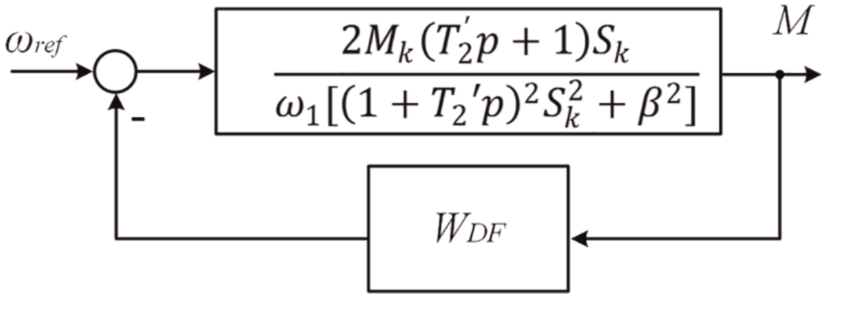


Figure 30.
Structural diagram of AED with a local feedback electromagnetic torque.

slip. The sign (−) in front of the formula means that the relationship must be positive. We call this relationship positive dynamic feedback (PDF). It should be noted that the correction of the coefficient from the frequency is very easy to implement in frequency converters; several options for partial (indirect) adaptation of the connection to the load will be discussed below. Thus, the proposed positive feedback, selected by condition (15), makes it possible to compensate for the effect of the external load and the nonlinearity of the AED, spreading the transfer function of the motor as a link of the first order for any values of β. In addition, the block diagram (**Figure 13**) and the transfer function of the torque formation link (6) connecting the torque and slip allow us to offer an estimate of the efficiency of the torque formation algorithm: the algorithm that generates the necessary torque with the smallest absolute slip will be more effective.

Next, we consider the correction of the AED with the parameters corresponding to the frequencies of the supply voltage of 10 and 50 Hz. The initial frequency characteristics are shown in **Figure 19**. The transfer functions of the original AED with such parameters and the transfer functions of the corrective units are given in **Table 3**, and the initial and corrected frequency characteristics of the AED are shown in **Figures 31** and **32** for the frequencies of the supply voltage of 10 and 50 Hz, respectively.

As expected, the frequency characteristics of the AED with the structural correction proposed in the work are close to the frequency characteristics of the first-order linear link.

In widely used AEDs, it is very difficult to realize the mechanical torque feedback. Given that the electromagnetic torque is equal to $I_1{}^{*}\Psi_2$ and in almost all calculations it is assumed that the rotor flux linkage is constant, you can replace the original signal in this local connection with the effective value of the stator current or its active component, which is calculated in all the inverters.

To communicate with the stator current, the linearization conditions will vary somewhat:

$$\omega_1\beta^2 = -2M_kS_k\left(T_2'p+1\right)\frac{W_{DF}}{\Psi_2} \tag{17}$$

This expression shows that when controlling the flux linkage, the linearization conditions can be refined, thereby providing high-quality regulation.

On the other hand, it is easy to show that with some inaccuracy in the fulfillment of the linearization condition, that is,

$$\frac{\beta}{S_k}-\frac{2M_k\left(T_2'p+1\right)\cdot W_1}{\Psi_2}\neq 0=\Delta, \tag{18}$$

Frequency, Hz	Slip*	Electromagnetic torque transfer function, W(p)	Dynamic feedback transfer function, W_{DF}
10	β_1	$\frac{0.038p+0.226}{0.0002p^2+0.0229p+1.38}$	$\frac{3.128}{0.017p+1}$
	β_2	$\frac{0.038p+0.226}{0.0002p^2+0.0229p+4.52}$	$\frac{16.99}{0.017p+1}$
50	β_1	$\frac{0.027p+1.548}{0.006p^2+0.628p+20.56}$	$\frac{0.09}{0.017p+1}$
	β_2	$\frac{0.027p+1.548}{0.006p^2+0.628p+21.19}$	$\frac{0.497}{0.017p+1}$

β_1 corresponds to slip at low load, and β_2 corresponds to slip at nominal load.

Table 3.
The transfer functions of the channel of formation of the electromagnetic torque and dynamic feedback for different values of the frequency of the stator voltage and slip.

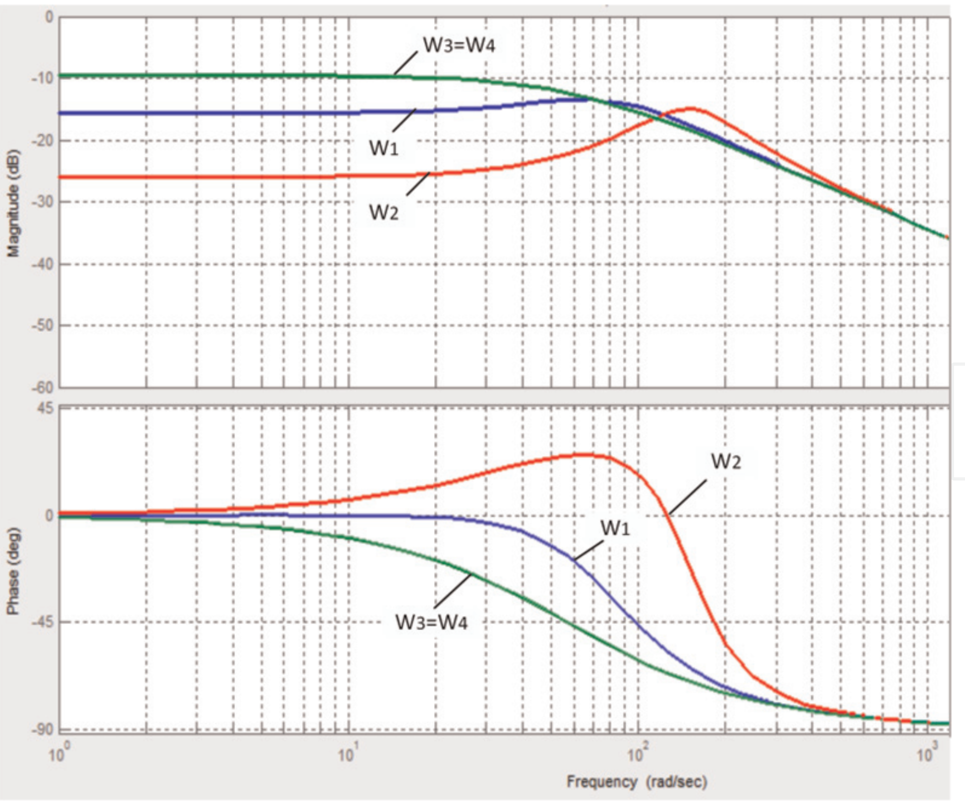


Figure 31.
Frequency characteristics of the formation of the torque: the original (W1, W2) and adjusted (W3, W4) for the frequency of the supply voltage 10 Hz.

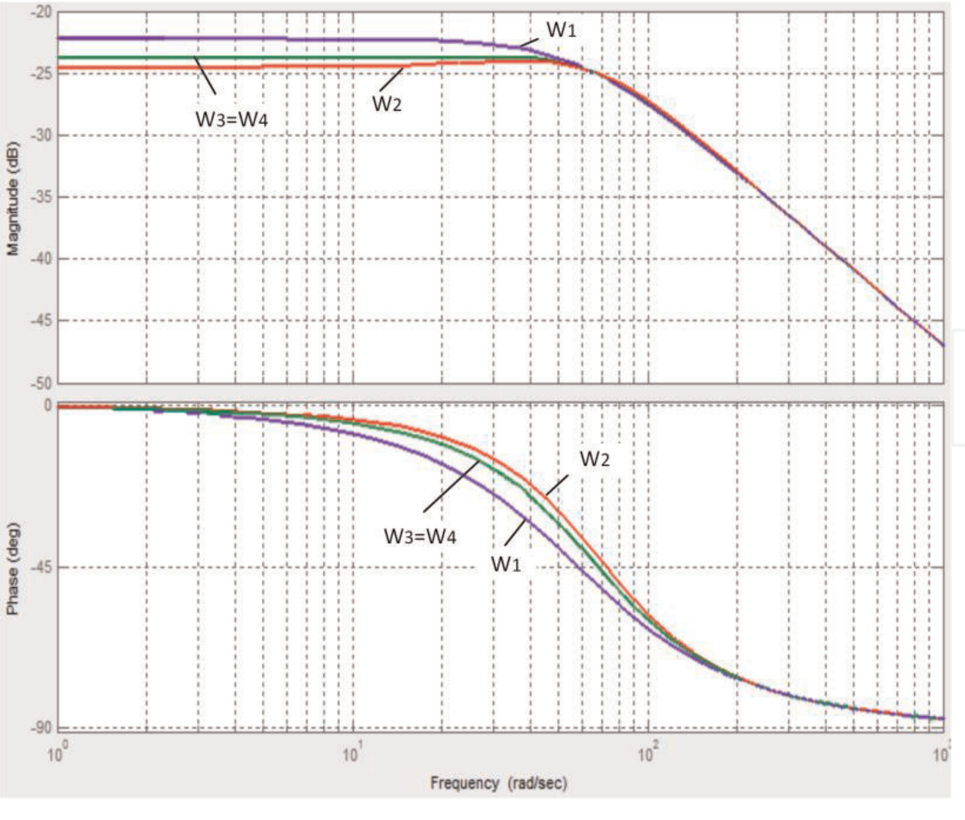


Figure 32.
Frequency characteristics of the formation of the torque: the original (W1, W2) and adjusted (W3, W4) for the frequency of the supply voltage 50 Hz.

DOI: http://dx.doi.org/10.5772/intechopen.88223

the transfer function (TF) and frequency characteristic (FC) of the torque driver will differ slightly from the TF and FC of the first-order linear link.

Consider the case of the deviation of the parameters of the corrective element by 5% for the frequencies of the supply voltage of 10 and 50 Hz. The frequency characteristics of the torque driver link with accurate correction (W1, W2) and the correction factor transfer coefficient deviation of ±5% (W3, W4) are presented in **Figures 33** and **34**.

It was previously shown that when the signal of the motor rotation speed deviates by 5%, the vector control at some speeds "falls apart." Thus, the proposed method of analyzing processes in an asynchronous drive with frequency control according to varying frequency characteristics ("families" of characteristics with frozen frequency and slip parameters) made it possible to offer effective, from the point of view of theoretical analysis, correction without speed sensors, which allows linearizing a substantially nonlinear structure.

In the future, the effectiveness of the proposed relationship is confirmed by modeling and experiment.

Comparative speed diagrams (static and dynamic characteristics) for an open-loop system, speed closed system, and stator current closed system are shown in **Figure 35**. The results of studies of the frequency properties of AED are presented in **Table 4**.

The formulas of the frequency characteristics of the electric drive with positive feedback on the stator current shown in **Figure 36** have significantly less variability in frequency characteristics due to changes in frequency (f) and slip (S). This

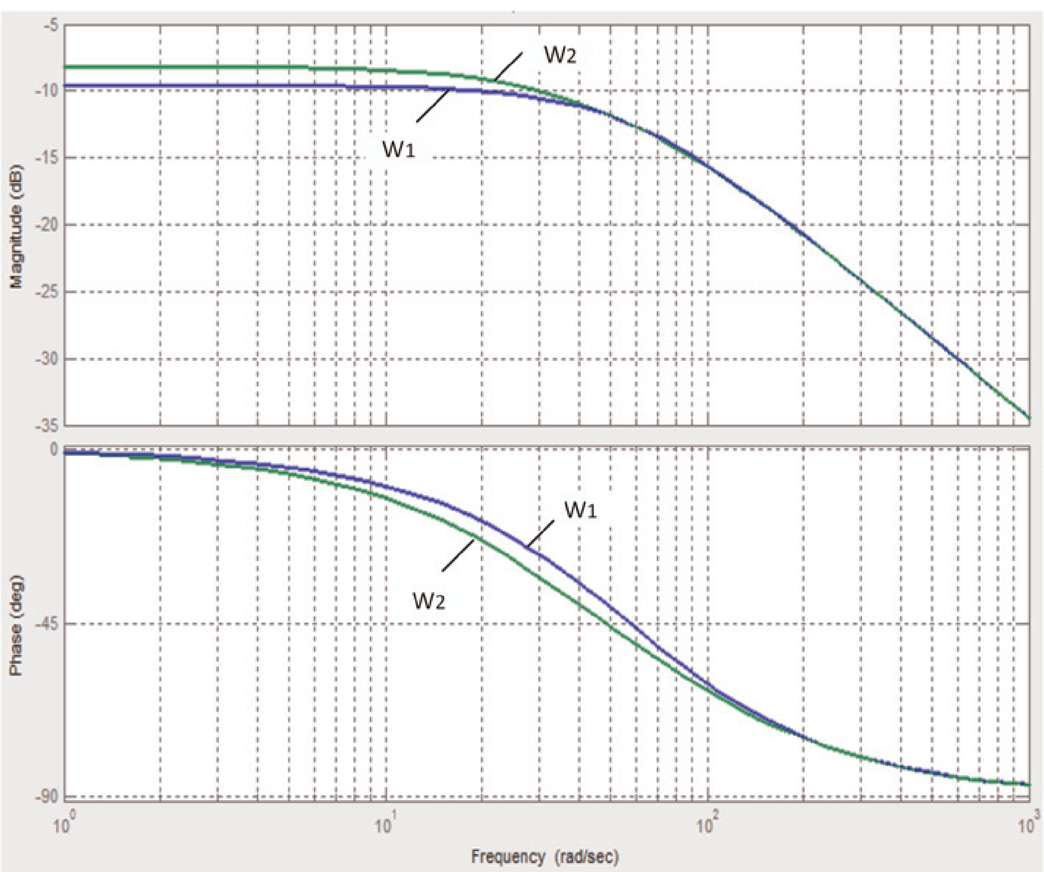


Figure 33.
Frequency characteristics of the torque driver and transfer functions of the corrective element for the frequency of the stator voltage of 10 Hz, accurate (W1) and with a deviation of the transmission coefficient of the corrective element by 5% (W2).

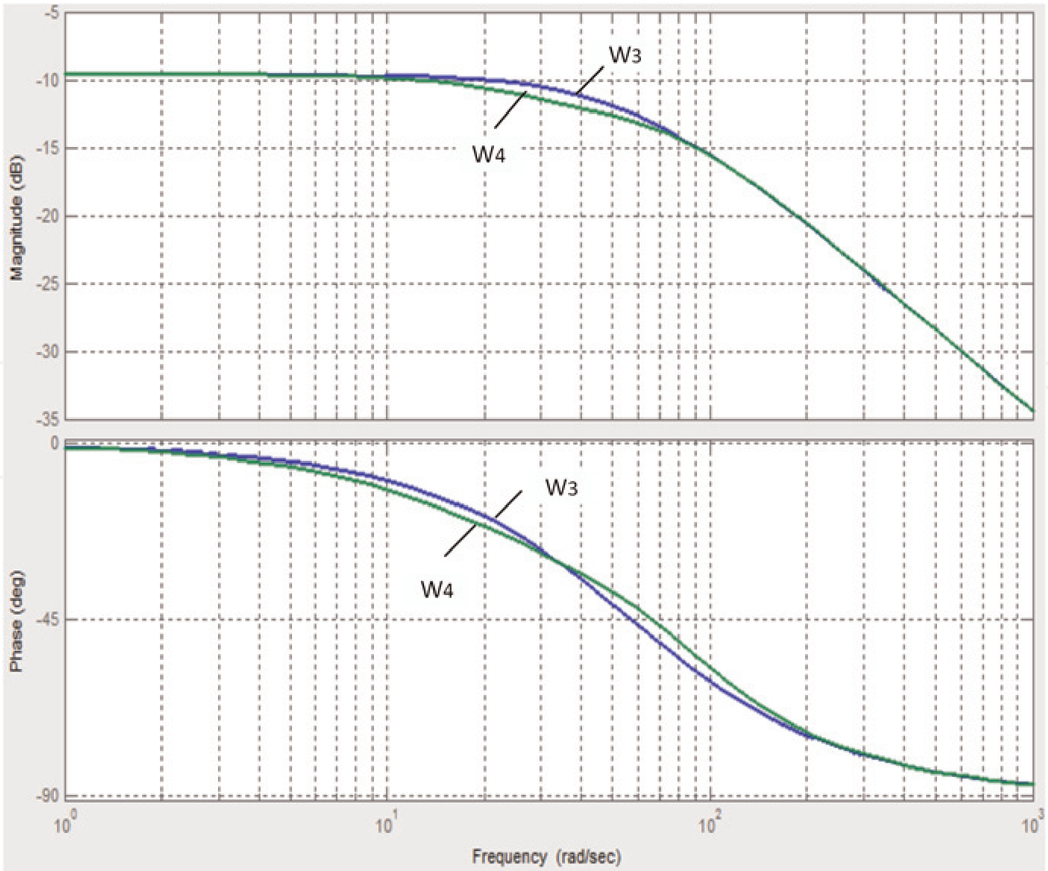


Figure 34.
Frequency characteristics of the torque driver and transfer functions of the corrective element for the frequency of the stator voltage of 50 Hz, accurate (W3) and with a deviation of the transmission coefficient of the corrective element by 5% (W4).

explains the stability of transients during acceleration and load buildup at various speeds of rotation. This also explains the significantly smaller differences in processes at different speeds of rotation. These frequency characteristics are close to the frequency characteristics of DC drives, which open up prospects for their use in complex mechanisms, including in drives of complex industrial mechanisms.

Spectral analysis of rotor currents also showed a higher efficiency of the proposed correction—both the model and experimental studies showed significantly lower frequencies of rotor currents and the absence of a spectrum below the fundamental frequency.

Particular attention should be paid to the same frequency of rotor currents in the model when the load is loaded at different speeds of rotation. This indicates the stabilization of the rotor flux linkage, which will be confirmed by special modeling. Attention should be paid to smaller values of stator currents, both in models (**Figure 37**) and in experiments (**Figure 36**).

The frequency of the rotor current under load (at a speed of 90 rad/s) with vector control, scalar without feedback, and scalar with feedback on the stator current is 10.6, 2.72, and 1.74 Hz, respectively.

The frequency of the rotor currents is the lowest in the model of the system with a positive feedback on the stator current, which indicates a more efficient algorithm for the formation of a mechanical torque. At that, in comparison with the scalar control in an electric drive with a positive stator current connection, work at low speeds is stabilized, and, in practice, there are no speed dips in the case of load surges, and in comparison with the vector, there are significantly lower frequencies of the rotor current and, accordingly, the frequency of real slip. Analytic way to explain and, even more so, to predict this situation is almost impossible, so let us

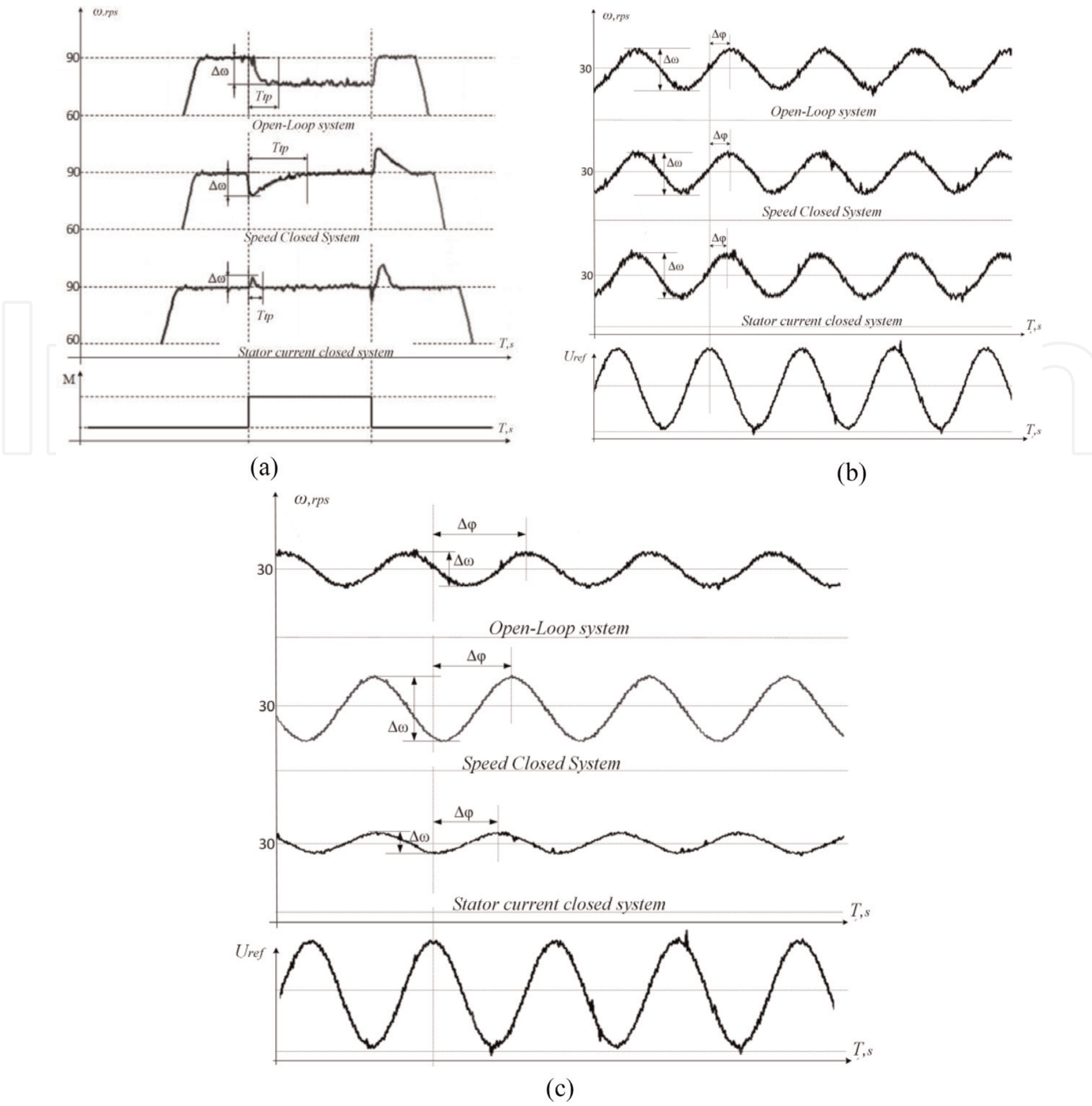


Figure 35.
Comparative speed diagrams (static (a) and dynamic (b, c) characteristics) for an open-loop system, speed closed system, and stator current closed system.

Electric drive control system	Static load		Periodic speed reference		Periodic load	
	Δω, rad/s	Ttp, s	Δω, rad/s	Δφ, el. deg	Δω, rad/s	Δφ, el. deg
Open-loop system	10	0.3	±5.03	84	±2.19	270
Speed closed system	10	0.6	±4.99	84	±3.31	230
Stator current closed system (PDF)	4	0.1	±6.4	72	±1.19	200

Table 4.
The parameters of the experimental signals for various control systems AED shown in **Figure 35**.

turn to experiments. The values of the fundamental frequencies under load and no-load are shown in **Table 5**.

Attention should be paid to the possibilities of further improvement of control algorithms, which are opened using the rotor current signal, for example:

1. You can get accurate information about the speed of electric motor rotor rotation.

2. It is possible to accurately calculate the rotor flux linkage and remove one of the essential assumptions from the control.

These changes in algorithms can significantly improve the controllability of asynchronous electric motors. To solve the problem of measurement in various ways, the most obvious is to use electric motors with a phase rotor, which the Russian industry continues to produce. They are not as technologically advanced as squirrel-cage induction motor, but as the experience of the entire twentieth century shows, controllability is worth the price. You only need to define it.

Thus, spectral analysis of the rotor currents of an asynchronous electric drive can be a very effective method of identifying control algorithms for nonlinear structures, which include an asynchronous electric drive with frequency control. This analysis showed that the most effective method used in standard frequency converters for the formation of time would be frequency control with positive feedback of the stator current. This control is dominated by pronounced harmonic components, which indicates the proximity of this structure to the linear and significantly better controllability of the drives, which makes them promising to be used in high-tech mechanisms, in particular, in industrial robots.

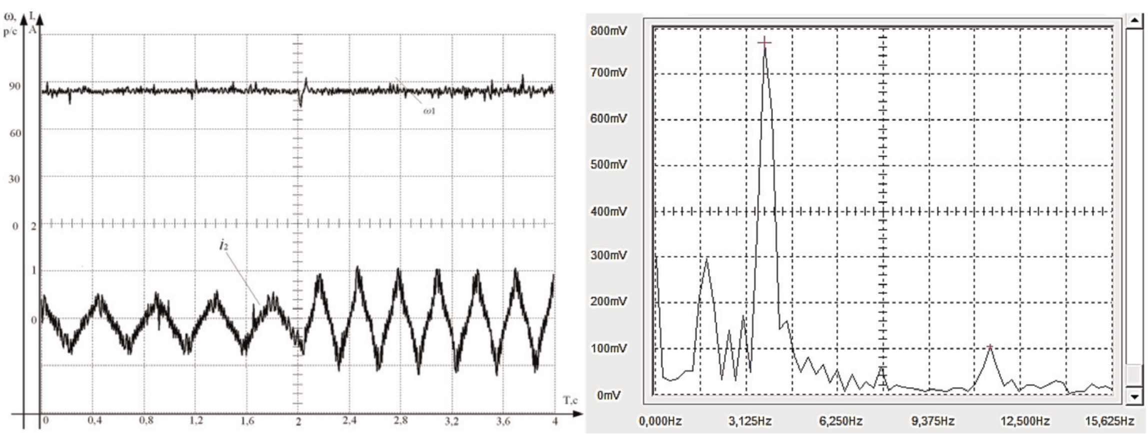


Figure 36.
Diagram of the speed and current of the rotor of an asynchronous drive with scalar control and stator current feedback. Spectrum of the rotor current signal.

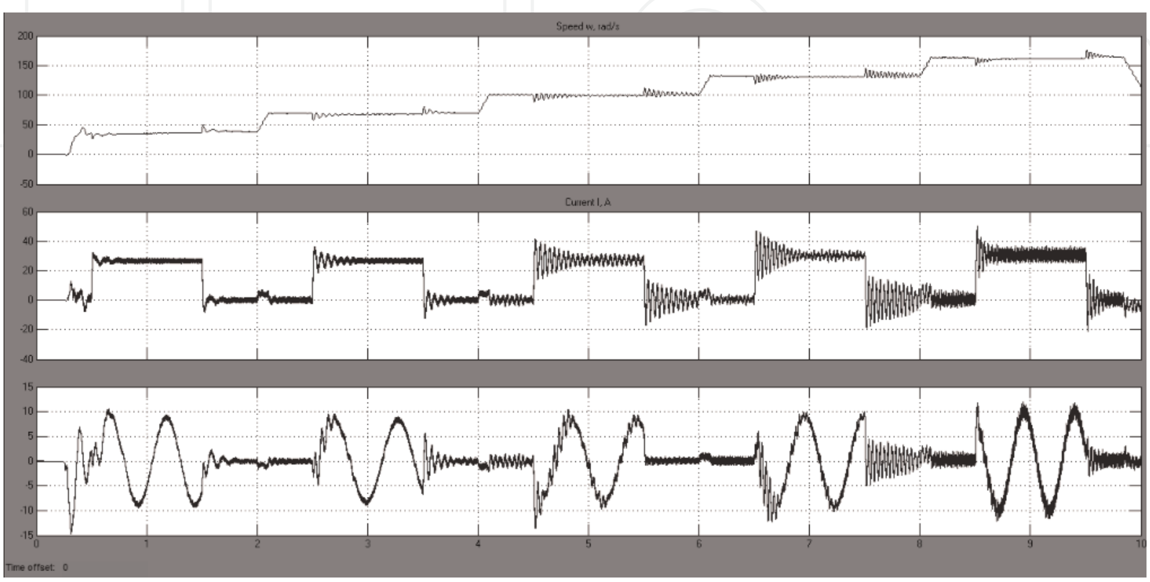


Figure 37.
Modeling processes in an asynchronous electric drive with scalar control with feedback on the stator current (PDF).

Control system	No-load	Under load
Vector control	2.1 Hz	6.25 Hz
Vector speed feedback control	2.1 Hz	8.75 Hz
Scalar control without feedback	1.69 Hz	4.75 Hz
Scalar control with stator current feedback	1.75 Hz	3.5 Hz

Table 5.
Frequency and value of the fundamental harmonic for various control algorithms.

4.6 Structural stability of AED

The described analysis and examples show that stability of electric drive or a good stability margin ensuring required processes may be obtained not only by bringing the system elements closer to ideal as first- and second-order elements (which often entails material costs) but also by finding necessary structural solutions. Along with that, for systems with oscillations in the direct channel elements, the best effect is reached with the help of additional cross couples and, for nonlinear negative couples, with the help of dynamically adjusted positive feedback. It should be admitted that there is still no universal method of solving nonlinear differential equations, but in some cases the effective solution is possible. The suggested interpretation of the criterion allows the logic transition to the notion of "structural stability." For that, conditions of stability at $K \to \infty$ should be considered. Here, conditions (7) and (8) will be as follows:

$$\mathrm{Re}[(1 + j\omega q)W_{\sim}] > 0 \tag{19}$$

and for the phase shift,

$$\varphi[(1 + j\omega q)W_{\sim}] > -90°, \tag{20}$$

along with that, stability will influence the Bode phase plot throughout the whole frequency range.

In the real electric drive, especially in alternating current one, there are both nonlinearities and high-order dynamic elements; therefore, it is not permissible to reduce them to linear variants. The suggested interpretation makes it possible to analyze stability and stability margin and to find structural solutions for stability problem for nonlinear structures. At the same time, the structural correction effectively works with sinusoidal disturbance signals, which suggests the possibility of applying frequency-controlled AEDs in systems with master signals and disturbances of complex spectral composition. In which until today, they have not been applied.

5. Conclusions

The proposed structural transformations - positive dynamic feedback on the stator current does not require constructive changes in the engines (e.g., installation of flow coupling sensors) and complex calculations (as in DTC). At the same time, it can provide a state of AED that is closer to LSS than scalar and vector control. Experiments will be conducted to ensure the best dynamic and static characteristics of the AED with "PDF."

1. The complex of the conducted studies confirmed the need to analyze the dynamics of asynchronous electric drives with frequency control as nonlinear non-stationary systems. Vector control implemented in standard frequency converters of world leading companies widely used in industry and power engineering in dynamic modes performs inefficient linearization by "direct" conversions, which, under numerous assumptions and use of linear stability and optimization criteria, leads to inefficient dynamic parrying of external loads. The proposed formulation of the stability criterion for systems with nonlinear dynamics in terms of amplitude and phase frequency characteristics has shown its effectiveness for the synthesis of structural solutions in AED.

2. The proposed method for identifying asynchronous electric drives by a family of frequency characteristics and transfer functions allows describing the main problems arising in the practical implementation of electric drives, namely, the nonlinear response from loads at different speeds of rotation of the electric motor, unprovoked control failures, non-sinusoidal processes in the electric drive, and dynamic processes with external disturbances in the first place.

3. It is shown that the AED correction in the zone of the cutoff frequency, based on the Nyquist criterion, is ineffective due to significant nonlinearities of the electric drive, and structural solutions operating in the entire frequency range can significantly improve a number of very important dynamic characteristics of the electric drive. The proposed correction method, based on the introduction of dynamic positive feedback of the stator current, allows to provide the drive advantage in dynamic modes of operation to a large extent to ensure the overload characteristics of the drive.

4. The proposed comprehensive method for studying complex control systems with essentially nonlinear links, combining qualitative analysis with detailed experiments and modeling, has shown its effectiveness. It allows you to establish cause–effect relationships in the processes and suggest ways to improve them.

5. The proposed method of identifying control algorithms and the dynamics of the electric drive using the rotor currents of the motor is very effective and has significant prospects in new ways of AED control.

6. Studies have shown that the frequency control of AED when improving its algorithms has significant prospects for application in precise technologies in the development of complex reference and disturbing signals.

Author details

Vladimir L. Kodkin*, Alexandr S. Anikin and Alexandr A. Baldenkov
South Ural State University (National Research University), Chelyabinsk, Russia

*Address all correspondence to: kodkina2@mail.ru

References

[1] Kodkin VL, Khaybakov ER. Direct motor speed controller. No. 2006106477/09; Claimed: March 02, 2006; Publ.: March 02, 2006, Bull. No. 29. 11p. Patent No. 2336624 Russian Federation, IPC H02P 27/06

[2] Malcher MA, Anikin AS. Problems of introduction of frequency regulation in the mining industry. Mining Equipment and Electromechanics. 2011;**4**:40-46

[3] Kodkin VL, Anikin AS, Malcher MA. Problems of implementation of frequency control in mining industry. Bulletin of the South Ural State University Series: Energy. 2012;**18**(37): 67-71

[4] Kodkin VL, Anikin AS. Frequency control of asynchronous electric drives in transport. 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

[5] Kodkin VL, Anikin AS, Shmarin YA. Effective frequency control for induction electric drives under overloading. Russian Electrical Engineering. 2014;**85**(10):641-644. DOI: 10.3103/S1068371214100101

[6] Kodkin VL, Anikin AS, Baldenkov AA. Experimental research of asynchronous electric drive with positive dynamic feedback on stator current. In: 2017 International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM) – Proceedings; 2017. DOI: 10.1109/ICIEAM.2017.8076179

[7] Kodkin VL, Anikin AS, Shmarin YA. Dynamic load disturbance correction for alternative current electric drives. In: 2nd International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM); South Ural State University Chelyabinsk – Proceedings; 2016. DOI: 10.1109/SIBCON.2015.7146978

[8] Kodkin VL, Anikin AS, Baldenkov AA. Spectral analysis of rotor currents in frequency-controlled electric drives. In: 2nd International Conference on Automation, Mechanical and Electrical Engineering (AMEE 2017) – Proceedings; 2017. DOI: 10.2991/amee-17.2017.26

[9] Kodkin VL, Anikin AS. The device for frequency control of an asynchronous electric drive. No. 2010108563/07; Claimed: March 09, 2010; Publ.: February 20, 2011; Bull. No. 5. 12p. Patent No. 2412526 Russian Federation, IPC H02P 23/00

[10] Solomin EV, Anikin AS, Sirotkin EA, Solomin EE, Sirotkin AA, Kozlov SV. Adaptive combined device for regulating the rotor speed of the wind power plant. No. 2014154564/06; Claimed: December 31, 2014; Publ.: October 10, 2015; Bull. No. 28. 5p. Patent No. 155 351 Russian Federation, IPC F03D 7/04, F03D 1/00, F03D 3/00

[11] Kodkin VL, Anikin AS, Shmarin YA, Baldenkov AA. The device for frequency control of an asynchronous electric drive. No. 2014151549/07; Claimed: November 17, 2015; Publ.: October 10, 2016; Bull. No. 28. 12p. Patent No. 2599529 Russian Federation, IPC H02P 25/02

[12] Kodkin VL, Anikin AS, Baldenkov AA. The dynamics identification of asynchronous electric drives via frequency response. International Journal of Power Electronics and Drive Systems. 2019; **10**(1):66-73

[13] Kodkin V, Anikin A, Baldenkov A. Families of frequency characteristics, as

a basis for the identification of asynchronous electric drives. In: 2018 International Russian Automation Conference (RusAutoCon); 2018

[14] Usoltsev AA. Vector Control of Asynchronous Motors. Tutorial.—Spb.: ITMO. 2002. Available from: http://servomotors.ru/documentation/frequency_control_of_asynchronous_motors/chastupr.pdf. 120p

[15] Kodkin VL, Anikin AS, Baldenkov AA. Analysis of stability of electric drives as non-linear systems according to Popov criterion adjusted to amplitude and phase frequency characteristics of its elements. In: 2nd International Conference on Applied Mathematics, Simulation and Modelling (AMSM 2017) – Proceedings; 2017. pp. 7-14. DOI: 10.12783/dtetr/amsm2017/14810

[16] Kodkin VL, Anikin AS, Baldenkov AA. The analysis of the quality of the frequency control of induction motor carried out on the basis of the processes in the rotor circuit. Journal of Physics: Conference Series. 2018;**944**(1):1-10

[17] Popov VM. Hyperstability of Dynamic Systems. Berlin: Springer-Verlag; 1973

[18] Kodkin VL. 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. In: Proceedings of SPIE - The International Society for Optical Engineering; 2016