ISSN 1330-3651 (Print), ISSN1848-6339 (Online)
https://doi.org/10.17559/TV-20221015124239
Original scientific paper

Vector Control System Taking into Account the Saturation of an Induction Motor

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Abstract: In modern traction drive systems for electric rolling stock with induction traction motors, vector systems have found the greatest use as control systems. The reduction of losses in the traction drive system and, as a result, the reduction of electrical energy consumption depends on the accuracy of regulation of the controlled parameters. An analysis of studies devoted to the development of vector control systems has shown that taking into account the saturation of the magnetic system of an induction motor increases the accuracy of adjusting the controlled parameters. This study proposes a method for taking into account the saturation of the motor magnetic circuit through the main motor inductance, as a function of the magnetic circuit flux linkage. On the basis of the proposed method in the MATLab software environment, a simulation vector control system was performed with and without saturation. Comparison of the simulation results showed that neglect of saturation leads to an increase in the slip of the motor rotor by 0.0111 relative units and, as a result, to a decrease in the efficiency of the rotor by 1.02%.

Keywords: induction motor; saturation of an induction motor; vector control system

1 INTRODUCTION

The continuing global trend towards rising prices for electricity requires the system of transmission, distribution and consumption of electricity to develop measures aimed at reducing its losses, and hence consumption [1]. Transport is one of the most energy-consuming sectors of the economy. Among the modes of transport, electric transport consumes more electric energy: electric rolling stock of railways [2], subways [3] and urban electric transport [4]. Therefore, the development of measures aimed at reducing the power consumption of electric transport is an urgent task.

In traction power supply systems, reducing electricity consumption without negatively affecting the consumer is one of the most common ways to save energy [5]. Measures to reduce losses in the traction power supply system can be divided into measures aimed at reducing active power losses and measures aimed at reducing reactive power. Among the measures aimed at reducing active power losses, one can single out measures aimed at reducing the negative impact of an increase in frequency and temperature [6]. Measures aimed at reducing the consumption of reactive power in the traction power supply system are primarily related to the compensation of the higher harmonic components of the voltage of the contact network and balancing the phases of the traction power supply system [7].

Another important way to reduce electricity consumption is measures aimed at reducing losses in electric rolling stock. Among the measures aimed at reducing the reactive energy generated by the electric rolling stock in the contact network, it is necessary to single out the use of various topologies of the circuits of input electrical energy converters and the use of input converter control algorithms aimed at reducing the higher harmonic components in the traction current and reducing the angle of shift between the voltage and traction current [8]. Reduction of active power losses is achieved by increasing the accuracy of the control system of the output converter of the traction drive of the electric rolling stock [9].

In traction drive systems of electric rolling stock, induction motors are most widely used [10]. Currently, the following drive control systems with induction traction motors are known: scalar control [11], vector control [12], direct torque control [13]. In [14], the dynamic properties of traction drives with different control systems are compared. In this work, it is indicated that the most effective when the traction drive is operating in both normal and emergency modes is the vector control system.

When developing a vector control system for an induction traction drive, one should take into account the features of the operation of both the induction motor itself and the vector control system. Such features on the part of an induction motor include the dependence of magnetic losses in the steel of an induction motor on a change in the speed of rotation of the motor shaft and taking into account the saturation of the magnetic circuit of the motor [15]. The features of the control system operation include sudden changes in speed and load [16], the effect of interference in the control system caused by a change in the temperature of the inverter [17], motor windings and current sensor noise [18].

Thus, increasing the accuracy of adjustment of a vector control system with induction traction motors in order to reduce losses in the traction drive system of electric rolling stock can be considered as an important task. This article proposes a model of a vector control system for the traction drive of an AC electric locomotive with induction motors, taking into account the saturation of the magnetic system of the motors.

To accomplish this task, the following objectives were solved in the work:

- calculation of the equivalent circuit of an induction motor is carried out, taking into account the saturation of the magnetic system of the induction motor;
- the elements of the vector control circuit are calculated taking into account the saturation of the magnetic system of the induction motor;
- simulation modeling of the operation of the vector control circuit was carried out without taking into account and taking into account the saturation of the magnetic system of the induction motor;
- comparison of the obtained results of simulation of the operation of the vector control circuit without taking into account and taking into account the saturation of the magnetic system of an induction motor is made.

2 SIMULATION THEORY AND MODEL CONSTRUCTION

In this section, the parameters are calculated and a simulation model of the vector control system of the induction traction motor is developed. The parameters of the vector control system were calculated taking into account the saturation of the magnetic system of the induction motor. This simulation model allows you to conduct research with and without taking into account the saturation of the magnetic system of the induction motor without structural changes in it. For the convenience of analyzing the obtained results, a simulation model of the vector control system without an autonomous voltage converter was developed.

2.1 Analysis Process

Vector control systems for induction motors are frequency-controlled systems. There are the following principles of frequency control:

- constant speed control U_s / f (U_s - the stator phase voltage; f - the stator voltage frequency);
- speed control with constant stator flux linkage (ψ_s);
- speed control with constant magnetization flux linkage (ψ_μ);
- Speed control with constant rotor flux linkage (ψ_r).

In [19], it is shown that the most effective principle of frequency control in the organization of vector control of an induction motor is speed control with constant rotor flux coupling (ψ_r), since with this control the dependence of the torque on the motor slip (mechanical characteristic) is linear.

The operation of the vector control system is based on the control over the vector of the controlled parameter, expressed in a two-phase coordinate system. The controlled parameter is obtained by calculation based on the values of the motor stator phase currents. The stator phase currents are vectors expressed in a three-phase coordinate system. Therefore, in the vector control system, the phase stator values are converted from a three-phase coordinate system to a two-phase one.

In [20], the authors analyzed the advantages and disadvantages of two-phase coordinate systems that can be used in the organization of the vector control system of an induction motor. As a result of the analysis, it was found that in the *xy*-coordinates the rotor model is quite simplified and allows to calculate the absolute value and phase of the rotor flux vector directly, eliminating the need for additional mathematical blocks and the frequency of all variables in the axes (x, y) is zero, which leads to an increase in accuracy of regulators and provides additional options when setting up circuits.

The analysis of works [19, 20] allows to assert that the most effective structure of the vector control system for the traction drive of electric rolling stock will be the control system in *xy*-coordinates, the scheme of which is shown in Fig. 1, with the principle of rotor flux linkage control (ψ_r), which is taken for further research in the work.

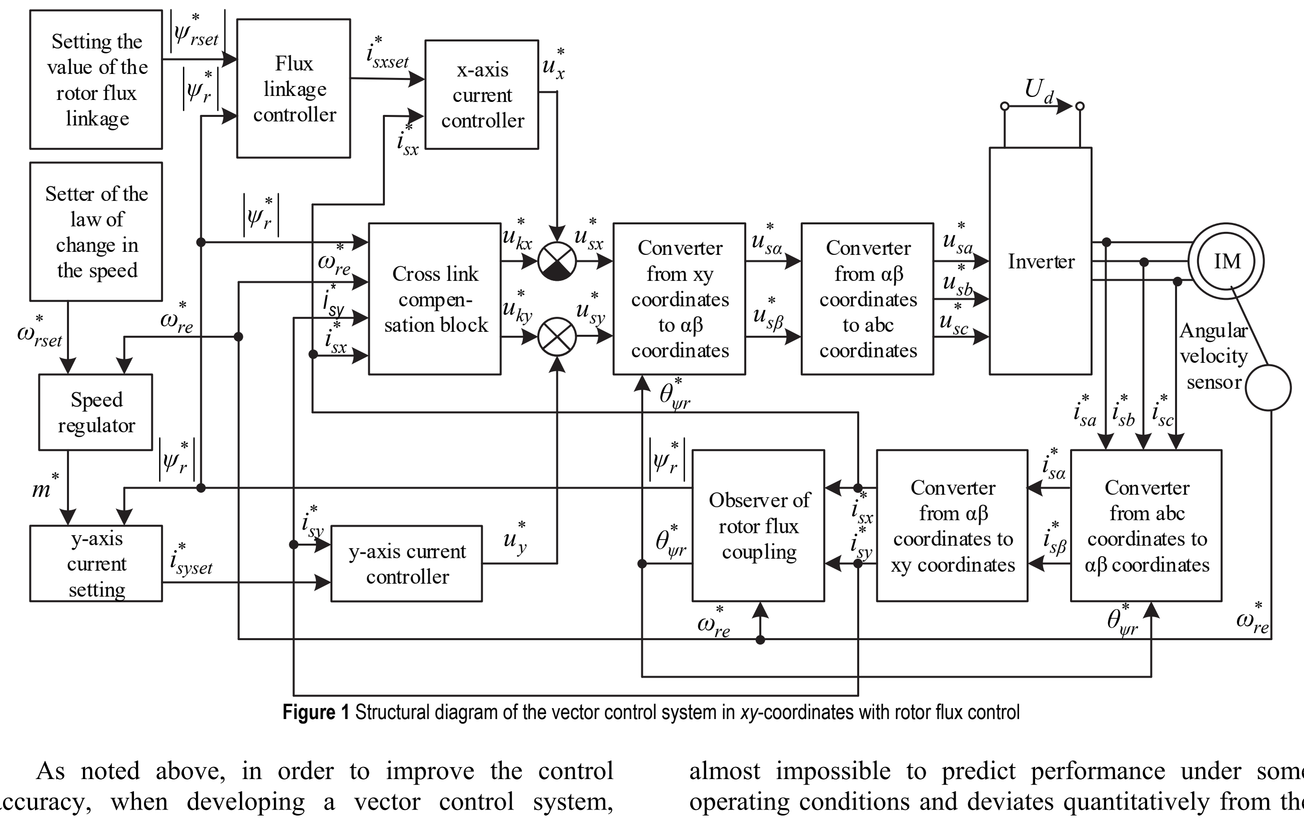


Figure 1 Structural diagram of the vector control system in *xy*-coordinates with rotor flux control

As noted above, in order to improve the control accuracy, when developing a vector control system, magnetic losses in steel and saturation of the magnetic system of an induction motor should be taken into account. In [21], the authors noted that due to the non-linear relationship between flux and currents, conventional linear simulation does not provide accurate results and makes it almost impossible to predict performance under some operating conditions and deviates quantitatively from the actual value. The reason for the deviation may be an assumption made in neglect of the saturation effect, iron losses and heating. They also noted that the saturation effect is the main reason for the discrepancy between simulation and experimental results.

Vector control ensures that the actual motor torque is equal to the set torque. If there is a difference between the actual magnetic flux and the given one, then the expression for the actual torque will be the product of the x-component of the stator current and the y-component of the rotor flux. Thus, the actual torque will be lower than the specified one. Neglecting iron losses and saturation effects in a vector control system causes a relationship between flux and torque. Therefore, it may be necessary to modify the circuit based on the measurement of the stator current and the rotor speed [20]. In the paper, the authors proposed to introduce an additional block into the model of an induction motor that takes into account saturation. This is achieved by taking into account the dependence of the main inductance of the motor on the magnetic flux of the magnetizing circuit. In a vector control system, a block is added to compensate for the relationship between flux and torque.

In [21] the authors proposed to take into account the saturation of the motor magnetic system when constructing a vector control system by expressing the main inductance of an induction motor as a function of the magnetizing current.

Despite the obviously correct approaches in constructing a vector control system, taking into account the saturation of the motor magnetic system, which were used in [20, 21], this approach does not allow to reflect the change in the harmonic composition of voltages and currents due to saturation (we are talking about the possibility of the appearance of higher time harmonics of voltages and currents when considering only a single (first) spatial harmonic of the magnetic flux in the air gap) - with a sinusoidal supply voltage, all voltages and currents will remain sinusoidal.

The solution to this problem can be found in [22, 23], where the authors proposed to take into account the saturation of the magnetic system of an induction motor based on the analysis of the higher harmonic components of induction in the air gap of the motor. In [22] the authors proposed, based on the analysis of the higher harmonic components of induction, to perform a linear approximation of the magnetic system of an induction motor. Then, based on a standard saturated model of an induction motor, derive the non-linear rotor flux relationship as a function of the desired torque, and based on these steps, develop a modified torque-flux controller for the saturated machine. This approach is obviously correct for an induction motor with symmetrical windings. The authors showed in [24] that with the symmetry of the windings, the local mutual inductances of the stator-rotor are not functions of the angle of rotation of the motor shaft, and when asymmetry of the windings occurs, these local mutual inductances are harmonic functions of the angle of rotation of the motor shaft, and therefore a linear approximation of the magnetic system.

In [23] the authors proposed a method for analyzing the high-frequency components of induction in the magnetic gap by comparing the higher harmonic components of the stator phase currents with a reference high-frequency signal introduced into the control system. The results obtained during the simulation showed a high convergence of the obtained electrical parameters with the experimental data, but the input of a high-frequency signal caused the appearance of additional torque ripples.

The authors in [15] took into account magnetic losses in steel when developing a mathematical model of an induction motor. They expressed the indicated losses as a function of the motor speed. This factor is useful when modeling the operation of a vector system with an induction motor when the operating modes of the traction drive change.

In the mathematical model of an induction motor in [15], the authors took into account the saturation of the magnetic system of the motor by introducing into the model the unit for calculating the main inductance of the motor, which is a function of the flux linkage of the magnetic system. This approach made it possible to determine the mutual inductance of the motor for each phase separately. This factor is useful when analyzing the operation of an induction motor by the asymmetry of its windings. But such an approach in modeling was used only for an induction motor, and not for the entire drive as a whole.

The literature review emphasizes the current research situation, when the development of vector control systems for an induction motor does not take into account the saturation of the magnetic system at all or is not taken into account quite correctly. The method proposed by the authors will allow developing a vector control system for induction motors of electric rolling stock in *xy*-coordinates, taking into account the characteristic features of the operation and operating conditions of the traction drive of the electric propulsion train.

2.2 Calculation of the Parameters of the Vector Control System, Taking into Account the Saturation of the Magnetic System of the Induction Motor

Electric locomotives of the DS-3 series are produced in Ukraine. The traction drive of the specified electric locomotive includes induction traction motors with a vector control system. Therefore, the traction drive of the electric locomotive of the DS-3 series was chosen as a prototype.

The traction drive of the DC-3 electric locomotive (Ukraine) with induction traction motors of the STA-1200 type was chosen as the subject of the study. The characteristics of the traction motor are given in Tab. 1[15].

Table 1 Technical parameters of induction traction motor STA-1200

Parameter	Units	Value
Power P_N	kW	1200
Operating value of linear voltage U_N	V	1870
Effective value of phase current I_{sN}	A	450
Rated frequency of supply voltage f_N	Hz	55,8
Number of phases m	number	3
Number of pole pairs $2p$	number	3
Rated speed n_N	rpm	1110
Moment on the shaft T_N	N·m	10326
Moment of inertia J_N	kg·m^2	39
Rated slip s_N	%	0.54
Winding stator active resistance r_s	Ω	0.0261
The active resistance of the rotor windings reduced to the stator winding r'_r	Ω	0.0265
Winding stator leakage inductance L_s	mH	0.65
The leakage inductance of the rotor winding reduced to the stator winding L'_r	mH	0.45
Total inductance of the magnetizing circuit $L_{\mu N}$	mH	19.4336

As a basic vector control system, a control system in *xy*-coordinates with the principle of control according to the rotor flux (ψ_r) was chosen (Fig. 1). To calculate the parameters of the vector control system, the characteristics of which are given in relative units (Fig. 1), basic values of the system of relative units are determined. Basic values of the system of relative units are added to Tab. 2.

Table 2 Basic values of the system of relative units

Basic values of the system of relative units	Expression	Units	Value
Voltage	$U_b = \sqrt{2} \cdot U_N$	V	1527
Current	$I_b = \sqrt{2} \cdot I_N$	A	636
Angular speed of the stator	$\Omega_b = \Omega_{sb} = 2 \cdot \pi \cdot f_N$	rad/s	350.6
Rotor angular velocity	$\Omega_{rb} = \Omega_b / 2p$	rad/s	116.87
Resistance	$Z_b = U_b / I_b$	Ω	2.4
Flux linkage	$\Psi_b = \Psi_b / I_b$	V·s	4.335
Inductance	$L_b = U_b / \Omega_b$	H	0.0097
Moment,	$M_b = (1{,}0084 \cdot P_b \cdot 60)/(2 \cdot \pi \cdot n_N)$	N·m	10410
Power	$P_b = M_b \cdot \Omega_{rb}$	kW	1216.7

Since in the vector control system, when calculating the parameters of its elements, the parameters of the equivalent circuit of an induction motor are used, the parameters of the L-shaped equivalent circuit were calculated. When calculating the parameters of the equivalent circuit, the saturation of the motor magnetic system was taken into account. In [15], the dependence of the main inductance of an induction motor on the value of the flux linkage of the magnetization circuit is given. On the simulation model, this dependence is made in the form of a separate block with the output of the value of the relative inductance. Therefore, in further calculations, to take into account the saturation of the magnetic circuit of the motor, the value of the main inductance is equal to

$$L_\mu = L_\mu^* \cdot L_{\mu N}, \tag{1}$$

where: $L_{\mu N}$ -the value of the main inductance of the induction motor.

The values of the equivalent circuit parameters are shown in Tab. 3. Since the number of equivalent circuit parameters depends on the main inductance, and the main inductance is a variable value, Tab. 3 contains only analytical expressions for determining the parameters.

Table 3 Meaning of equivalent circuit parameters in relative units

Equivalent circuit parameters	Expression
Relative active resistance of the stator winding	$r_s^* = r_s / Z_b$
Relative active resistance of the rotor winding	$r_r^* = r_r / Z_b$
Relative leakage inductance of the stator winding	$L_{\sigma s}^* = L_{\sigma s} / L_b$
Relative leakage inductance of the rotor winding	$L_{\sigma r}^* = L_{\sigma r} / L_b$
Relative main motor inductance	$L_\mu^* = L_\mu / L_b$
Mechanical time constant	$T_j = (J_\Sigma \cdot \Omega_{rb}) / M_b$
Normalizing energy factor	$\zeta_N = (3 \cdot I_b \cdot U_b) / P_b$
Model equation coefficients	$k_r = L_\mu^* / (L_\mu^* + L_{\sigma r}^*)$
	$L_{\sigma e} = L_{\sigma s}^* + L_{\sigma r}^* + L_{\sigma s}^* \cdot L_{\sigma r}^* \cdot L_\mu^{*-1}$
Test coefficients	$a_0 = L_{\sigma e} + (r_s^* \cdot (1 + L_{\sigma r}^* \cdot L_\mu^{*-1}))^2 - (1 + L_{\sigma s}^* \cdot L_\mu^{*-1})^2$
	$a_1 = 2 \cdot r_s^*$
	$a_2 = L_\mu^{*-2} \cdot ((r_s^*) + (L_{\sigma s}^* + L_\mu^*)^2 - 1)$
Correction factor	$\rho_N = (-a_1 + ((a_1)^2 - 4 \cdot a_0 \cdot a_2)^{1/2}) / 2 \cdot a_2$
Corrected active resistance of the rotor winding	$r_{rk}^* = \rho_N \cdot r_r^*$
Equivalent inductance	$L_e = k_r \cdot L_{\sigma e}$
Equivalent resistance	$r_e = r_s^* + (k_r)^2 \cdot r_r^*$
Electrical time constant	$T_e = L_e / r_e$
Rotor lap time constant	$T_r = (L_{\sigma r}^* + L_\mu^*) / r_{rk}^*$

The structures of the elements of the vector control system are given in [14]. Analytical expressions for calculating the coefficients of regulators are given in Tab. 4.

Table 4 The value of the coefficients of the regulators of the vector control system

Controller type	Coefficient	Expression
X-axis current controller	Proportional	$K_{pIx} = (T_e \cdot r_e)/(2 \cdot T_\mu \cdot \Omega_b)$
	Integral	$K_{iIx} = r_e / (2 \cdot T_\mu)$
Y-axis current controller	Proportional	$K_{pIy} = (T_e \cdot r_e)/(2 \cdot T_\mu \cdot \Omega_b)$
	Integral	$K_{iIy} = r_e / (2 \cdot T_\mu)$
Flux controller	Proportional	$K_{p\psi} = T_r / (4 \cdot n \cdot T_\mu \cdot \Omega_b \cdot L_\mu^*)$
	Integral	$K_{p\psi} = 1/(4 \cdot n \cdot T_\mu \cdot \Omega_b \cdot L_\mu^*)$
Speed controller	Proportional	$K_{p\omega} = T_j / (4 \cdot T_\mu)$
	Integral	0

In Tab. 4, $T_\mu = 0{,}0025$ s - the uncompensated constant time; n = 2 - the multiplicity of uncompensated constant time [14].

2.3 Simulation Model of a Vector Control System

The simulation model is made in the MATLab software environment. When developing a simulation model, it is necessary to implement a block for setting the change in the applied rotation speed (speed controller). It was organized on the building block of the Simulink "Signal Builder" library. The parameters of the dragger were chosen on the basis of considerations. An analysis of the torque and speed diagrams in [15] showed that the transient processes in the motor with direct voltage supply last 0,7 s. That is, the speed controller delay will be 0,7 s. since there are no additional restrictions, the rise time to reach the steady state is assumed to be 3 s. The time for the vector control system to reach the steady state was 3,7 s. In the steady state, the relative value of the generator frequency will be equal to 1. The delay time for applying the load, which is made in the form of a "Step" block, will also be 3,7 s.

The induction motor is made in the form of the "Induction Motor" block, the control system - in the form of the "Control System" block, the implementation of the calculation of the parameters of the equivalent circuit (Tab. 4) - in the form of the "Parameters" block. When organizing the power supply system of an induction motor, controlled voltage sources were used as stator phase voltage generators, the control input of which is the product of phase voltages from the output of the control system and the nominal instantaneous value of the stator voltage. Controlled voltage sources are used, since the electrical part of the induction motor model is made on the elements of the SimPower System library [15, 16]. The simulation model of a vector system with an induction motor is shown in Fig. 2.

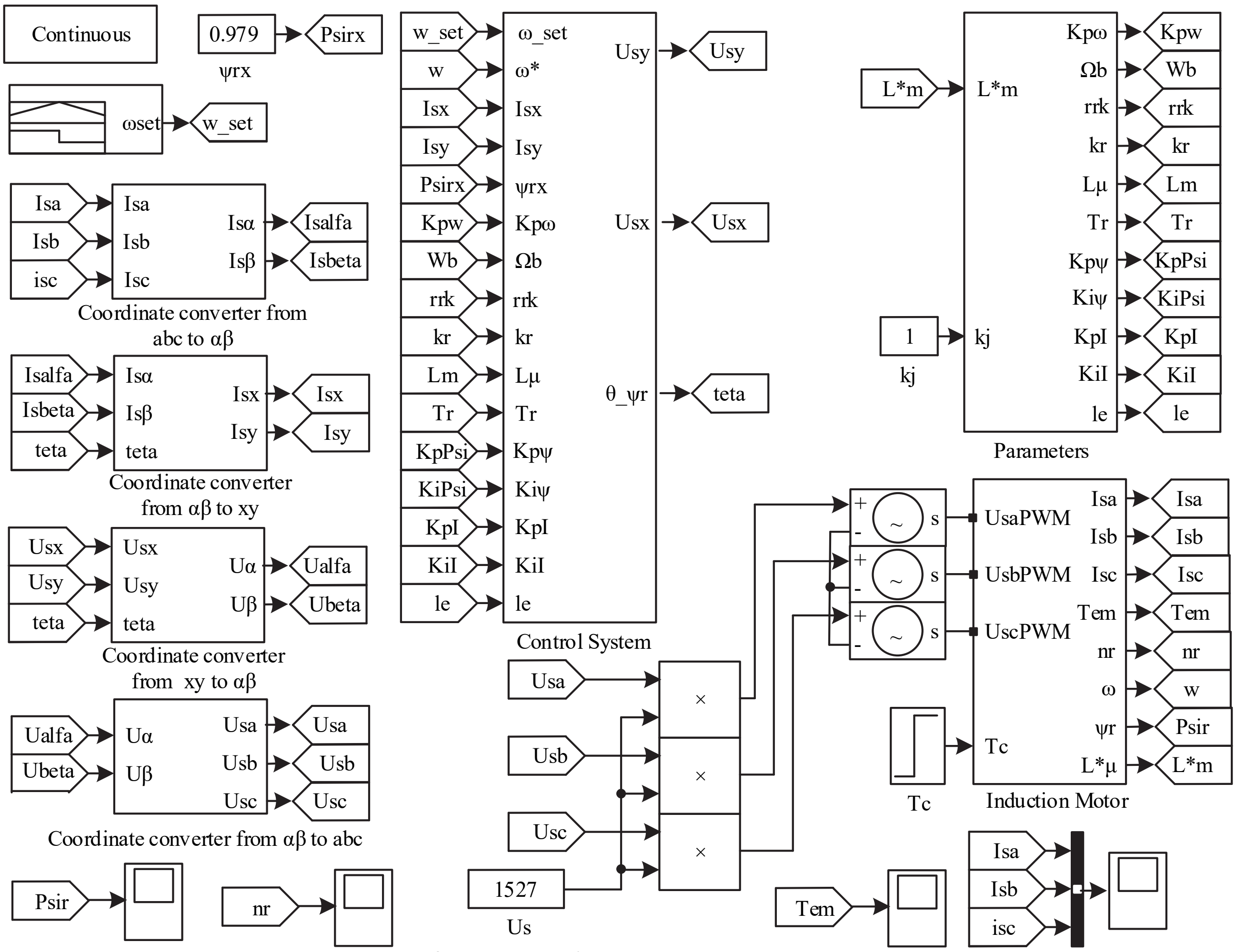


Figure 2 Simulation model of a vector system by an induction motor

The given flux linkage was calculated by the formula

$$\psi_{rN} = \sqrt{\frac{r_r^* \cdot m_N^*}{\zeta_N \cdot s_N}} = 0.979, p.u. \tag{2}$$

where: $r_r^* = 0.011, p.u.$ - the active resistance of the rotor winding in relative units (Tab. 3); $s_N = 0.0056, p.u.$ - nominal slip (Tab. 3); $\zeta_N = 2.43, p.u$ - normalizing energy coefficient (Tab. 3); m_N^* -nominal value of torque in relative units.

$$m_N^* = \frac{P_N}{P_b} = 0.986, p.u. \tag{3}$$

The simulation model (Fig. 2) provides for the possibility of operating the system with different loads. To do this, list the load on the motor shaft and enter the resulting value in the Step T_c block. In addition, it is possible to list the moment of inertia on the motor shaft, divide it by the nominal value, and write the resulting coefficient as a coefficient k_j. There is

$$k_j = \frac{J_\Sigma}{J_N}, \tag{4}$$

where: J_Σ - the total value of the moment of inertia on the motor shaft; J_N - the nominal value of the moment of inertia on the motor shaft.

3 RESULTS AND DISCUSSION

Motors in traction drives of rolling stock of railways are located on wheeled carts. This circumstance leads to the fact that the limiting factor in the design of traction motors is their mass and overall dimensions. In connection with this factor, traction induction motors are designed with saturation of the magnetic system in the nominal mode of operation. The purpose of the work is to investigate the effect of taking saturation into account on the operation of the vector control system of traction induction motors. To achieve the goal, the authors compare the starting characteristics of the traction drive, both with and without taking into account the saturation of the magnetic system of the traction induction motor when designing the vector control system. When conducting these studies on the electric locomotive itself, a number of difficulties arise, namely:

- since the traction induction motor is designed with saturation of the magnetic system, it is impossible to realize the operation of its magnetic system without saturation;

- high consumption of electricity during the study of starting characteristics, taking into account the saturation of the magnetic system of the traction induction motor (nominal power of one motor of the STA-1200 series is 1200 kW. There are six such motors on the electric locomotives of the DS-3 series).

It is also inpractical to make a device for carrying out the mentioned studies using induction motors of lower power, since:

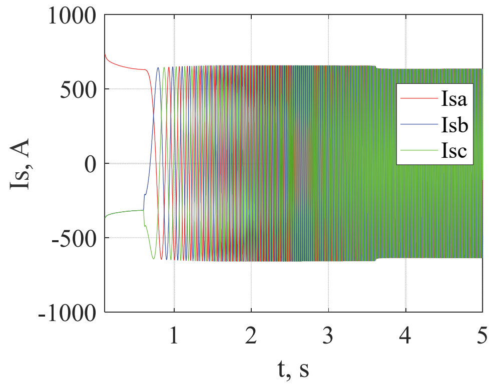
- it is difficult to organize the operation of an induction motor in a mode without saturation;
- in these induction motors, the magnetic system is significantly less saturated than in traction motors. This circumstance will lead to the fact that the start-up characteristics of the specified and the traction motor will be qualitatively different.

That is why the authors decided to conduct a study of the impact of taking into account saturation on the operation of the vector control system of traction induction motors on a simulation model

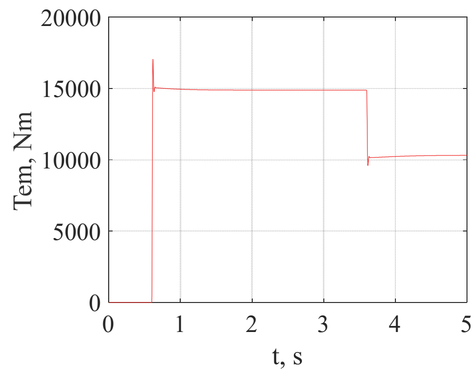
3.1 Modeling Results

Two cases were studied on the simulation model. The first consisted in obtaining on a simulation model the time diagrams of phase currents, moment, speed of rotation of the motor shaft and flux coupling at the nominal parameters of the traction motor, taking into account the saturation of its magnetic system. The second case is similar to the first, but without taking into account the saturation of the magnetic system of the traction motor.

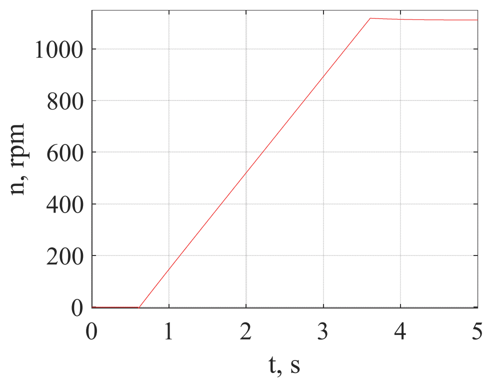
The simulation results for the first case are presented in Fig. 3.



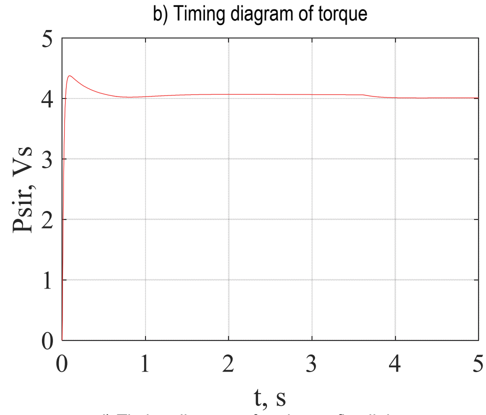
a) Timing diagram of phase currents



b) Timing diagram of torque



c) Timing diagram of motor shaft rotation speed



d) Timing diagram of and rotor flux linkage

Figure 3 Time diagrams obtained on the model taking into account saturation

During the second case, instead of the signal L_m^* (Fig. 2), 1 was applied to the input of the "Parameters" block. This means that the scheme does not take into account the saturation of the motor magnetic system. The simulation results for the second case are shown in Fig. 4.

The following variable designations are used in Fig. 3 and Fig. 4:

Isa, *Isb*, *Isc* - stator phase currents; *Tem* - torque; *n* - frequency of rotation of the motor shaft; *Psir* - rotor flux linkage; *t* - time.

The values of phase currents, torque, motor shaft speed and rotor flux linkage are listed in Tab. 5.

As a result of the simulation for both cases, the values of the phase currents, torque, speed of rotation of the motor shaft and flux coupling of the rotor were determined for the stable mode of operation (Tab. 5). Based on the results of Tab. 5, the deviations of the obtained values were calculated in the form of a relative error calculated by the formula

$$\delta = \left| \frac{A_N - A}{A_N} \right| \cdot 100\%, \tag{5}$$

where: A - the value of the controlled parameter; A_N - the nominal value of the controlled parameter.

The calculation results are listed in Tab. 5.

The slip was also calculated:

$$s = \frac{n_{rN} - n}{n_{rN}} \tag{6}$$

and rotor efficiency

$$\eta = 1 - s. \tag{7}$$

The results of the calculations are listed in Tab. 5.

Table 5 Analysis of simulation results system

Controlled parameter	Rated value	Simulation values			
		Case 1		Case 2	
		Value	Error / %	Value	Error / %
Instantaneous value of phase current I_s, A	636	635	0,16	416,6	34,5
Torque, T_{em}, N·m	10 326	10 320	0,06	10 330	0,04
Motor shaft speed, n_r, rpm	1110	1111	0,09	1103	0,63
Rotor flux linkage, ψ_r, V·s	4.0	4,008	0,2	3,098	22,55
Slip, s, %	0,0054	0,0044	1,85	0,0165	205
Efficiency of the rotor winding, η, %	99,46	99,56	0,1	98,35	1,12

3.2 Analysis of Simulation Results

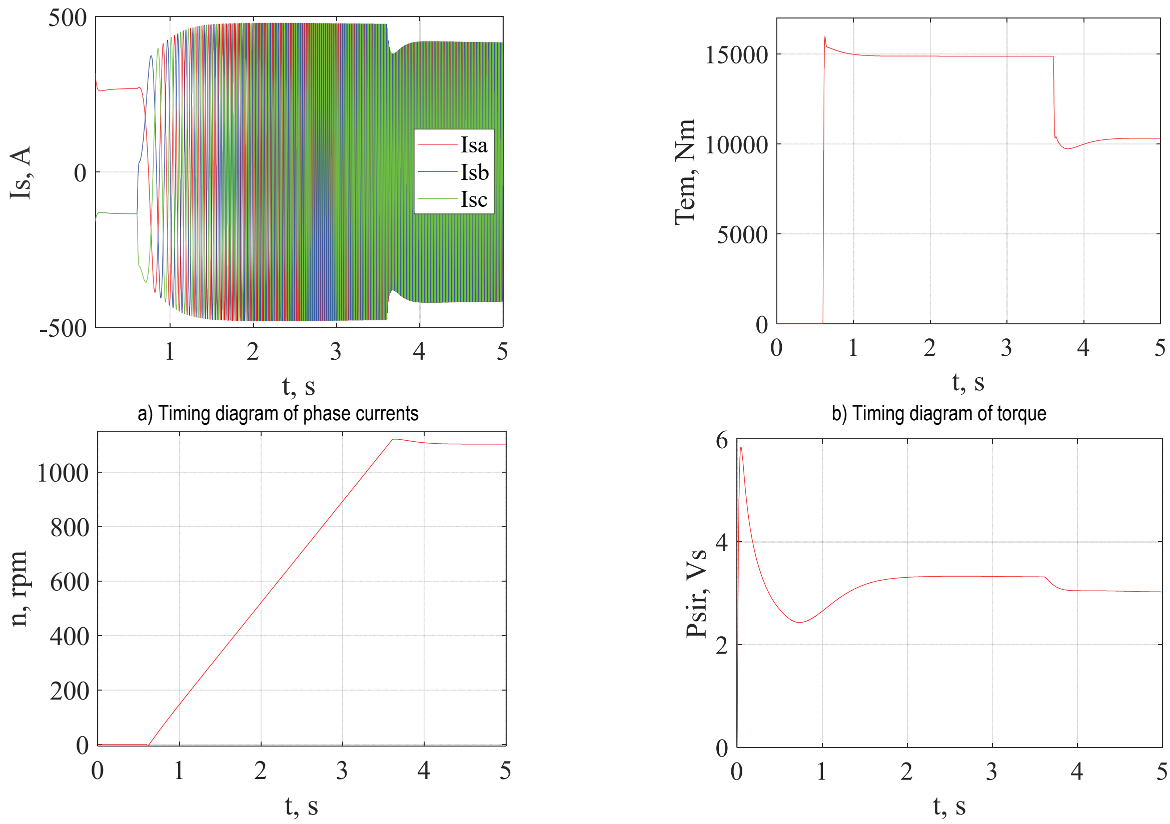
Analysis of the simulation results shown in Figs. 3 to 4 and Tab. 5 showed the following:

Taking into account the saturation of the magnetic system of an induction motor in the vector control system made it possible to determine the parameters of the motor close to the values obtained with a direct supply voltage to the motor. The maximum error was 1.85%.

In the vector control system, without taking into account the saturation of the motor magnetic system, such parameters as torque and motor shaft speed are close in terms of the values of the parameters determined when the supply voltage is directly applied to the motor. The value of the phase current decreased by 34.53%, the rotor flux linkage by 22.55%. These factors led to an increase in slip by 0.0111 relative units and, as a result, to a decrease in the efficiency of the rotor by 1.02%.

The disadvantages of the work include:

- impossibility of verifying the results obtained with experimental data on electric rolling stock in real conditions of its operation;
- lack of consideration of thermal conditions in the elements of the traction drive when building a vector control system.



a) Timing diagram of phase currents; b) Timing diagram of torque; c) Timing diagram of motor shaft rotation speed; d) Timing diagram of and rotor flux linkage

Figure 4 Time diagrams obtained on the model without taking into account saturation

This work can be continued by studies related to the analysis of thermal conditions of traction drive elements for control accuracy and studies related to the development of control system controllers, the operation of which is adapted to changing the influence of interference acting on the vector control system.

4 CONCLUSIONS

The simulation model of the vector control system, taking into account the saturation of the magnetic circuit of the induction motor, was developed in the MATLab software environment. When comparing the simulation results with and without taking into account the saturation of the magnetic system of the induction motor, the following was established:

(1) Errors in determining the controlled parameters on the simulation model, taking into account the saturation of the magnetic system of the induction motor, did not exceed 1,85% compared to the nominal values of the motor;
(2) The error in determining the phase currents on the simulation model without taking into account the saturation of the magnetic system of the induction motor was 34,53%;
(3) The error of determining the flux linkage of the rotor on the simulation model without taking into account the saturation of the magnetic system of the induction motor was 22,55%;
(4) The rotor slip on the simulation model without taking into account the saturation of the magnetic system of the induction motor increased by 0,0111 conventional units;
(3) The efficiency of the rotor on the model without taking into account the saturation of the magnetic system of the induction motor decreased by 1,02%.

Acknowledgements

This work was supported by the Ministry of Education and Science of Ukraine in the project DR No. 0120U101912: Increasing the energy efficiency of rolling stock based on resource-saving technologies and smart energy systems.

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