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Energy-Saving Control for Asynchronous Motor Motion System Based on Direct Torque Regulator

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Abstract: Energy saving issues occupy a leading position in all control systems. This article provides a detailed analysis of control systems and is conducted by considering the complexity of implementation and response to the control action. The implementation of energy-saving control systems is directly related to the selected control system and the proposed energy-efficient algorithm. A system with direct torque control is proposed, which provides energy savings in the mechanisms for moving goods. A detailed analysis of the implementation of systems with direct torque control is carried out. New methods to save energy in the control system by minimizing the stator current have been proposed.

Keywords: asynchronous motor; direct torque control; alternating current; squirrel-cage rotor; frequency control

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1. Introduction

The development of energy efficient control systems for movement mechanisms is a popular area for research [1–4]. Regarding the mechanisms for movement of goods, it is possible to use both DC motors and asynchronous motors [5–7]. The massive use of DC motors was due to the lack of AC motor control systems, allowing a wide range of speed control. In DC motors, it is possible to achieve the desired results by controlling the values of voltage and current, which allows the flow and torque parameters to be adjusted, providing a quick response to the control action. Although DC motors have a number of advantages, their disadvantages exist in the form of design features, such as the presence of a collector and brushes that need constant maintenance and impose restrictions on use in explosive and aggressive environments [8]. For a long time, DC motors have been widely used in cargo transportation systems, but the rapid development of microprocessor technology has led to the gradual replacement of these motors with AC motors. In order to ensure high rates of performance along the torque loop, reliability, reliability, and precise control of output coordinates, it is advisable to use asynchronous motors with a squirrel-cage rotor on the mechanisms for moving goods; this is important since asynchronous AC motors with a phase rotor are very difficult to maintain, have significant dimensions, and require constant attention. The emergence of systems with frequency control is a breakthrough in the development of fundamentally new control systems for asynchronous motors. Drives with frequency control have enabled various types with various complexity, of frequency-current control [9]. To control asynchronous motors, systems with scalar, vector, and direct torque control are widely used. Scalar control systems are based on the regulation of frequency indicators and one or more parameters of an induction motor [10,11]. Two control options are possible; the supply frequency and voltage can be simultaneously changed, or the frequency and stator current can be simultaneously controlled. The mathematical apparatus of scalar control is formed for the steady-state operation of the engine, using constant speed and load torque. In dynamics, the correct operation of systems of this type is violated due to the slow response of scalar systems to the control action, which is a clear disadvantage of such systems. The speed control range in such systems lies within 1:10; it rarely has larger ratios, but it must be considered that an increase in the speed control range should not lead to a decrease in the magnitude of the electromagnetic torque generated on the motor shaft. Despite the ease of implementing the scalar type of control, the speed sensor in these systems must be present for the speed of the rotor shaft's rotation to be controlled. For the torque indicators to be controlled, a torque sensor must be installed, but even this expensive measure will not increase the system speed. The obvious disadvantages of scalar-type systems also include the lack of the possibility of simultaneous control of speed and torque. Therefore, in this study, the current is a variable parameter is chosen for correction, as it is most relevant for a particular object or process. The first studies in which vector control systems are Blaschke [12] and Hasse [13], and these became the basis for the research by Professor Leonhard [14]. A significant contribution in this direction was made by scientists from different countries, such as Canada, Germany, Italy, Japan, Great Britain, the USA, and Russia. In [8], based on [15–19], it is indicated that asynchronous motors have the same mechanism for generating torque as DC motors. This statement is formed on the basis of the conclusion that the electromagnetic torque of an asynchronous motor, in the same way as of DC motor, can be expressed as the product of the currents that are forming the magnetic flux and the torque. The system proposed in the first case can be implemented in the form of the diagram shown in Figure 1, which reflects the physical basis of vector-controlled drives. In this system, the real (x) and imaginary (y) axes of the rotating reference frame are tied to the spatial vector of the flow coupling of the stator. The stator currents, which depend on the torque, are identical to the armature currents of a DC motor.

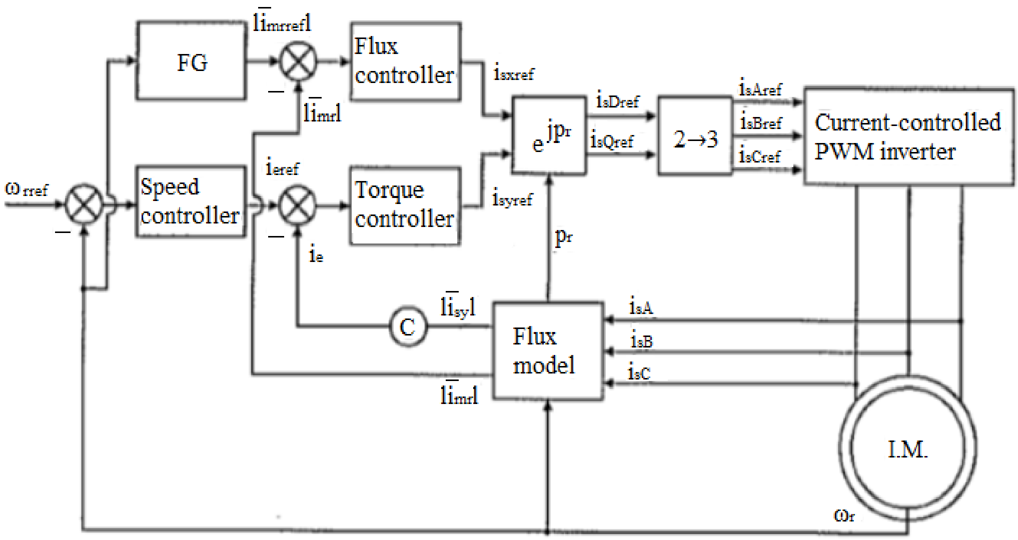

Figure 1. Vector control system based on stator flux linkage.

In the second case [8], the orientation follows the rotor engagement (Figure 2). The stator current, which creates torque and flow as well as the angular slip frequency, is formed from the electromagnetic torque and the magnetization current module of the rotor. The rotor position angle is added to the reference value of the slip angle to obtain the position of the space vector of the rotor magnetization current.

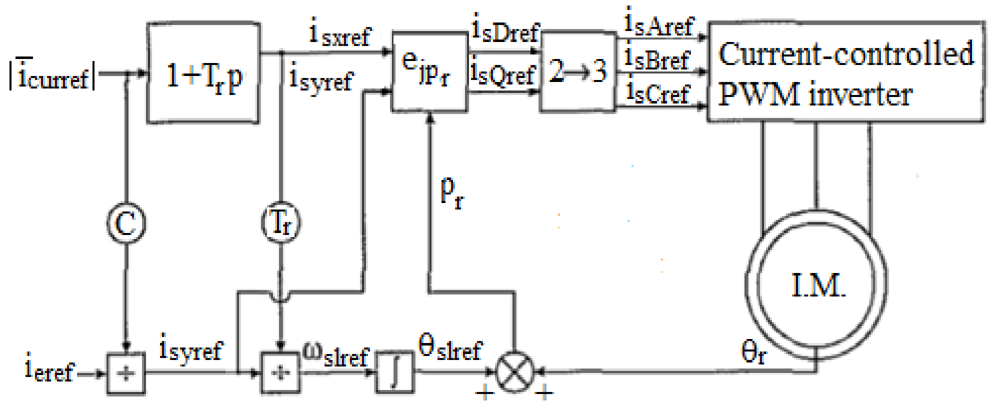

Figure 2. Vector control system oriented by rotor flux linkage.

In [20], the classification and analysis of AC motor control systems is given [Figure 3].

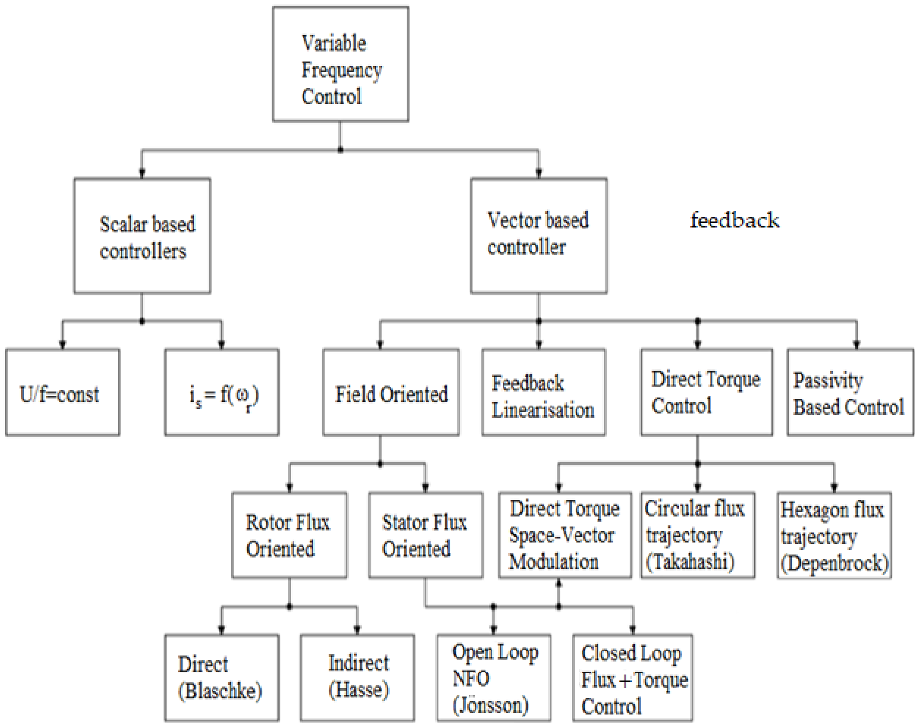

Figure 3. Classification of control systems.

Vector control systems were first patented by Siemens. These systems made it possible to control the current vector in a coordinate system oriented along the flux linkage. The control variables in vector systems are vectors of quantities of an electromagnetic nature located in space. The mathematical apparatus is dominated by differential equations. The formation of the required torque values is achieved by influencing the current vector or stator voltage. Systems with vector control should be more convenient classified based on the methods of generating information regarding the current parameters. In some systems, direct control of values is carried out based on the sensor readings, and in other systems, indirect determination of parameters is conducted based on the mathematical model of the electric motor. Systems with direct measurement provide more accurate information about the state of the parameter, in contrast to the unstable data obtained from a mathematical model. The use of vector control systems makes it possible to build control systems with good dynamic properties, high accuracy, and good speed control performance. Despite the obvious advantages of vector systems in comparison with scalar control systems, vector systems require a heavier mathematical apparatus, including multiplication functions, the use of which leads to the expenditure of significant computing power and the appearance of a delay in the indicators of the electromagnetic torque when the control variable is applied to the control system. It is possible to optimize the system under consideration by forming a constant value of the stator current's magnetizing component [21,22].

The advent of transistorized IGBT switches brought electric drive control systems to a new stage of development. The rapid improvement of the semiconductor element base made it possible to create intelligent high-speed systems with complex mathematical apparatus. The next step in the development of electric drive control systems has led to the emergence of well-proven systems with direct torque control that are both high speed and operate stably even when accurate indicators of the measurement parameters are not available and when disturbing influences occur during the control of the object. Unlike vector control systems, systems with direct torque control do not need to perform coordinate transformations; there is also no need for the presence of blocks in their structure to compensate for cross-links, and they do not require stator current controllers. The principle of operation provides for the possibility of adjusting the values of the stator flux linkage and the torque of the induction motor. Minimization of the stator current is achieved by regulating the indicators of the stator flux linkage affecting the magnitude of the torque setting. The use of systems with direct torque control for asynchronous motors with a squirrel-cage rotor installed on travel mechanisms makes it possible to take into account a number of requirements for systems of this type, allowing the speed of the systems and the device's energy-saving performance to be increased, and simplifying the maintenance of the object by the control system [23,24].

It is possible to achieve an increase in the energy efficiency of the electric drive in several ways [25]:

- Making the right selection of an asynchronous electric motor in terms of heating and power while also considering that the value of the load factor should be more than 50 percent;
- Carrying out modernization in order to increase efficiency by changing the design of the asynchronous machine and choosing the best materials for its manufacture.
- Transitioning to a system with a frequency-controlled electric drive;
- Improving both the structure of the frequency-controlled system and its control algorithms.

In [26], a method for obtaining energy savings when using a scalar control system by minimizing power losses using a search algorithm is considered. The operation of the algorithm is based on achieving the the maximum value from minimum values of power losses due to introducing increments in the amplitude value of the voltage into the setting signal until the optimal result is achieved (Figure 4). The disadvantage of the proposed solution is the high inertia associated with a cumbersome mathematical apparatus. The positive factor of systems with this type of correction is that the value of the correction signal does not depend on the parameters of the control object changing (Figure 5). Tracking the change in processes occurring both in dynamics and in statics allows taking into account the fluctuations of the resistance of the stator windings. It is also necessary to consider the effect of current displacement, which has a significant impact on the operation of the electric drive at frequencies below the nominal ones (Figure 6). An increase in temperature indicators in the windings of an asynchronous machine which occurs during engine operation leads to a change in both the electromechanical characteristics and the indicators of controlled and uncontrolled values of the control system. The use of IR compensation leads to a decrease in the voltage drop of the magnetic circuit, i.e., magnetic flux [27].

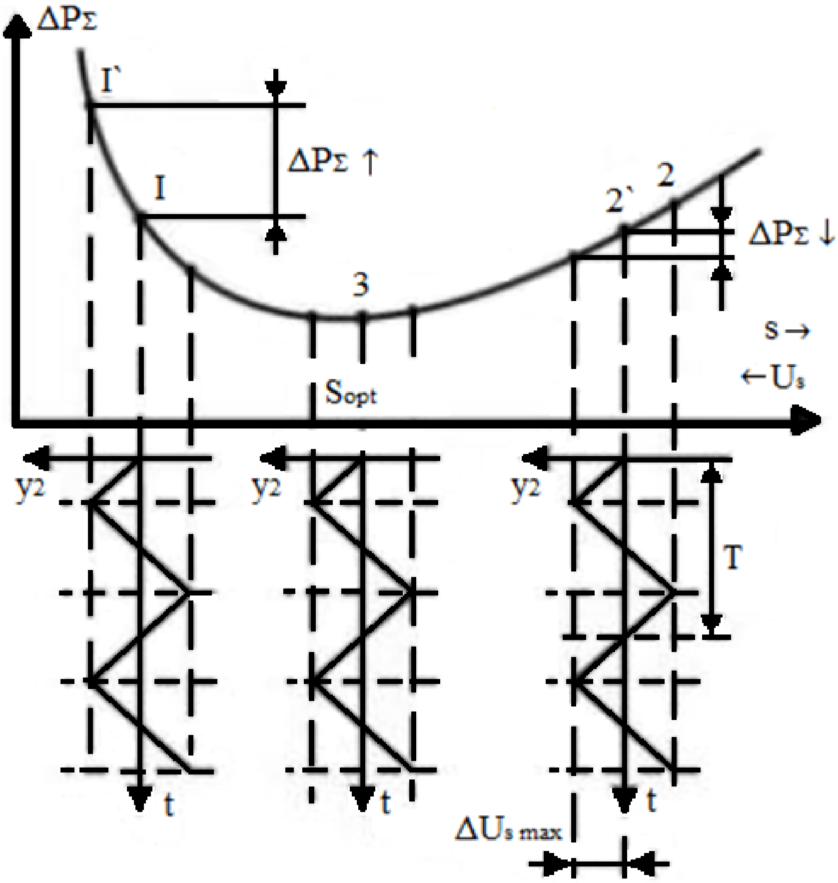

Figure 4. Searching for the minimum power mode.

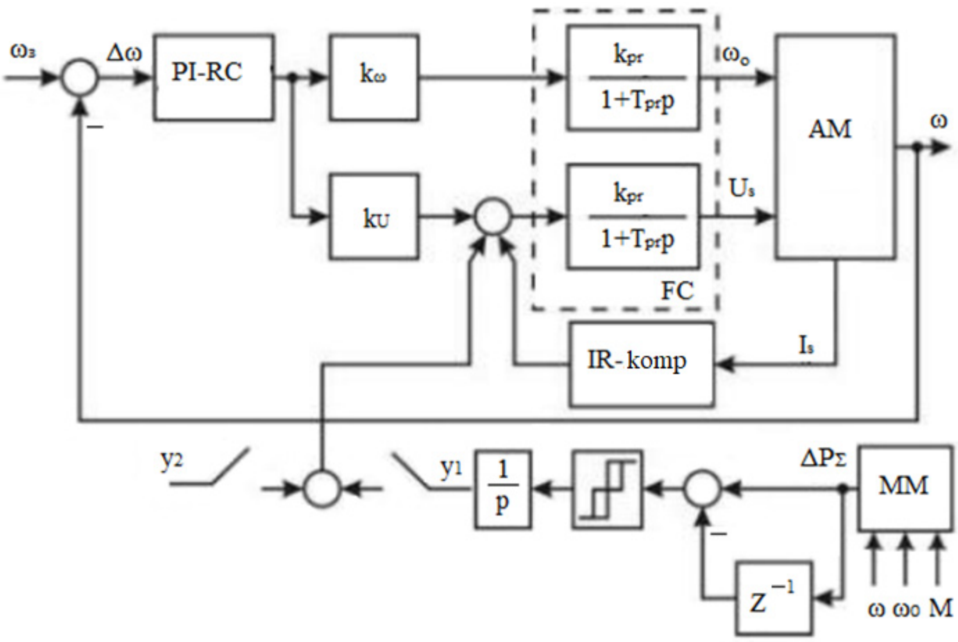

Figure 5. Electric drive block diagram.

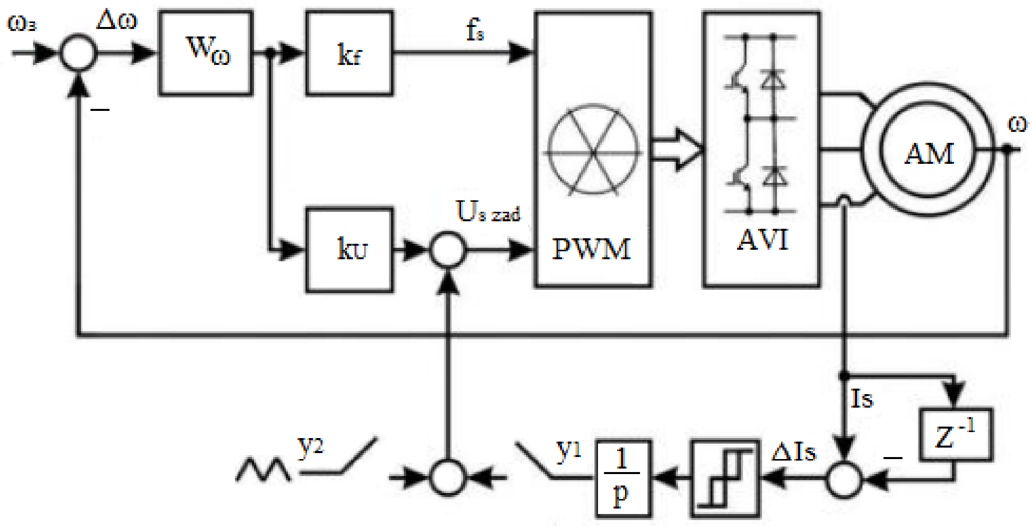

Figure 6. Control system, including the minimum stator current researching loop.

In the article [28], the authors provide a detailed analysis of the dynamic processes occurring in a system with vector control. At the same time, the study revealed that the vector control system based on the laws of rigid implementation of the control algorithm makes it possible to achieve energy efficiency using the criterion of minimum additional losses. In the articles [29–32], which are dedicated to energy saving issues, the authors provide methodologies for achieving optimal performance in a vector control system by influencing the stator current so as to achieve its minimum consumption. This becomes possible by maintaining a certain value of the angle between the torque-generating vectors of the stator current and one of the vectors: the vector of the rotor flux linkage, the stator flux vector, or the main flux linkage. Optimization of stator current consumption [29] is possible by maintaining a certain value of the angle between the stator current vector and the rotor flux linkage vector. Construction options and functional features of three-phase and two-phase fixed coordinate systems are considered. The authors in [33,34] are devoted to the development of energy efficient algorithms. With direct torque control, it is possible to achieve a good response to the control of the torque parameters. The use of intelligent systems based on fuzzy logic has made it possible to achieve good energy performance in terms of energy efficiency. The authors in [35] propose using a fuzzy controller to provide the angle required from the standpoint of energy efficiency, and the main criterion in this system is the minimum of losses. The authors in [36] present an analysis of the reduction of torque pulsations and an increase in the power factor for three-phase switching jet engines (MCSRMS) with excitation by a sinusoidal current. These systems use an unconventional voltage source in the frequency converter and standard vector control. The influence of the angle of the current's excitation on the saturation indicators of the motor and the value of the power factor are also investigated. This action profondes harmonics of the current caused by excitation of a sinusoidal current are investigated. The data obtained during the study were used as a basis for the development of an optimized control method to reduce torque pulsations and increase the power factor [Figure 7]. In the proposed control method, the power factor and phase voltage are calculated based on knowledge of the ratio between the values of phase flow and current.

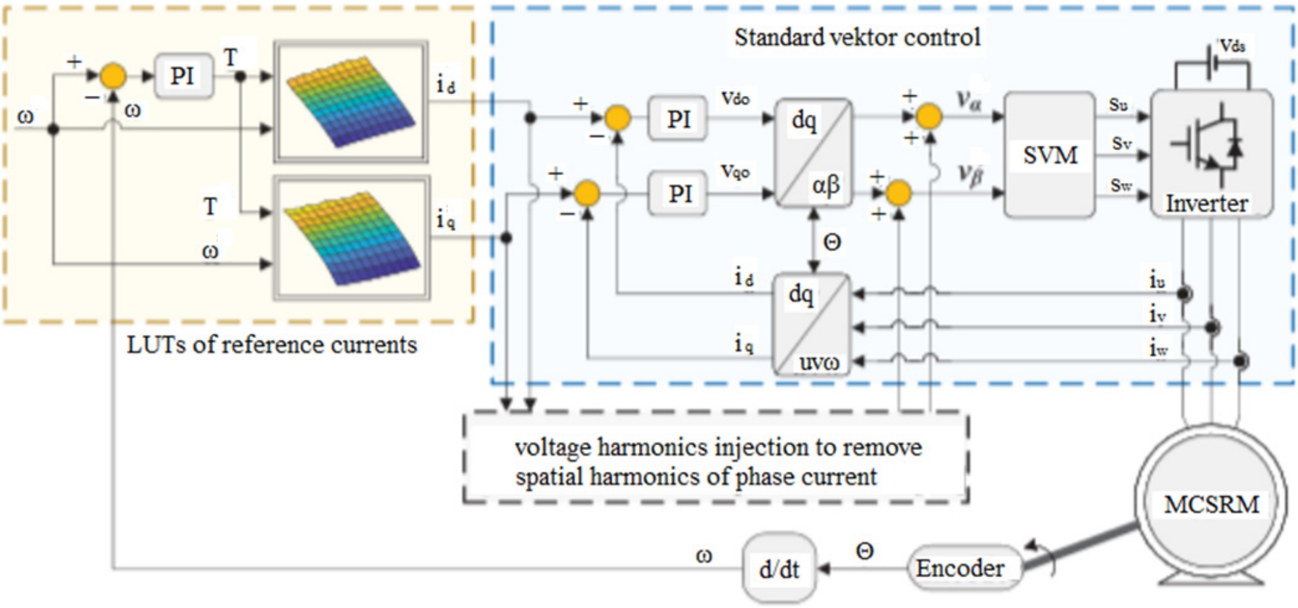

Figure 7. Optimized torque ripple control method and power factor improvement.

In [37], a comparison of a classical vector control system with a system with direct torque control is made; the optimality of the implementation of static and dynamic processes in an electric motor is then analyzed. The direct torque control system has proven itself to be very good in dynamic modes as it has provided a good response to the control signal. However, in statics, when used for electric drives that provide high accuracy, significant torque ripples were recorded. There are a number of studies aimed at calculating the value of the driving signal for the stator flux linkage and the angle between the vectors that form the torque, providing an increase in energy efficiency. Minimizing current consumption involves controlling the magnetic flux of the machine, the value of which is based on load indicators. The coordinate system underlying the study will directly depend on the control system taken as the basis and the features of the implementation of control algorithms in practice. Systems providing maintenance of the value of the rotor flux vector at the required level have become widespread [35]. The coordinate system used to control the electric drive conditionally rotates together with the control vector, which makes it possible to simplify the mathematical apparatus of the system since there is a clear simplification of differential equations. In this case, the determination of the amplitude and phase indicators of the controlled vector depends on the values of the projections on the axes of the considered coordinate system since the controlled vector does not rotate relative to the selected coordinate system. In a standard study, a T-shaped equivalent circuit is taken as the basis, which implements the model of an induction motor, this circuit considers the saturation of the magnetic circuit, but losses are not taken into account due to the small value of the active component of the current, compared with the magnitude of the magnetization current. In this case, the method of space vectors is used to write a system of equations describing the mathematical model of an induction motor [37].

In [37,38], an analysis of the ratio between the indicators of torque, flux linkage and the values of the projections of the stator current on the d and q axes was carried out. These studies show that the slip directly depends on the torque and gives an idea of the overload capacity of the electric drive. In [39,40], the ratio between the magnetization flux and the magnetization current was revealed, which can be perceived as the main inductance. Since the magnetic circuit is saturated, the main inductance is in direct proportion to the magnetizing current. When researching, it is important to consider the saturation of the magnetic circuit of the electric motor, especially when it comes to the development of energy-saving systems in which the optimal algorithm is compiled for flux linkage control. This is necessary because the transition to the saturation zone can be associated with significant losses (magnetic and electrical) and the creation of additional temperature in the engine; at certain values, these problems can cause a decrease in the useful power factor, and the engine can become out of order.

The analysis of the studies carried out in the literature showed that the value of the stator current projection on the d axis (the value of the longitudinal component of the stator current) in a separate section of the magnetization curve directly depends on the motor magnetization indicators. However, the torque parameters do not affect it. It was also found that, with low inductance values and knowing the magnitude of the flux linkage, it is possible to make an expression reflecting the direct proportionality between the magnitude of the motor torque and the transverse component of the stator current. This suggests that the impact on the projection of the stator current along the d axis allows the electromagnetic torque of the electric motor to be controlled without inertia. At the heart of the optimization of all vector control systems (including the system with direct torque control, which is a kind of vector control system) is the search for the optimal value of the flow with a known torque value. Accordingly, in the d-q system built on the basis of the orientation of the electric motor rotor along the field, it is necessary to find the value of the rotor flux linkage, which will correspond to the minimum values of the consumed current [41]. If the magnetic circuit is not saturated, it was also found in [42,43] that the value of the optimal angle between the torque-generating vectors of the stator current and the rotor flux linkage tends to 45 degrees, and this angle corresponds to the minimum value of the consumed current. In the range of current loads corresponding to frequency-controlled asynchronous electric drives, it is advisable to conditionally take the values of the leakage inductance of the stator and rotor to be constant, considering that the angle between the stator flux linkage and the rotor flux linkage depends only on motor load fluctuations. Therefore, in the absence of saturation in the range of minor loads that are 0.1 of the nominal load, the optimal value of the angle between the stator current and the stator flux linkage should tend to a value of 45 degrees. An increase in load and flux linkage indicators (up to approximately 0.4–0.5 of the nominal value, also in the absence of saturation), provided that the system under consideration is energy efficient, should be reflected in the indicators of the considered angle, leading to its gradual decrease to a value limited to 40 degrees due to the insignificant value of the leakage inductance [42]. Further loading and flux linkage to values exceeding 50 percent of the nominal parameters can lead to saturation of the magnetic circuit of the induction motor. This saturation is reflected in the coordinate system associated with the rotor of the induction motor in the form of a violation of the proportional ratio between the longitudinal components of the stator current and the rotor flux linkage, leading to an increase in the value of the optimal angle to 55–60 degrees [42]. From [42], it can be concluded that the value of the angle between the stator flux linkage and the rotor flux linkage depends on the change in the motor parameters. In [44], the authors studied the optimal control system for an asynchronous motor and found that, if the load corresponds to the nominal values, the angle between the current and the stator flux linkage, which is optimal in terms of the minimum stator current criterion, should be in the range from 44 to 51 degrees.

Creation is possible in a system with direct torque control of an energy-saving algorithm based on the minimum consumed stator current by adjusting the task for the stator flux linkage depending on the current parameters of the task at the torque of the induction motor [45–48]. In [35,49], the implementation of energy-saving systems is proposed on the basis of achieving optimization of stator current consumption and (or) minimizing losses in the motor by changing the flux linkage of the induction motor. During the research, it was found that the values of the control, according to two criteria (minimum stator current and minimum losses in the electric motor), were very close to each other. Energy efficient control of a direct torque control system can be achieved by influencing the stator flux linkage in order to correct the angle between the torque vectors [42]. The research proposed in this article is aimed at developing an energy-saving algorithm. This is done by creating mathematical models and Matlab Simulink simulations that correspond processes occurring in a real engine.

2. Materials and Methods

To develop energy-saving systems, it should be checked and refined some indicators on the basis of mathematical dependencies. The calculation needs to defined indicators should be checked and refined. This is done by mathematical calculations made by graphical and analytical. The graphical-analytical technique implies finding the optimal dependence of the stator flux linkage on the torque values and determining, for these indicators, the optimal stator current from the standpoint of its consumption, as well as finding, under the listed conditions, the optimal value of the angle between the torque-forming stator current vectors and the stator flux linkage, based on non-linear dependence of the indicators of mutual inductance (L_m) on the value of the magnetizing current (I_m). The parameters of the studied engine are power 470 kW and rated speed 427 rpm. The developed algorithm is acceptable for engines with other power indicators. To study the processes occurring in an asynchronous motor, a T-shaped equivalent circuit of an asynchronous motor was used to implement a mechanical model, taking into account the saturation of the magnetic circuit. In this scheme, losses in the magnetic circuit of an induction motor are traditionally not taken into account, which simplifies the system of equations for an induction motor. For further analysis of the minimum stator current, this is also quite justified, since the active component of the current, which determines the magnetic losses of the induction motor, is negligible compared to the magnetization current. Limitations are imposed on the reduction of the stator flux linkage in order to maintain the overload capacity of the motor.

This technique has a certain structure.

The first step is to enter the motor torque values corresponding to the calculated reference points. In this case, the calculation is made at certain frequency indicators (f_1). Then, the stator voltage (U_s) effective value is assigned for each reference point and the slip (S) data is calculated at the reference points.

At the second stage, taking as a basis the T-shaped equivalent circuit of an asynchronous motor, it is necessary to find the value of the rotor current (I_R) reduced to the stator circuit.

$$I_R = \frac{U_s}{(R_s + (1 + \frac{Z_S}{Z_m}) \cdot \frac{R_R}{S}) + j \cdot (X_S + (1 + \frac{Z_S}{Z_m}) \cdot X_R)}, \quad (1)$$

where Z_S—stator circuit impedance, Z_m—magnetizing circuit impedance, R_s—active resistance of the stator, R_R—active reduced rotor resistance, X_s—inductive resistance of the stator, and X_R—inductive resistance of the rotor.

The third stage consists of calculating the magnetization current (I_m) for each reference point based on the passport data for the motor used for the study, reflecting the dependence of the main inductance on the magnetization current. The value obtained as a result of mathematical calculations must be compared with the data taken using the magnetization curve. If a large discrepancy between the readings is detected, it is necessary to repeat the calculation of the magnitude of the magnetizing current by selecting the inductance.

$$I_m \approx \frac{U_s}{jX_m}, \quad (2)$$

where X_m—inductive resistance of the magnetizing circuit.

The fourth stage involves finding the stator current (I_s) based on the T-shaped equivalent circuit. Next, we find the value of the electromotive force (E) and correct the value of the magnetization current (I_m). We correct the readings of the rotor current (I_R) using the value of the electromotive force calculated at the previous stage, if necessary, and we re-calculate the magnetization current until the minimum discrepancies are obtained.

$$I_s = I_m + I_R,$$

$$E = U_S - I_S \cdot Z_S,$$

$$I_m = \frac{E}{Z_m},$$

$$I_R = \frac{E}{\frac{R_R}{S} + jX_R}.$$

At the next stage, it is necessary to calculate the indicators of the stator flux (Ψ_S) linkage, consisting of the sum of the vectors of the main flux (Ψ_m) linkage and the leakage flux ($\Psi_{\sigma S}$) linkage. We adjust the stator voltage (U_s) in both directions from the initial value for each torque (M) reference point, we perform these manipulations in order to determine the minimum value of the stator current and find the stator flux linkage corresponding to this value. These manipulations will allow us to determine the only reference point that reflects the optimal ratio between the given stator flux linkage and the current parameter of the electromagnetic torque. By changing the values of the torque (M) and the flux (Ψ) linkage in a certain range from the nominal value (M_{nom}, Ψ_{nom}), we find the dependence of the indicators that are optimal from the standpoint of energy efficiency and the corresponding angle (Θ_S) between the torque-generating vectors. From the studies carried out, it was found that the temperature of the windings, which can be up to 110 degrees, has an insignificant effect on the value of the optimal flux linkage of the task and the optimal angle. During the study, the following reference points were obtained, reflecting the ratio between the optimal performances at maximum temperature (Figures 8 and 9). Figure 10 shows the characteristics of the dependence of the stator current on the load torque in both the standard system and the energy saving system. To build an energy efficient control system, the optimal dependence of the stator flux linkage on the load was found. Based on numerical methods, the optimal accuracy was found with an acceptable number of mathematical operations using the approximation method. The obtained approximated data expressing the dependence of the stator flux linkage indicators on the electromagnetic torque indicators are presented in Figure 11. Figure 12 shows the approximated data expressing the dependence of the optimal angle indicators on the indicators of the electromagnetic torque.

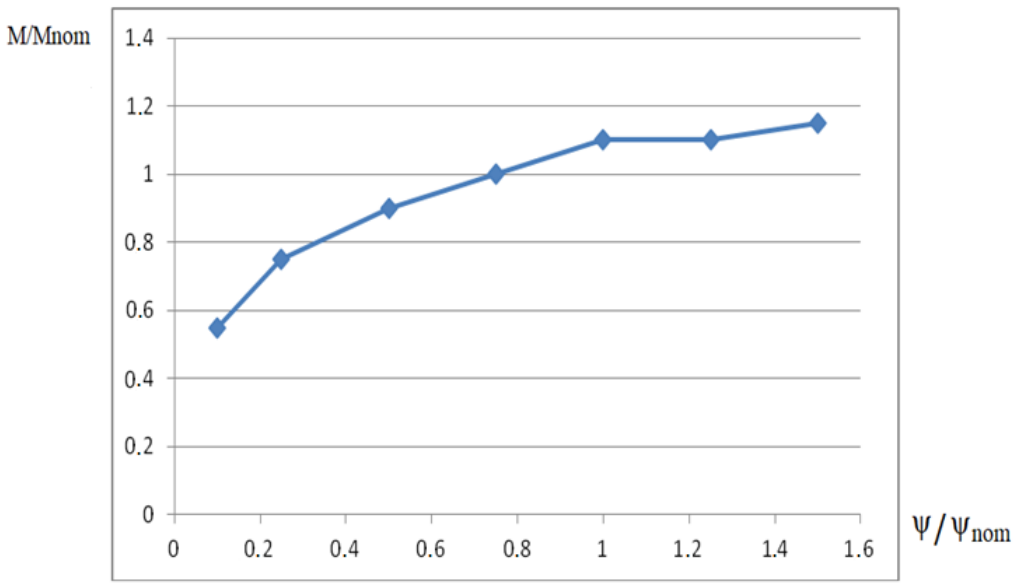

Figure 8. The ratio between the ratio of the selected torque value to the nominal torque and the selected flux linkage value to the nominal flux linkage.

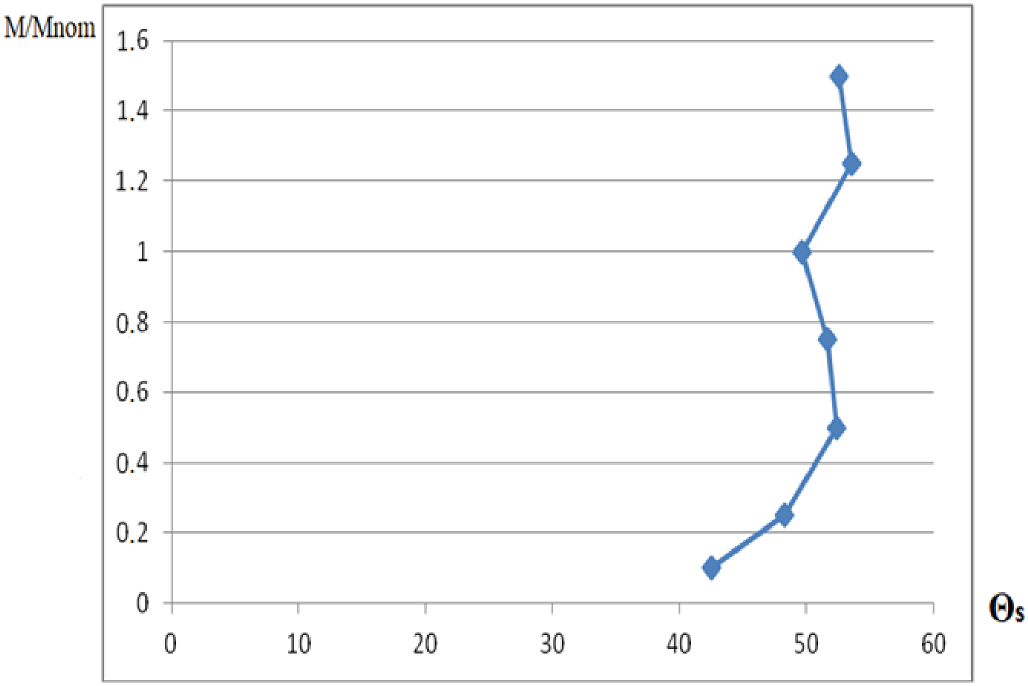

Figure 9. The ratio between the ratio of the selected torque value to the nominal torque and the optimal angle for a given ratio.

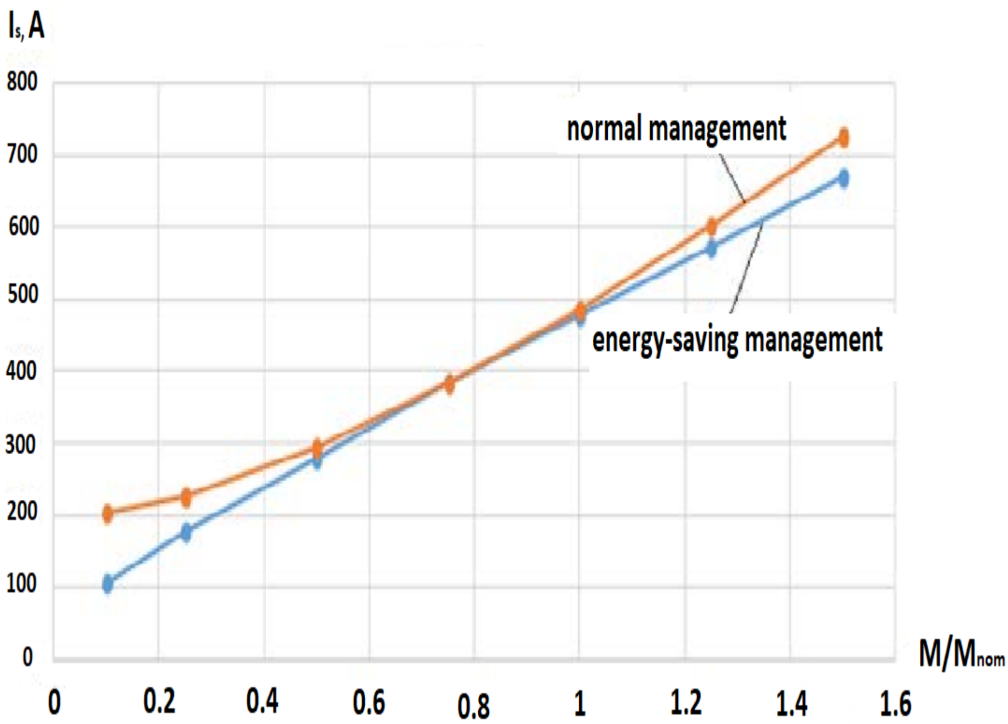

Figure 10. Dependencies between the ratio of the selected torque value to the nominal torque and the stator current.

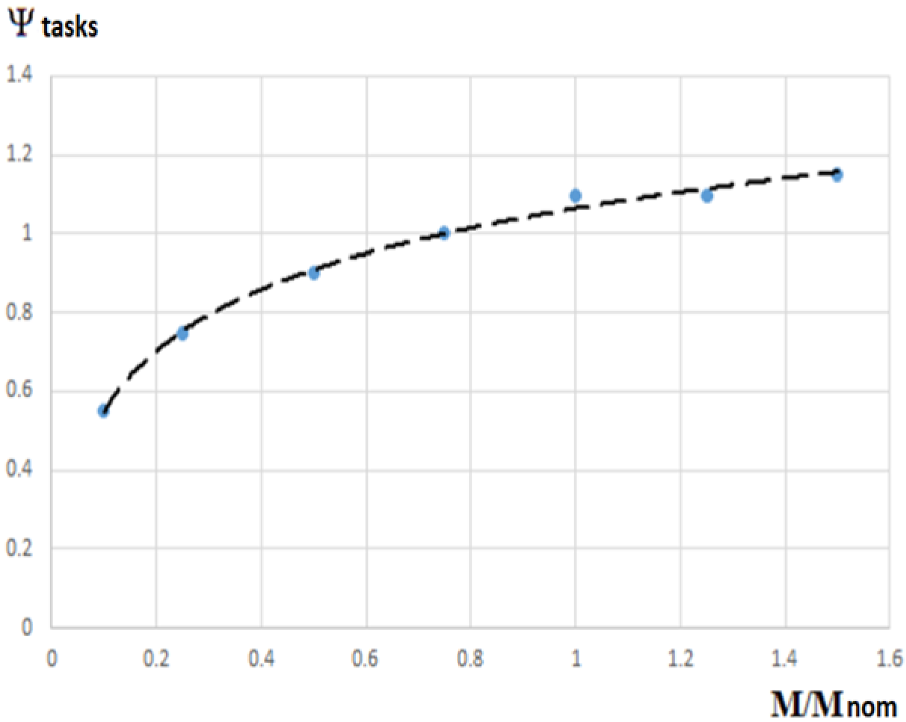

Figure 11. Dependence of the flux linkage on the ratio of the selected torque value to the nominal torque.

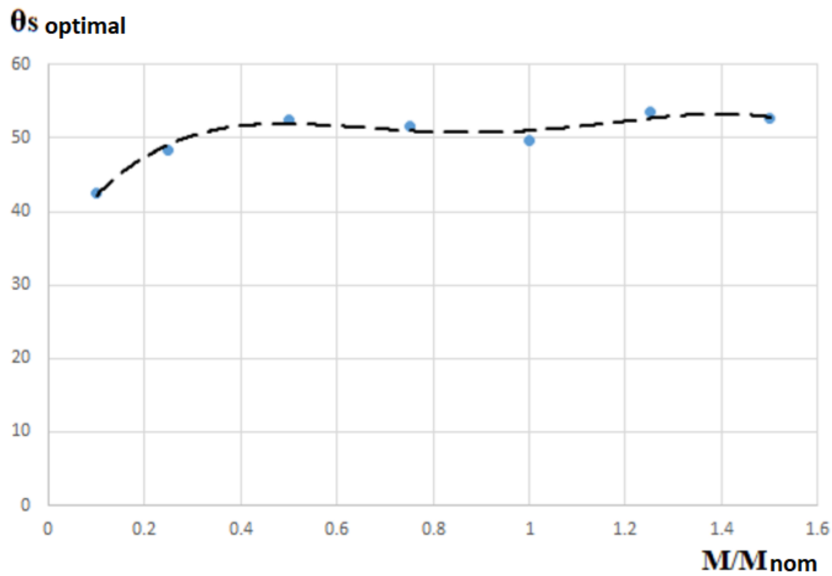

Figure 12. The dependence of the optimal angle on the ratio of the selected torque value to the nominal torque.

The dependence shown in Figure 11 is fed to the input of the stator flux controller in the direct torque control system, realizing the regulation of the magnetizing part of the stator current. These manipulations make it possible to maintain the optimal value of the angle between the torque-generating current vectors and the stator flux linkage while ensuring the minimum stator current consumption. The value of the average approximation error of the given dependencies is no more than 1.0098% in nodes of the nominal value with a ratio coefficient of 0.998. The least squares method makes it possible to analytically obtain the curves of the dependencies to be studied by a continuous function, which prevents the appearance of both discontinuities and kinks of extreme dependencies obtained when differentiated.

3. Results

Correction of the stator flux linkage is possible using the intermittent control system of an asynchronous motor. This is achieved due to the presence in the system of direct torque control of the relay controller of the stator flux linkage, since the modulus and phase of the stator flux vector are calculated using the adaptation of the motor model. The proposed energy efficient system is shown in Figure 13. In the presented system, there is a linear speed sensor that allows the acceleration (deceleration) of the movement mechanism to be calculated.

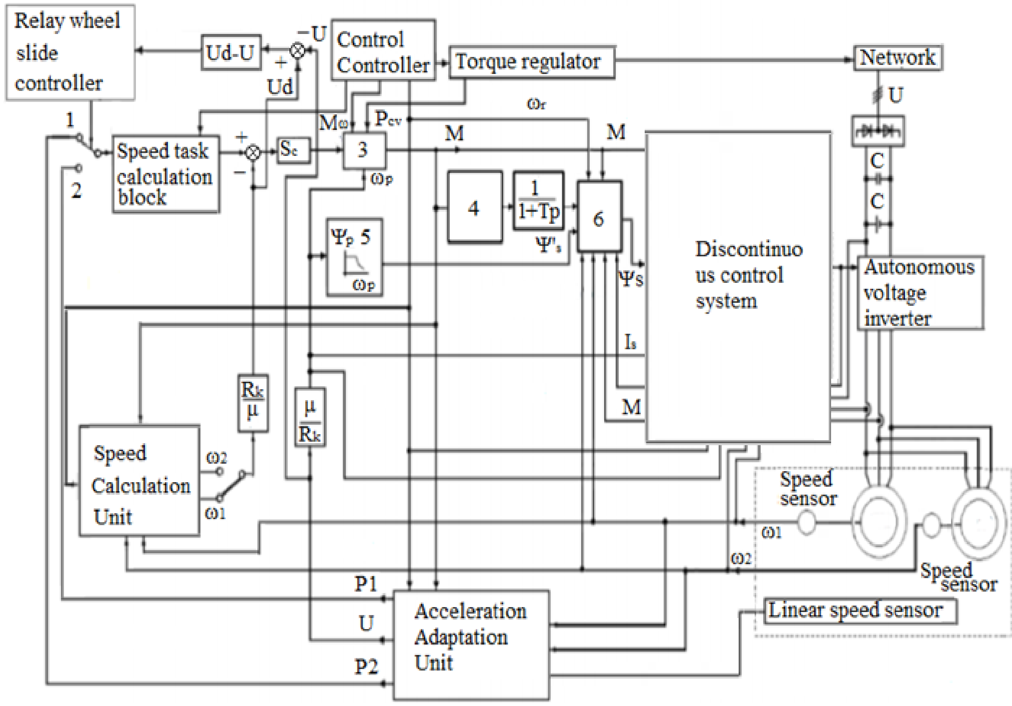

Figure 13. Energy efficient system with direct torque control.

The system introduces a speed reference signal, which enters the speed reference calculation unit. The speed obtained at the output in the speed loop restricts the task of forming the rotational frequency of the asynchronous motor. In the block for calculating the speed reference, the engine speed is determined by setting the acceleration of wheel pair P1 and P2. The speed reference calculation unit determines the rotational speed reference of the asynchronous motor by integrating the acceleration value of wheel pair P1 and P2, which is formed in the acceleration adaptation unit. In this system, P1 is used to increase acceleration, and P2 to decrease acceleration. Parameters P1 and P2 will change their direction if the braking mode occurs in the system. The acceleration of the movement mechanism is calculated in the acceleration adaptation block based on an estimate of the change in the speed of the movement mechanism in a certain period of time. It is possible to install a linear speed sensor in the system, information from which can be fed to the acceleration adaptation unit. This sensor is shown in Figure 13. The system operates in two modes, acceleration (1) and braking (2), which are realized by switching the relay wheel slip controller between positions 1 and 2, which has a hysteresis tolerance. The input signals of the relay wheel slip controller are the value of the module between the difference in the movement speed of the movement mechanism, the real one and the current one. When the speed difference exceeds the upper threshold value set in the settings of the speed reference calculation unit, the P2 signal is sent, until the specified value is reached, the P1 signal is used in the control system. The speed calculation block performs the function of switching between operating modes. In the block for calculating the speed reference, the integration of the output value of acceleration takes place while the value of the linear motor speed reference is formed at the output; the conversion into the value of the electric motor's angular velocity for an energy-efficient control system is an input signal. The obtained value can be compared with the feedback signal indicators obtained from the motor shaft speed sensor, and the error signal obtained as a result of the comparison serves as an input signal for the speed controller. This signal can be implemented as a proportional controller or a proportional-integral controller. From the output of the speed controller, a signal is sent to the input of block 3, which is a block for calculating the torque setting of an asynchronous motor. Depending on the current task in the stator flux linkage generator, the output value of the stator flux linkage is formed according to the optimal dependence shown in Figure 11, which is optimal according to the criterion of minimum stator current, that is, the task of stator flux linkage provides a minimum of stator current consumption. The values generated in the stator flux linkage generator directly depend on the current task for the torque indicators. Flux linkage indicators directly depend on the function they perform to ensure the minimum current consumption of the stator. In blocks 4 and 5, which calculate the flux linkage task, the value of the flux linkage is formed depending on the speed of the movement mechanism. In the system under consideration, there is a block of the stator flux linkage generator, in which there is an energy-efficient ratio between the flux linkage task and the torque task. The signal for setting the electromagnetic torque of the engine, in systems of this kind, is the base for determining the optimal value of the stator flux linkage at a certain value of the electromagnetic torque. Since there is a possibility of its sharp change during the electric drive's operation, it is necessary for a block that can filter ripples coming from the generator's output to be present in the block that calculates the stator flux linkage. The flux link setting logic block controls the process of switching between the stator flux reference signals by choosing between a standard flux link change or an energy-saving dependency change. It should be considered that the presence in the system of the magnetization flux reaction aimed at reducing the motor torque entails a decrease in the speed of the electric drive. Accordingly, it is necessary to strike a balance between the performance indicators of the control system and its energy efficiency. The structure of the proposed discontinuous control system includes a three-position controller of torque indicators operating on a relay principle and a two-position flux linkage controller also operating on a relay principle, as well as a logic automaton unit, a phase sector determination unit, and an adaptive motor model. The input signal of the stator flux controller is the output signal from the logic block for setting the flux linkage. The input signal of the torque controller is the output signal from the block for determining the torque reference. Further, according to the typical operation of the control system with direct torque control, the position at the current time of the voltage vector and its movement associated with the control action and based on the switching table, typical for systems with direct torque control, are found in the source [50]. The voltage vector obtained as a result of the considered manipulations enters the unit that implements the autonomous voltage inverter, where the necessary combination of keys is formed in order to ensure the energy-efficient operation of the control device for the electric drive of the movement mechanism. Regardless of the selected motor parameters, the process of magnetization of an asynchronous motor is formed according to traditional methods for setting flux linkage values. At high sacristies between adjacent signals, a block for smoothing current surges is introduced in the system to set the flux linkage.

The logic block for setting the stator flux linkage operates is based on the algorithm that follows.

1. Motor magnetization according to the traditionally accepted dependence. The first stage of the system operation involves starting an asynchronous motor with a standard formation of the circuit magnetization and at a standard nominal value of the stator flux linkage.

2. Operating mode selection:

(A) Acceleration mode:

- Setting the conditions for the transition to an energy-efficient mode—during a given period of time, an energy-efficient task is formed at the torque;
- Setting the conditions for the termination of energy-efficient operation—the completion of acceleration or a sharp decrease in speed;
- Setting the conditions for the transition to the traditional mode—completion of acceleration or exceeding the task at the torque by an amount greater than the allowable deviation within a certain time set in the algorithm;

(B) Mode of moving with a given speed:

- Setting the conditions for the transition to the mode with a given speed—during a given period of time, the formation of a standard, accepted for systems with direct torque control, task for the torque;
- Setting the conditions for stopping operation in the mode with a given speed—a sharp decrease in speed;
- Setting the conditions for the transition to an energy-efficient mode—the constancy of the task at the torque.

According to the presented algorithm, the analysis of the operation of the electric drive takes place in the logic block for setting the flux linkage, and in the case of a decrease in load for more than a certain period of time, a switch to an energy-efficient mode of forming the stator flux linkage is performed. When operating in this mode, the flux linkage indicators decrease, including the magnitude of the stator current and the magnetization current, along with the electrical and magnetic losses in the electric motor. Since the negative consequence of all of the above is a decrease in the magnitude of the critical torque, this circumstance must be considered, and taking measures to ensure the necessary voltage in the intermediate circuit makes it possible to restore the overload capacity of the motor in a short time. For stable indicators that lie within a certain time range while maintaining the stability of the electric drive movement mode, the validity of switching to energy-efficient control are evaluated by the logic block for setting the flux linkage, which analyzes the signals of traditionally formed flux linkages and flux linkages formed in an energy-efficient mode, the magnitude and rate of change of the task at the torque, and the rotation frequency of the asynchronous motor. With a sharp change in any of the system indicators exceeding the specified indicator in the time range, the block for setting the flux linkage logic initially sends a signal generated in the mode that precedes the sharp change in parameters. Further violation of the regime leads to the transition to the traditional formation of flux linkage indicators until favorable conditions arise for the transition to the energy saving mode. The possibility of switching to energy-efficient control is expedient even at high loads, which are reflected in [51,52], where the described operation is possible with a stable flux linkage of the electric drive speeding up. This action is expedient under the condition of magnetization of the electric motor at the beginning of the start. The logic block for setting the flux linkage controls the current speed of the movement mechanism, and when the speed of the transition to a single switching of the keys of an autonomous voltage inverter is exceeded, a transition to the traditional formation of flux linkage values occurs. At the same time, since the specified block controls the violation of the torque control process in the system with direct torque control, this phenomenon (violation of the torque generation process) can occur as a result of a decrease in the overload capacity of the electric motor caused by a decrease in the stator flux linkage. Under these conditions, there is a transition to the standard formation of flux linkage indicators. If the task for the torque of the asynchronous motor exceeds the value of the actual value of the torque of the asynchronous motor by an indicator greater than the value of the hysteresis tolerance in the range of more than a specified time interval, a signal is issued to switch to the standard mode of flux linkage formation.

The mathematical description of a system with direct torque control is based on a standard system of equations describing an asynchronous motor with a squirrel-cage rotor in the α-β system, which is a stationary system relative to the stator [53,54]. In this case, the formation of the motor torque occurs in the form of a product of the stator and rotor flux linkage vectors, multiplied by the sine of the angle between these vectors. Direct torque control is based on ensuring the speed of motor torque formation by changing the angle between the stator and rotor flux linkage vectors [19,54]. This condition is achievable when a certain voltage vector is found; the vector will cause both flux linkage vectors to react in the form of mutual displacement, which will provide the necessary torque increment on the electric motor shaft and the necessary increment of the stator flux linkage. A system with direct torque control containing a two-level autonomous voltage inverter (Figure 14) has a set number of basic voltage vectors (Figure 15). The operation of the direct torque control system is based on the operation according to the information given in Table 1 about switching the power switches of an autonomous voltage inverter.

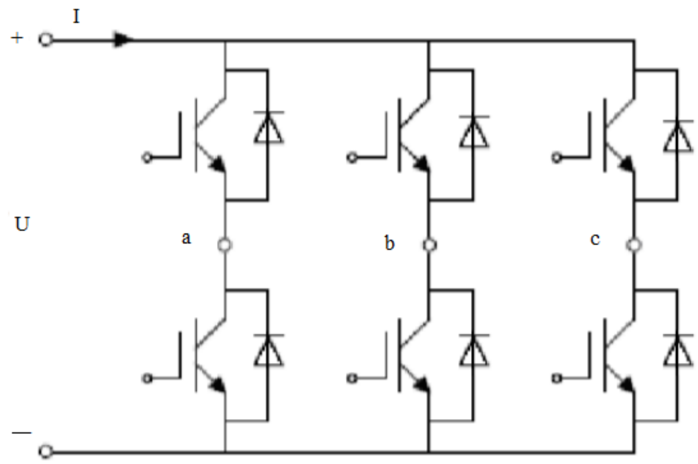

Figure 14. Simplified three phase voltage inverter.

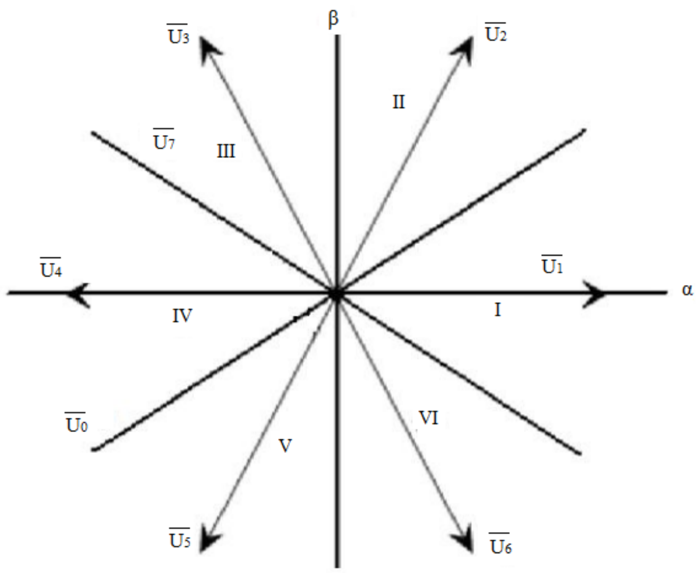

Figure 15. Simplified orientation of stress vector with considering Fig. 14 and listed In Table 1.

Table 1. Dependence of the position of the inverter keys on the flow coupling and torque.

ΔΨs	ΔM	Sector					
		I	II	III	IV	V	VI
↑	↑	$\overline{U_2}$	$\overline{U_3}$	$\overline{U_4}$	$\overline{U_5}$	$\overline{U_6}$	$\overline{U_1}$
	0	$\overline{U_7}$	$\overline{U_0}$	$\overline{U_7}$	$\overline{U_0}$	$\overline{U_7}$	$\overline{U_0}$
	↓	$\overline{U_6}$	$\overline{U_1}$	$\overline{U_2}$	$\overline{U_3}$	$\overline{U_4}$	$\overline{U_5}$
↓	↑	$\overline{U_3}$	$\overline{U_4}$	$\overline{U_5}$	$\overline{U_6}$	$\overline{U_2}$	$\overline{U_2}$
	0	$\overline{U_0}$	$\overline{U_7}$	$\overline{U_0}$	$\overline{U_7}$	$\overline{U_0}$	$\overline{U_7}$
	↓	$\overline{U_5}$	$\overline{U_6}$	$\overline{U_1}$	$\overline{U_2}$	$\overline{U_3}$	$\overline{U_4}$

The table shows the position of the inverter vectors depending on the correction signals for torque and flux linkage. Shown in Figure 16, the plane is divided into six sectors; each of the listed sectors corresponds to certain values of corrective signals for torque and flux linkage [55–57]. The values of corrective signals for flux linkage and torque lead to changes in output signals from relay controllers.

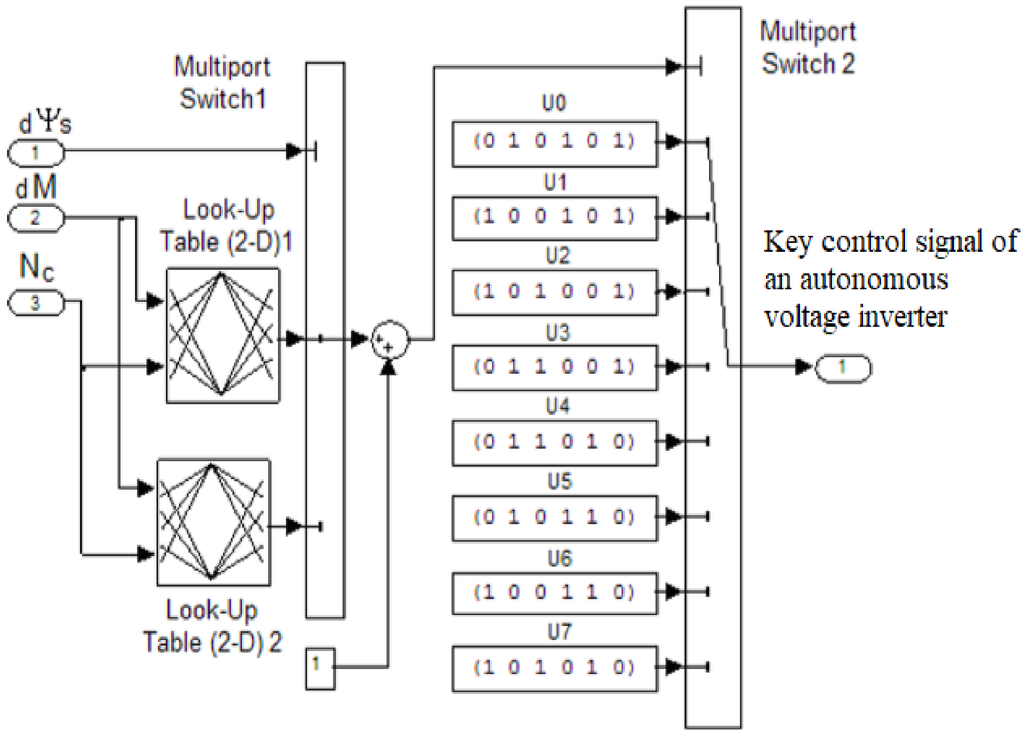

Figure 16. Implementation of the optimal switching table.

In [52,58,59], tables are considered that reflect the positions of the inverter keys, based on a relay with three positions for the electromagnetic torque and a relay with two positions for the stator flux linkage. The principle of forming the table is determined by the following indicators:

- Provided that positive signals are generated at the output of both relay controllers, in the presented table, this condition corresponds to the arrows pointing upwards and the resulting voltage vector moves following the stator flux linkage vector by one range in the reduced plane;

- Provided that positive signals are generated at the output of both relay controllers, in the presented table, this condition corresponds to the arrows pointing upwards and the resulting voltage vector moves following the stator flux linkage vector by one range in the reduced plane;
- If a positive value is formed at the output from the torque controller, and a negative parameter is formed at the output from the flux linkage controller, then the resulting voltage vector moves in the same direction as the flux vector by two ranges in the reduced plane;
- Provided that the output signals from both regulators have negative values, in the presented table, this condition corresponds to the arrows pointing down and the resulting voltage vector moves in the opposite direction relative to the rotation of the stator flux linkage vector by two ranges in the reduced plane;
- If a zero value is found from the torque controller, which is formed when the torque feedback signal is equal to the torque reference signal, then the resulting voltage vector will take one of the voltage values corresponding to the zero parameter, which corresponds to the standby mode formed in the system, until the next non-zero formation of the resulting voltage vector, with the above conditions [53,58,59].

The displayed technique allows signals that control the autonomous voltage inverter and switch the keys to be generated. The dependencies presented in the table give an idea of the optimal states of the parameters included in it for proper regulation of both the magnitude of the torque and the indicators of the stator flux linkage at a given rate. The implementation of the optimal switching table in the mathematical modeling environment (Figure 16) is possible using the functionality available in the Matlab Simulink mathematical modeling environment [60,61]. The positive or negative state of the value of the stator flux linkage $d\Psi_S$ affects, through the Multiport Switch1 key, the range of the switching table of the autonomous voltage inverter switches involved in the process: the "plus" sign corresponds to Look-Up Table (2-D)1, and the "minus" sign is typical for Look-Up Table (2-D)2. Having determined the effectiveness of the state of the indicators at the torque, it is connected with the current sector Nc, which is expected according to the reaction from the model of the induction motor's stator flux linkage vector. Further, using the Multiport Switch2 key, according to the indicators of the voltage vector from the positions of its numbering, we find the state of the power switches of the autonomous voltage inverter meet the listed criteria: position 0 will correspond to the closed position of the autonomous voltage inverter key, and position 1 will correspond to the open state of the autonomous voltage inverter. By controlling the location sector at a given time of the stator flux vector, it becomes possible to generate information about the indicators of the induction motor's rotating magnetic field. The phase sector control function also includes coordinate transformation processes in an indirect form, in contrast to the classical representation of their mapping. Receiving the torque and stator flux various is necessary as operating the table by direct measurement. This is problematic if the available sensors are unacceptable for use in terms of cost and availability. Therefore, preference is given to using an adaptive motor model for systems with direct torque control.

When creating a model in the Matlab Simulink environment, an adaptive-type motor model was created based on the equations calculated for a system interconnected with the stator (α-β). The use of an adaptive type of model makes it possible to increase the accuracy of calculations. The integration process inherent in determining the value of the stator flux linkage used in systems with direct torque control leads to the appearance of high sensitivity in the event of errors in determining the value of the active resistance in the stator windings. The stability of the control system is maintained if the calculation error is not more than five percent; when this indicator is exceeded, the stability of the system begins to decrease, and when the ten percent threshold is passed, the system destabilizes. The use of temperature sensors provides ease of obtaining data about the temperature indicators of the stator windings, which cannot be implemented in a rotor circuit when using a vector control system [53]. With direct torque control, the controllable parameters are located in the frequency converter. In sensor-less control systems, the speed parameters are obtained based on data from an adaptive engine model, and in this case, there will always be an error in the calculations caused by the error of the instruments used for measurement, speed indicators of data transmission, etc. To implement the control system of the movement mechanism, the parameters of voltages and currents in the phases are reduced to the axes α, β, the stator flux linkage, and its projections on axes α and β.

The authors in [61] reflect the possibility of finding the phase sector by introducing fuzzy logic algorithms into the control system. In the study, when implementing the phase sector, methods based on trigonometric functions and vector diagrams were chosen. Finding that belonging to the phase sector of the phase of the stator flux vector is possible using the following algorithm as long as the phase of the stator flux vector is located in the range from -180 to 180 degrees:

- When the angle is in the range from -30 to 30 (inclusive) degrees, the stator flux linkage is located in the first sector;
- When the angle is in the range from 30 to 90 (inclusive) degrees, the stator flux linkage is located in the second sector;
- When the angle is in the range from 90 to 150 (inclusive) degrees, the stator flux linkage is located in the third sector;
- When the angle is in the range of more than 150 degrees, but less than -150 (inclusive) degrees, the stator flux linkage is located in the fourth sector;
- when the angle is in the range from -150 to -90 (inclusive) degrees, the stator flux linkage is located in the fifth sector;
- when the angle is in the range from -90 to -30 (inclusive) degrees, the stator flux linkage is located in the sixth sector.

In systems with direct torque control, two-position relay controllers are often used for flux linkage control that does not contain a dead zone, and three-position controllers are used for torque control that contains a dead zone. In both types of regulators, hysteresis tolerance is implemented. To increase the speed of response to a disturbing effect, the dead zone in the relay torque controller tends to be brought closer to zero. Correct functioning of the controllers requires proper calculation of the hysteresis parameters and, if necessary, the dead zone, as well as the values of the feedback gains. The required frequency of pulse signals is formed by setting in the blocks contained in each circuit. The implementation of the control loop is possible in the form of an aperiodic link of the first or second order. The stability of the circuit under consideration is formed by maintaining the self-oscillating mode, and without it, the system becomes inoperable. When implementing a system with direct torque control, it is also necessary to adjust the torque controller, which can be represented as a P, PI, PID controller. The magnitude of the speed feedback signal is formed indirectly in the adaptive model or is taken from the shaft speed sensor. The speed of the system response to the control action is determined by the oscillation frequency of the relay controllers (Figure 17). An energy-efficient control mode is provided in the system when specifying a control signal for flux linkage based on the energy-saving law discussed above. The adequacy of the proposed system can be assessed by its implementation in the Matlab Simulink mathematical modeling environment. In the implemented model, saturation is formed according to the magnetization curve, which is the dependence of the mutual inductance on the indicators of the magnetization current. The engine is presented in the form of a block shown in Figure 18.

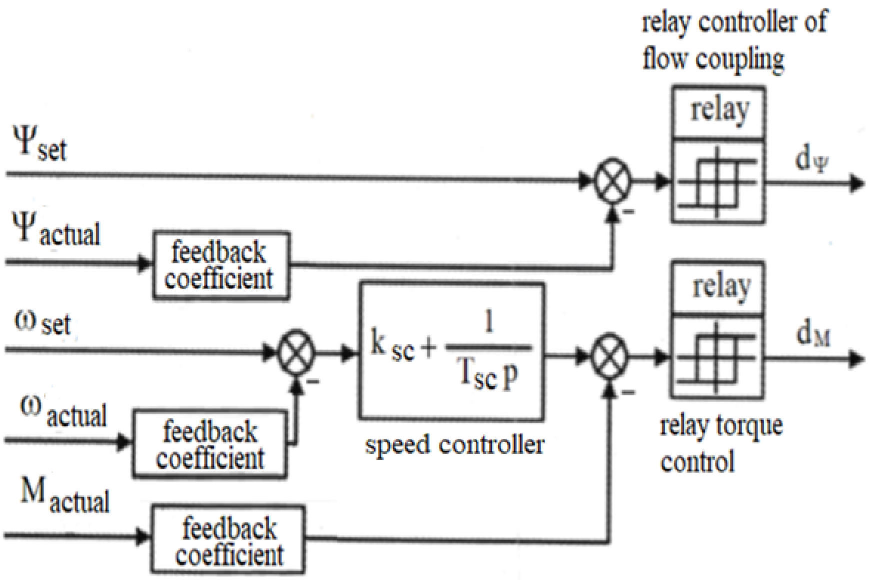

Figure 17. Regulators in a system with direct torque control.

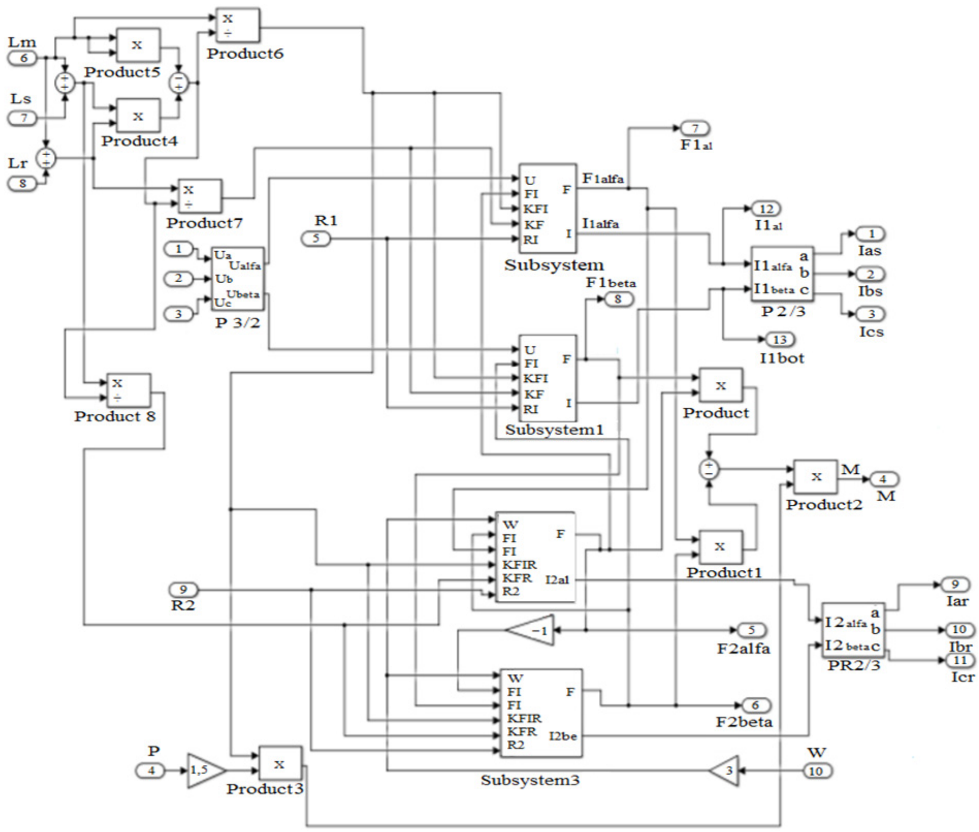

Figure 18. Engine Subsystem.

The simulation results of the system assembled in the Matlab Simulink mathematical modeling environment, without taking into account the load on the motor shaft, operating with nominal parameters, and with an increased torque of inertia, are shown in Figure 19. The analysis of the results indicates the adequacy and performance of the model, since the error of the characteristics, in comparison with the passport data, does not exceed 0.45 percent. The engine starts at idle; it reaches a steady speed value after 3.1 s, and the nominal value of the torque rises. The current indicators obtained in Figure 20 also characterize the system as adequately assembled with adequately calculated and selected parameters. At the next stage, a study of the proposed energy-efficient control was carried out. This is done for the various modes of operation for cargo moving mechanisms. In particular, the movement mode was considered at steady speeds with a small load on the motor shaft, which makes it possible to evaluate the effectiveness of the proposed system with an energy-efficient component. It is important to evaluate the performance of the proposed energy-efficient system with joint mathematical modeling of the electrical and mechanical components of the system.

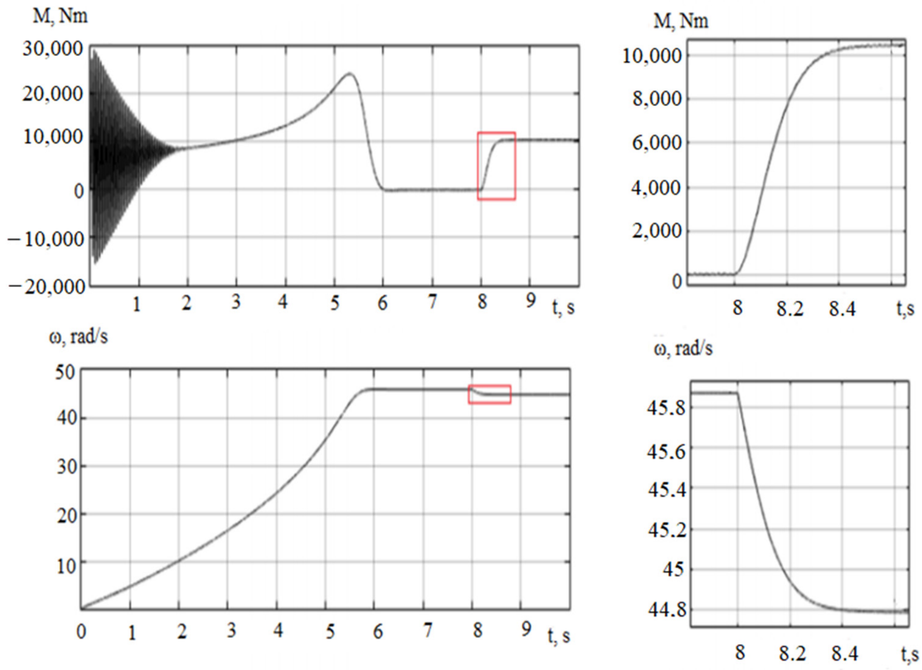

Figure 19. Torque and speed versus time with amplified part of the graph in the red box.

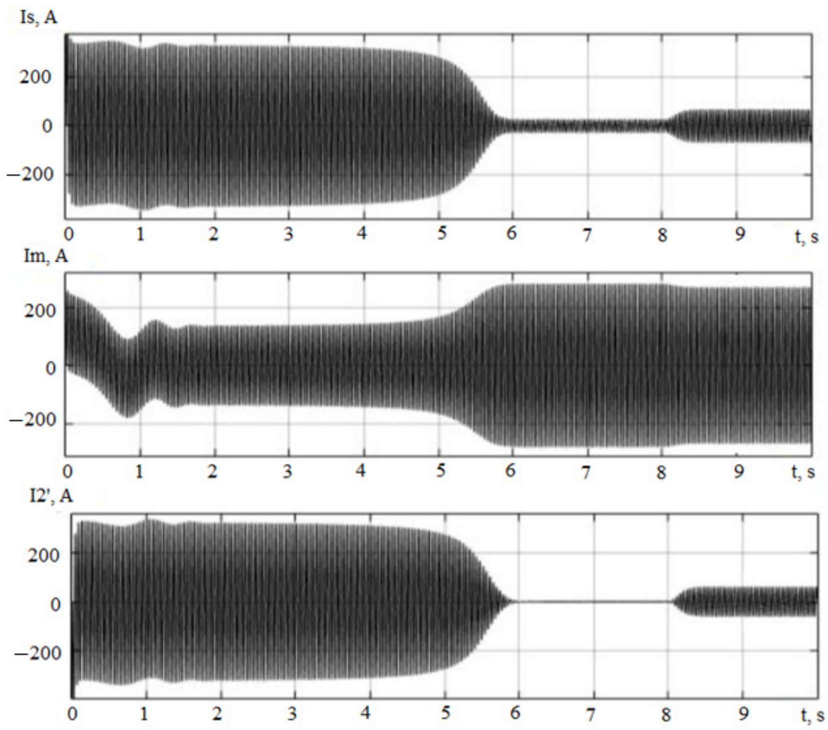

Figure 20. The dependences of stator currents, magnetization, rotor current on time.

The Matlab mathematical modeling environment, and the Simulink and SimPowerSystems libraries used to create mechanical and electrical components of systems in particular, make it possible to reflect the real processes occurring in the components of electric drive control systems. This system offers a qualified support service and contains a significant amount of material that is a reference. The annual improvement of the Matlab environment allows more accurate systems to be created which consider a significant number of parameters of a real object, gradually bringing the mathematical model closer to the prototype. In the Matlab environment, there is a ready-made model of an asynchronous electric drive with direct torque control in the application library, which is an integral part of the SimPowerSystems power electronics application package. The considered model from the library can be simultaneously combined with mechanical subsystem models that have some assumptions and are present in the Simulink library. When modeling, the electrical component was connected to a simplified mechanical part of the electric drive, the control system was supplemented with blocks in the form of a stator flux linkage generator that were created according to the criterion of minimizing the stator current indicators, as well as a logic block for setting the stator flux linkage signal, and thereby implementing an energy-efficient algorithm (Figure 21).

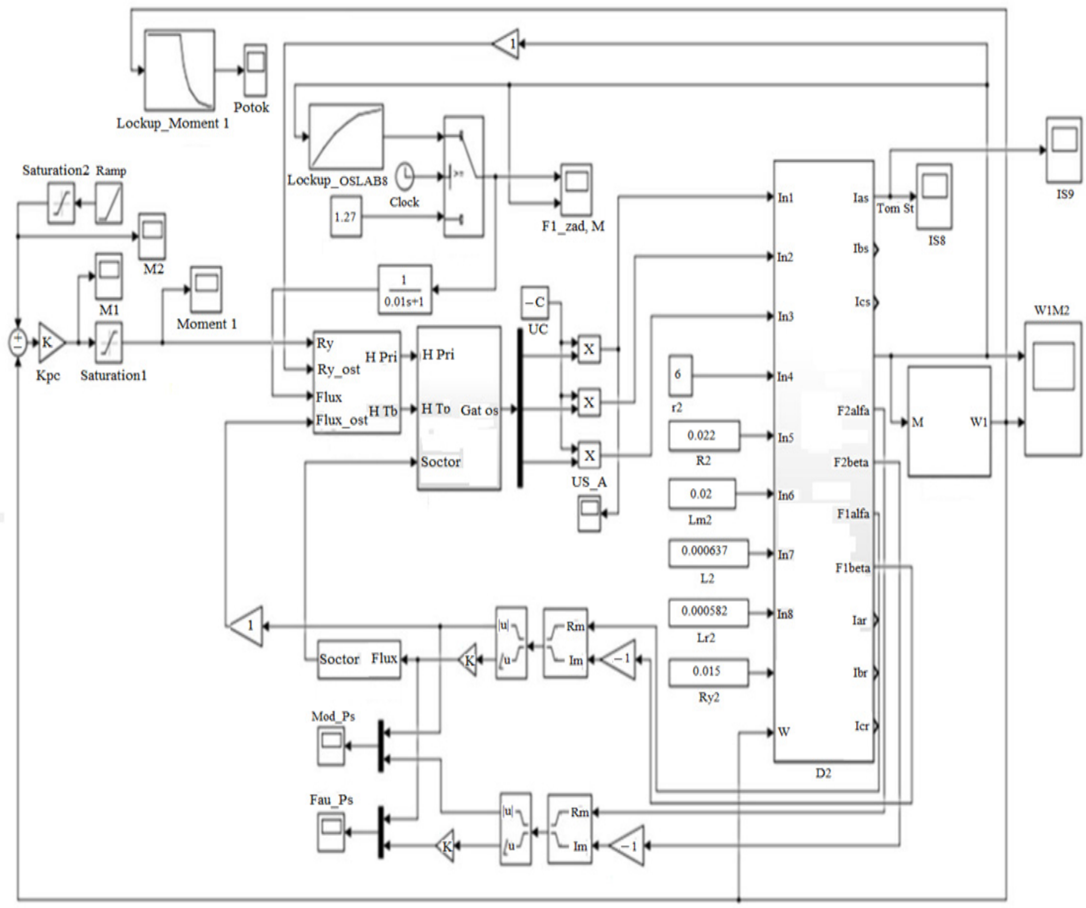

Figure 21. Energy Efficient Management System.

The acceleration of the mechanism for moving the load was carried out on the basis of the acceleration characteristic taken from a real object, then a steady speed value was reached. After reaching a steady speed value, an energy-efficient algorithm was put into operation until one switching of the keys on an autonomous voltage inverter was reached (Figure 22). The discrepancy between the results obtained from the real object and between the data obtained from the mathematical model does not exceed 6.5 percent.

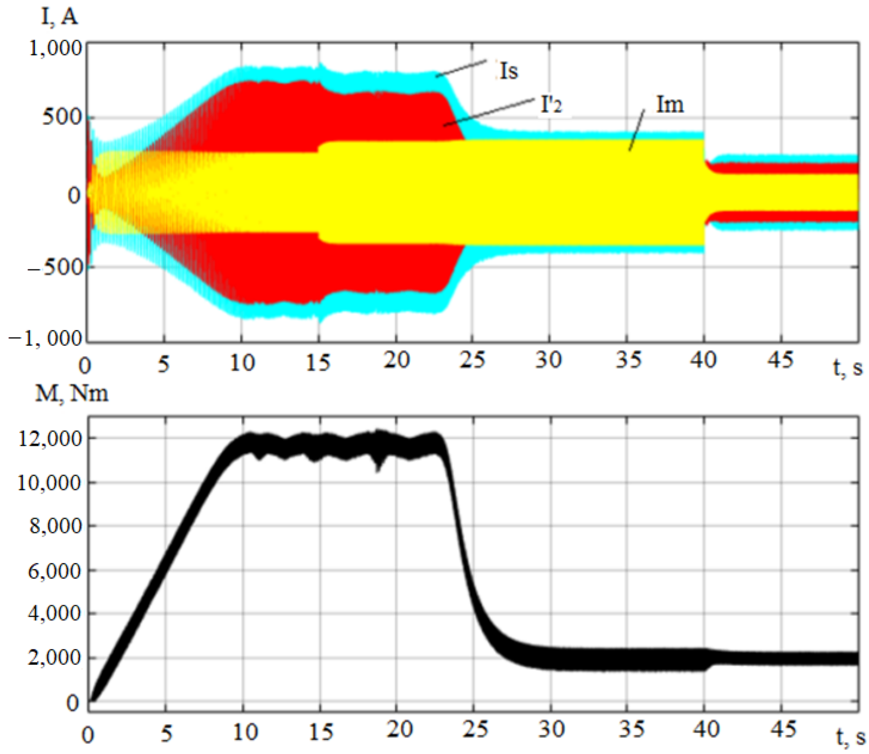

Figure 22. Movement acceleration characteristics.

When the speed reaches a stable state, for about 15 s, the electric drive control system switches to energy-saving formation of flux linkage values, which reduces the effective value of the stator current by about 4.2 percent, and this indicator corresponds to the angle between the torque-generating vectors equal to 52.3 degrees. Analyzing the graphs presented in Figure 16, we can conclude that an increase in load causes an increase in the stator flux linkage, a decrease in the stator and rotor currents, and an increase in the magnetization current. This measure leads to a decrease in the magnitude of the electrical loss components both in the stator windings and in the rotor windings. There is an increase in efficiency of about 2.5 percent, in response to the overall reduction in losses. The process of acceleration in a motor with a nominal value of flux linkage is accompanied by losses in the magnetic circuit and electrical losses; therefore, if mechanical and additional losses are not considered, the efficiency value will reach a maximum value in the case of equality of electrical and magnetic losses. The maximum value of the efficiency factor can be achieved at a load tending to nominal values, and the highest energy saving value will be characterized by a low speed of the movement mechanism, at which point the load decreases. In Figure 22, this discus previously section corresponds to the achievement of the set value by the speed. Implementation in the control system of mechanisms for moving different types of loads is possible by using the indicators of useful power, power of total losses, power of electrical losses, power of magnetic, mechanical, and additional losses at nominal mode. Based on the above indicators, the amount of loss can be found at any value of the engine load. Useful power is the sum of all the listed losses. Having determined the value of the input power, the useful power factor can be found as the ratio of the useful power to the input. By implementing an energy-efficient algorithm in the direct torque control system focused on minimizing the current consumed by the stator, we obtain a decrease in flux and, as a result of the above, found no decrease in losses. The maximum effect is observed at a load of less than 0.5 of the nominal value. Figure 16 shows that reducing the torque to 0.18 of the nominal torque leads to a decrease in the stator current by about 28 percent and an increase in efficiency by about 7.5 percent compared to the mode with the same parameters, and with the exception of flux linkage, it corresponds to the nominal value. With these changes in the electric drive, the number of switching actions in the autonomous voltage inverter increases; therefore, it becomes necessary to expand the hysteresis tolerance of the torque controller.

Figure 23 shows the dependence of the efficiency on the parameters of the load on the shaft when using the standard operating mode of the system (2) and with energy efficient control (1).

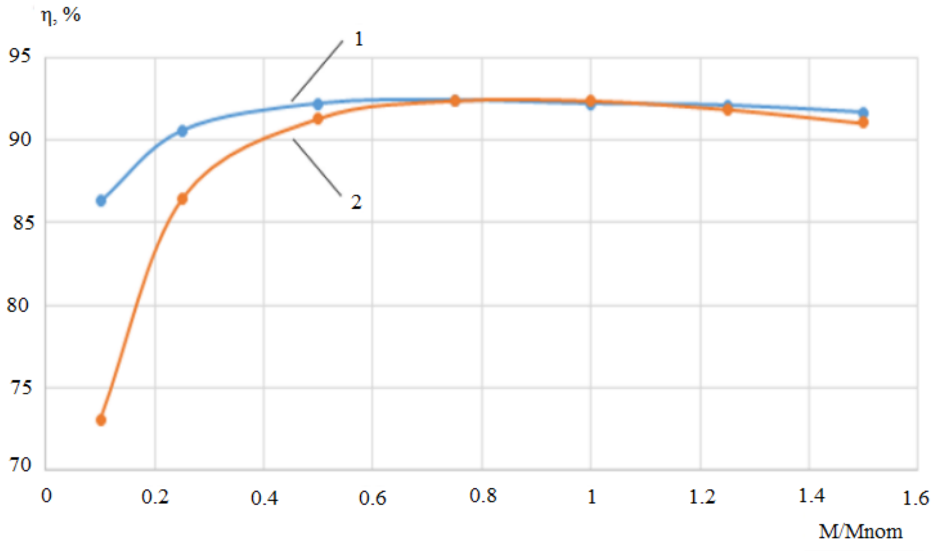

Figure 23. Dependence of the efficiency on the torque.

Figure 24 shows the ratio between the percentage of stator current and torque in energy-saving mode.

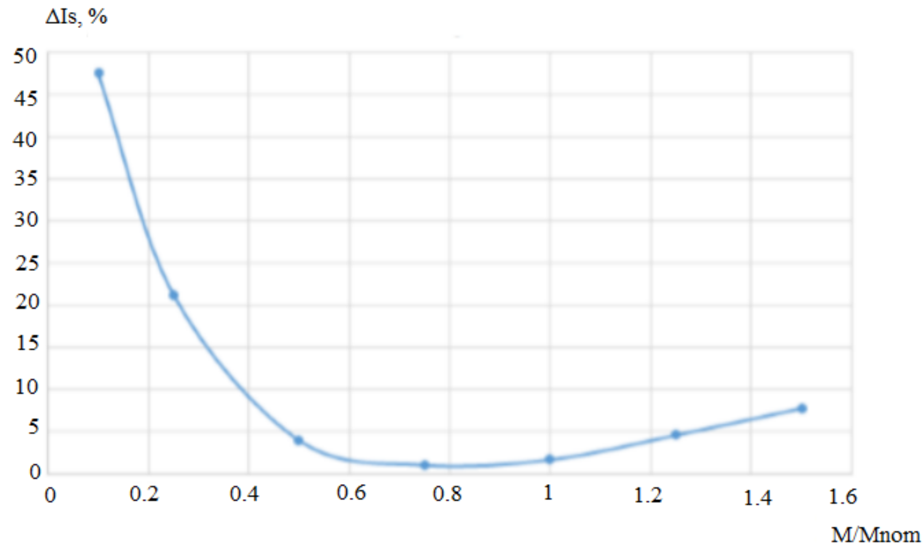

Figure 24. Dependence of the reduction of the stator current on the load.

4. Discussion

The implementation of an energy-saving algorithm in a system with direct torque control is optimal when using a mathematical description of the electric drive in the α-β coordinate system which is associated with the stator. However, in the case of an approximate preliminary estimate of the optimal angle between the torque-generating vectors, the d-q system is optimal for use, as it is associated with the field of the rotor of the electric motor. The development of a graphical and analytical technique for determining the optimal indicators of the value of setting the stator flux linkage, which ensures the minimization of the stator current and the search for the optimal angle between the vectors forming the torque, has been developed. The optimal indicators of the angle between the torque-generating vectors of the stator current and the stator flux linkage from the indicators of the electromagnetic torque for the displacement mechanisms are found, the use of which makes it possible to implement a control algorithm that provides energy savings and operates according to the criterion of the minimum stator current consumption. This study found that the value of the optimal angle between the stator current vector and the stator flux linkage vector depends on the data of the load torque and lies in the range from 42 degrees to 54 degrees. The value of the optimal angle between the vectors that form the torque in terms of the current minimum, obtained as a result of a graphical-analytical calculation, lies in the range obtained using the approximate preliminary assessment method. The development of a control system and an algorithm for controlling the movement mechanism has been carried out, which allows, when exposed to the control signal (stator flux linkage), to minimize the stator current indicators. By taking into account the current parameters and the mode of operation of the electric drive, the development of the sequence of operation of the logic block was developed, which allows the transition to an energy-saving control system from a standard control system.

The practical implementation of the proposed control system was performed on an experimental stand that contained a frequency converter and an asynchronous motor. A programmable controller and a personal computer with the necessary software were connected to the frequency converter. The block diagram of the stand is shown in Figure 25.

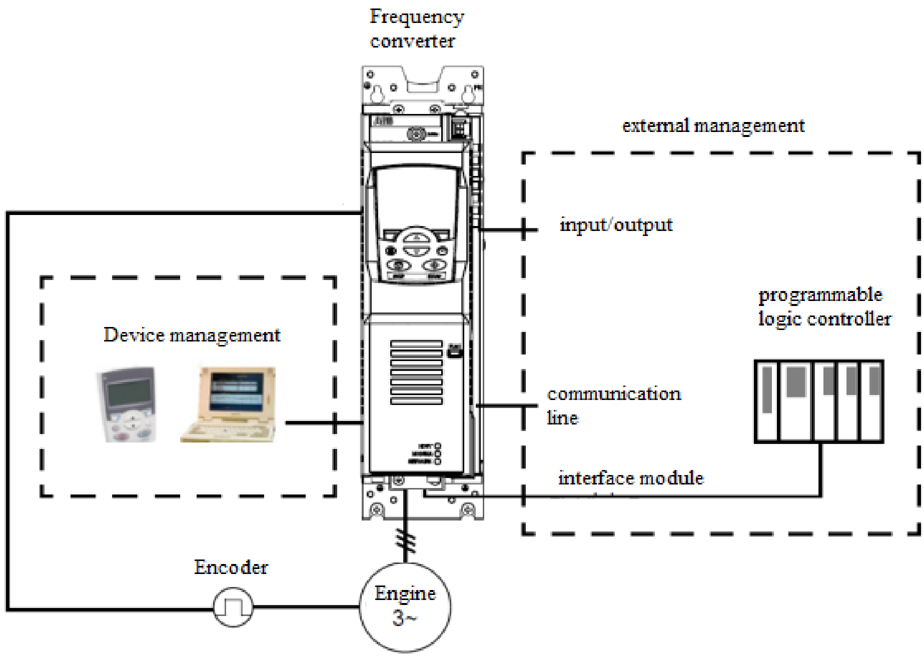

Figure 25. Structural scheme of the experimental stand.

The frequency converter and its controller were produced by ABB. This made it possible to use the DriveStudio v1.5 software. The association of a tachogenerator made it possible to compare real and simulated engine speeds. In the study, in order to search for the minimum stator current, the value of the stator flux linkage was regulated when using the optimal algorithm in the system. The performance of the proposed technique was tested at fixed torque values corresponding to 0.25, 0.5, and 0.75 of the nominal torque value. The data obtained as a result of the three experiments are presented in Figure 26, which shows the sections where the stator current at the listed torque indicators has a minimum value.

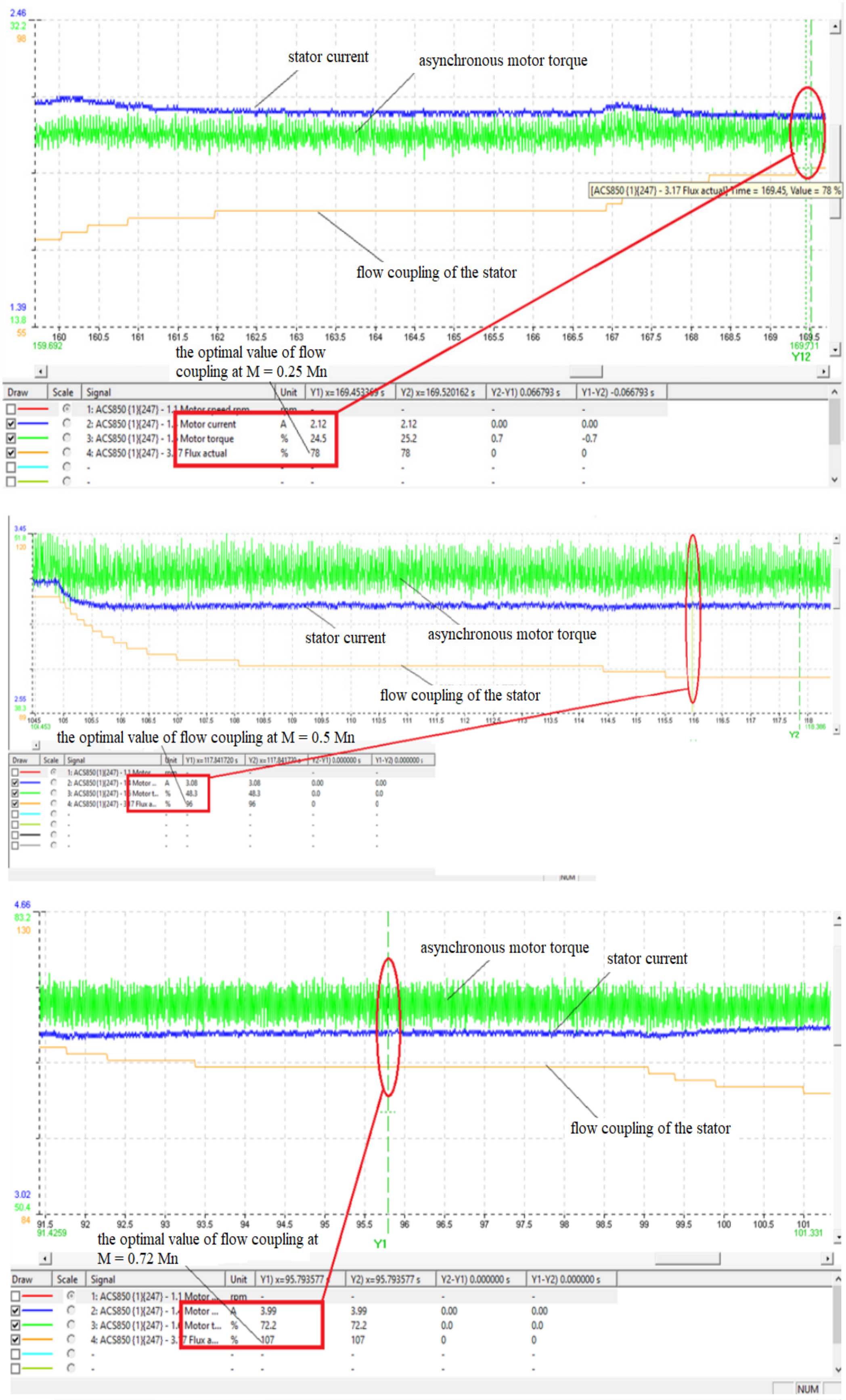

Figure 26. Obtained experimental data.

The analysis of the presented characteristics shows that, with a load torque equal to 0.25 of the nominal torque and a flux linkage equal to 0.78 of the nominal value of the flux linkage, the stator current decreased by about 10.5 percent relative to the current indicators when the flux linkage equal to the nominal value was introduced. With a load torque equal to half of the nominal torque and a flux linkage equal to 0.96 of the nominal flux linkage, the stator current decreased by about 1.5 percent relative to the current indicators when the flux linkage equal to the nominal value was introduced. With a load torque equal to 0.72 of the nominal torque and a flux linkage equal to 1.07 of the nominal flux linkage value, the stator current decreased by about 3.5 percent relative to the current indicators when the flux linkage equal to the nominal value was introduced.

Author Contributions: Conceptualization, S.V., A.S. and T.S.; methodology, S.V., V.M. and E.G.; formal analysis, A.S. and T.S.; investigation, V.M.; resources, V.M.; data curation, E.G.; writing—original draft preparation, S.V. and V.M.; writing—review and editing, A.S. and T.S.; visualization, S.V., A.S. and T.S.; supervision, T.S.; project administration, S.V. All authors have read and agreed to the published version of the manuscript.

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