Development of an Automatic Locomotive Traction Drive Control System to Reduce the Amount of Wheel Slippage on the Rail

Alexander Buynosov, Boris Sergeev,
Anatoly Kalinichenko, and Sergey Antropov

Ural State University of Railway Transport,
Kolmogorova Street, 66, Yekaterinburg 620034, Russia
`byinosov@mail.ru`

Abstract. The subject of the study is the structure of the vector control system. The relevance of this topic lies in the current trends in the development of traction drive control systems that provide stable operation of an electric locomotive. On the basis of the developed and described mathematical model, the basic principles of control of the traction drive with the task of speed and torque are determined. The simulation results reflect the key moments of electric locomotive drive control in the conditions of external disturbing factors. The control system for the traction drive will completely provide the realization of traction properties of a locomotive subject to achieve and automatically maintain specified speed until the construction regardless of the profile path with an acceleration due to the task utilization of time at the wheel of the locomotive.

Keywords: Locomotive · Traction · Drive · Wheel · Rail · Slippage · Control · Target · Reduction · Automatic · System · Development

1 Introduction

Modern traction electric drives of locomotives are complex electromechanical systems, the creation and development of which requires improving the methodology of their research [1].

One of the most promising options for automated traction drives can be called a frequency-controlled electric drive, which includes a bunch of "frequency Converter-asynchronous motor". The use of induction motors with squirrel-cage rotor in the traction drive of an electric locomotive is primarily due to the optimal price/quality ratio, high reliability, low maintenance costs and high efficiency [2].

Currently, the methods of frequency control of the electric drive include [3–6]:

– scalar control;
– vector control.

The most widespread in high-frequency drives, to which the traction drive of electric locomotives belongs, is vector control by flow coupling of the rotor, which can be both with a sensor and without an angular speed sensor. Sensorless control, like any

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other system, has its advantages and disadvantages, namely: the determination of the position of the rotor flux coupling can be calculated from the output data from the sensors of phase currents and phase voltages. However, at low frequencies of the supply voltage, the accuracy of data from the sensors decreases, which leads to unstable operation of the vector control system (IED) of the Converter.

Therefore, on the rolling stock is often used IED with a sensor of angular frequency of rotation of the rotor on the negative feedback.

It should be noted that vector control, in relation to scalar, has significant advantages, such as a higher level of accuracy in regulating the speed of rotation of the shaft and rapid response to possible changes in the load, provoked by external disturbing factors from the infrastructure and the environment [7].

In this case, vector control is divided into flow-oriented control and direct torque control [8].

2 Mathematical Model of Traction Drive Control System

2.1 The Main Provisions of the Vector Control System

The implementation of flow-oriented control is based on the direct measurement of the flow vector, which can be determined on the basis of data on the angular position of the rotor using a position sensor, or the so-called state observer with Sensorless control, which by means of mathematical transformations based on changes in the flow and stator currents calculates the flow-coupling of the rotor and its angular position.

The main disadvantage of the classical vector control system of the electric drive is its complex structure due to the need to perform operations of converting coordinate systems from stationary to rotating, oriented along the rotor field (x-y), and Vice versa, necessary to control the magnetic field vector by means of a current in the direction of the coordinate x and the quadrature component of the field in the orthogonal direction y. However, modern trends in the development of drive electronics allow us to create relatively cheap and high-performance frequency converters. For traction induction motors with squirrel cage rotor frequency control is the most perfect way of economical speed control over a wide range.

2.2 Construction of the Equivalent Circuit of the Asynchronous Traction Motor

In General, when designing asynchronous traction motors tend to ensure that magnetization losses, compared with active losses in the stator windings, can be neglected. Thus, as a model to illustrate the processes occurring in the engine, often use a simplified t-shaped equivalent circuit (Fig. 1).

In the equivalent circuit (Fig. 1): u_s – generalized vector of input voltage; i_s – generalized vector of stator current.

The stator current vector is divided into two components: i_m – generalized magnetization current vector; i_r – generalized rotor current vector. The values and ratios of motor currents at a given input voltage are determined by the parameters of the equivalent circuit. Stator resistance (R_s) characterizes the active losses in the stator windings and is equal to the resistance of the phase winding of the stator. Stator scattering inductance ($L_{\sigma s}$) characterizes the part of the stator flow that is not coupled to the rotor and does not participate in the creation of the moment. The main inductance (L_m) characterizes the part of the flow that is coupled to the stator and the rotor and participates in the creation of the moment. On the linear portion of the magnetization curve of the motor, the main inductance is a constant. When the saturation of the magnetic motor value of the main inductance decreases. The rotor scattering inductance ($L_{\sigma s}$) characterizes the part of the rotor flow that is not coupled to the stator and does not participate in the creation of the moment. In addition, the R_r/S – parameter characterizes the active losses in the rotor (R_r – rotor resistance in the short-circuit mode (the motor shaft is braked).

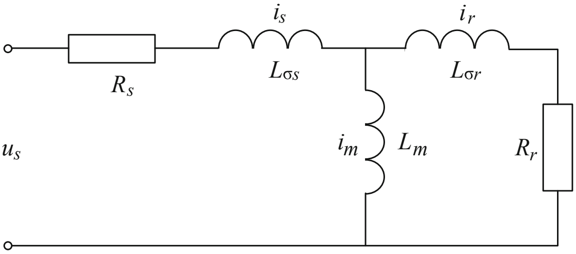

Fig. 1. Induction traction motor equivalent circuit

The slide S is defined as follows

$$S = \frac{n_1 - n_2}{n_1}, \tag{1}$$

where n_1 – the speed of rotation of the field; n_2 – the speed of rotation of the rotor.

Induction motor is characterized by the following state vectors: $\vec{u}_s$ – stator voltage vector; $\vec{i}_s$ – stator current vector; $\vec{i}_r$ – rotor current vector; $\vec{i}_m$ – magnetization current vector; $\vec{\psi}_s$ – stator flow vector; $\vec{\psi}_r$ – rotor flow vector; $\vec{\psi}_m$ – flow vector in the air gap (magnetization flow).

2.3 Vector Diagram of Asynchronous Traction Motor

Figure 2 shows a vector diagram illustrating the relationship of the induction motor state vectors.

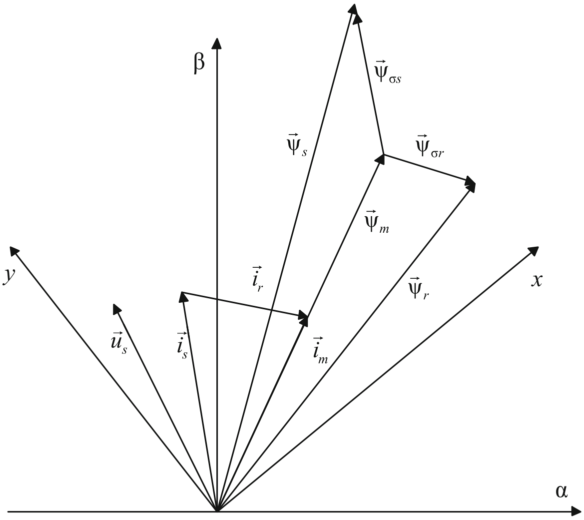

Fig. 2. Relationship of induction motor state vectors

In the presented vector diagram, the α and β axes are associated with a fixed stator, and the x and y axes are associated with the rotor position and its windings.

During operation of the induction motor, all vectors rotate in the cross-sectional plane of the induction motor around the axis of rotation of the rotor. At constant speed and load moment (in steady-state mode) the amplitudes, phase shifts and velocities of all state vectors remain constant. In dynamics, the amplitudes of state vectors and phase shifts between them change during transients.

Based on the above vector diagram, you can calculate the basic values. So the magnetization current vector is equal to the mousse of the rotor and stator current vectors:

$$\vec{i}_m = \vec{i}_s + \vec{i}_r. \tag{2}$$

The stator flux coupling vector is equal to the sum of the magnetization flux vector and the stator scattering flux:

$$\vec{\psi}_s = \vec{\psi}_m + \vec{\psi}_{\sigma s}. \tag{3}$$

The stator scattering flux is equal to the product of the stator current by the stator scattering inductance:

$$\vec{\psi}_{\sigma s} = L_{\sigma s} \cdot \vec{i}_s. \tag{4}$$

The rotor flux coupling vector is equal to the sum of the magnetization flux vector and the rotor scattering flux:

$$\vec{\psi}_r = \vec{\psi}_m + \vec{\psi}_{\sigma r}. \tag{5}$$

The rotor scattering flux is equal to the product of the rotor current by the rotor scattering inductance:

$$\vec{\psi}_{\sigma r} = L_{\sigma r} \cdot \vec{i}_r. \tag{6}$$

Based on these expressions, you can determine the relationship between the current triangle and the flow triangles. Here the magnetization flux is equal to the product of the magnetization current by the motor magnetization inductance:

$$\vec{\psi}_m = L_m \cdot \vec{i}_m. \tag{7}$$

By means of the above expressions the flows are expressed through the stator and rotor currents as follows:

$$\vec{\psi}_m = L_m \cdot \vec{i}_m = L_m \cdot \vec{i}_s + L_m \cdot \vec{i}_r, \tag{8}$$

$$\vec{\psi}_s = L_s \cdot \vec{i}_s + L_m \cdot \vec{i}_r, \tag{9}$$

$$\vec{\psi}_r = L_r \cdot \vec{i}_r + L_m \cdot \vec{i}_s, \tag{10}$$

where L_s is the inductance of the stator, L_r is the inductance of the rotor.

$$L_s = L_m + L_{\sigma s}, \tag{11}$$

$$L_r = L_m + L_{\sigma r}. \tag{12}$$

The electromagnetic torque of the induction motor arises due to the interaction of the rotor current with the flow coupling in the air gap (magnetization flow). Hence the electromagnetic torque of a three-phase motor is defined as follows:

$$M_{et} = \frac{3}{2} \cdot z_p \cdot \frac{L_m}{L_r} \cdot \psi_x \cdot i_x = \frac{3 \cdot z_p}{2 \cdot R} \cdot \psi_x \cdot \omega, \tag{13}$$

where z_p – the number of pairs of poles; L_m – mutual inductance of the stator and rotor; L_r – inductance of the rotor; ψ_x – flux coupling of the rotor; i_x – stator current; R – resistance of the rotor winding of the motor; ω –angular frequency of the rotor.

2.4 Varieties of Vector Control Systems Traction Drive Locomotive

The traction drive can be controlled in three ways:

- speed control (indirectly by torque);
- torque control;
- adjacent speed and torque control.

Figures 3 and 4 show both traction control structures.

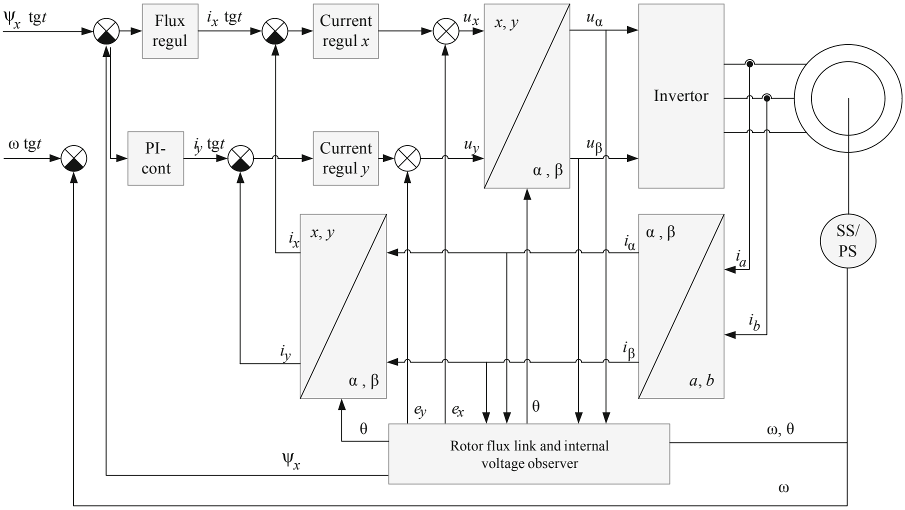

Fig. 3. The structure of the vector control system with the task of the moment

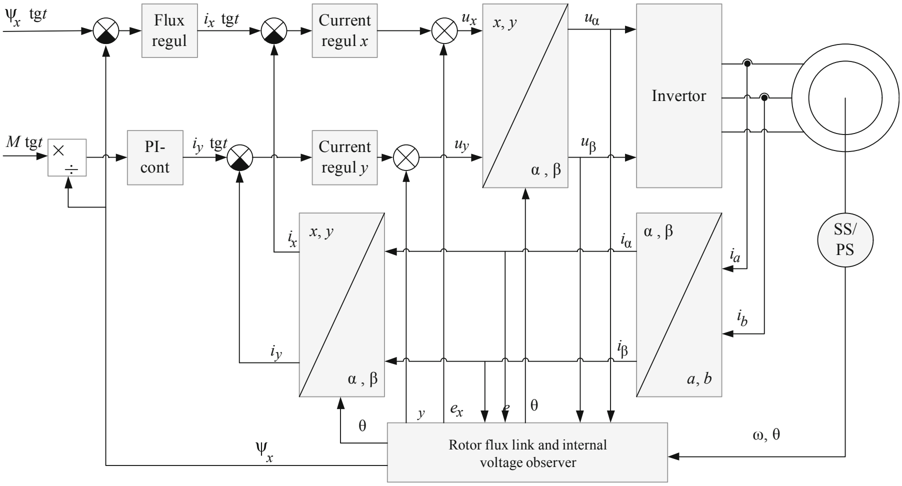

Fig. 4. Structure of vector control system with speed assignment

An important part of the vector control structure is the rotor flux coupling observer and EMF unit, which is used to calculate the amplitude and angular position of the rotor flux coupling vector. In addition, it is optionally able to calculate the components of the stator EMF along the axes in aid of current regulators. Depending on the implementation, the rotor flow coupling observer unit is capable of operating the speed and position of the rotor, the motor phase current and the applied voltages.

Estimation of the angular position used in the coordinate transformation job stresses from the x and y axes in α and β and the inverse transformation of the measured currents of α and β in x and y. Jobs for currents in the x and y axes are supplied from the flow regulator (RP) and from the reference signal point. A flow regulator is required to boost the transients in the magnetization loop. In the end, the current assignment on the x axis will be determined by the formula:

$$\vec{\psi}_r = L_m \cdot \vec{i}_s. \tag{14}$$

However, the transient time is determined by the rotor chain time constant. In relation to the traction motor of electric locomotives, this parameter will reach a few seconds.

To speed up the process, it will be necessary to create a larger current in the stator. Then the rotor current at the first moment of time, when the flux coupling is still equal to zero, will be determined by the expression:

$$i_r = \frac{L_m}{L_r} \cdot i_s \tag{15}$$

Control of the traction drive with an external torque task makes sense when directly regulating the traction force without reference to a given linear speed of the electric locomotive. As mentioned earlier, the traction drive of the electric locomotive before reaching full power is operated in critical operating modes with a limitation on the clutch exceeding the nominal torque [9, 10]. Thus, there are a number of difficulties in the implementation of the maximum traction properties of the drive at speeds below the design [11, 12]. If you control the traction drive of an electric locomotive in this range of speeds with the constancy of the electromagnetic moment, it will lead to underutilization of traction properties, and, as a consequence, reduce the technical speed of the train.

Vector control of the traction drive with the speed task has a greater potential in terms of the implementation of traction properties, since there is no direct control of the motor torque, i.e. it is possible to regulate the electromagnetic torque up to the maximum regardless of the task on the driver's controller. Thus, in case of deterioration of coupling properties of the electric locomotive, or short-term disturbing influences from infrastructure, this system is capable to fulfill with high speed on regulation of the electromagnetic moment of the asynchronous motor.

3 Comparison of Traction Drive Vector Control Systems

To verify these judgments, a simplified model of the electric drive control system in the Matlab software package was developed, which allows to visually assess the features of control with a task by moment and with a task by speed (Fig. 5).

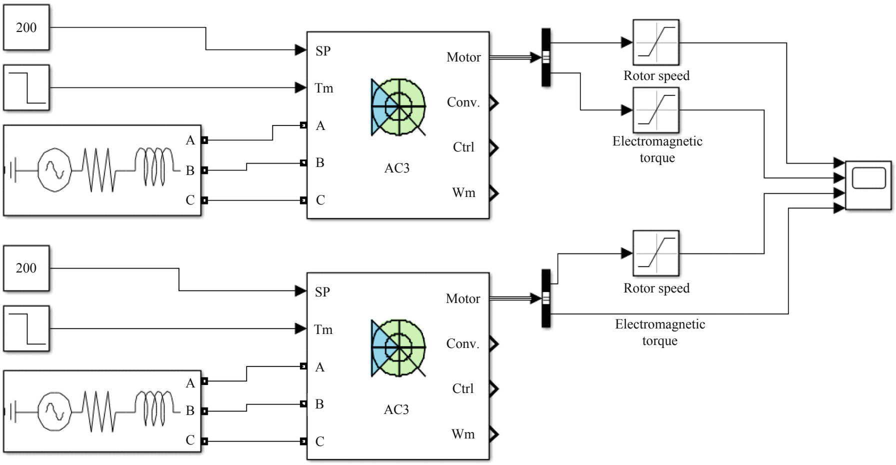

Fig. 5. Mathematical model of traction drive control system with torque and speed assignment

Figure 6 shows the results of the calculation of the mathematical model. The upper graphs show the angular rotational speed of the induction motor rotor with direct torque (left) and speed (right). The lower graphs show the current electromagnetic torque of the motor [13, 14].

At the time of 0–0.4 s, the engine is started with a starting torque of 50 N m. the torque Throw is caused by a jump in the starting current. At 0.4 s in the model with the task time is set torque equal to 200 N m. Thus, the angular frequency of rotation of the rotor of the motor is increasing. The moment at the same time, having an inversely proportional dependence to the angular frequency, is slightly reduced, which in our case can be taken as const [15].

In the model with the speed task, the angular speed of the rotor is controlled by a negative feedback on the speed sensor. At the same time, to achieve a given angular frequency of rotation of the rotor, the control system increases the torque on the engine to a value of 350 N m, while accelerating and then, reaching a steady speed, reduces the torque to a level that ensures the maintenance of a constant angular frequency of rotation of the rotor.

It should be noted that the absolute advantage of the control system with a speed task is its resistance to external disturbing factors. For clarity, in this model at a time of 1.5 s simulated failure of the wheel coupling with the rail ($F_{\text{friction}} < F_{\text{k}}$), in other words, decreased the moment of resistance on the rotor of the engine. As you can see from the left graphs, the task of the moment remained at the same level, the angular speed increased slightly. On the right graphs you can see that when controlling the traction drive with a speed task for 1.5 s with a decrease in the drag torque, the electromagnetic torque of the engine also decreased. The angular frequency of rotation has not increased.

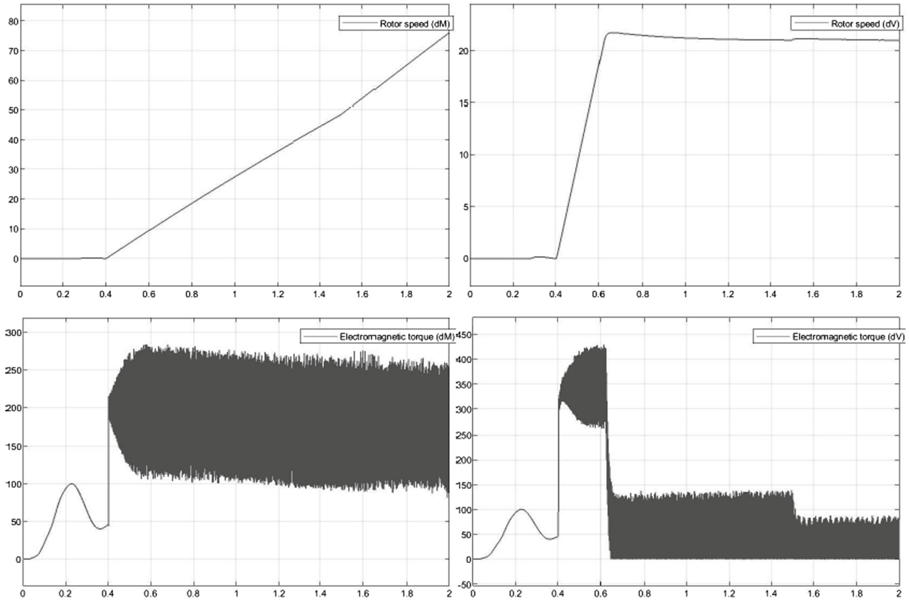

Fig. 6. Simulation results of traction drive control system with torque and speed assignment

4 Conclusions

The analysis of the results showed that the considered methods of controlling the traction drive of electric locomotives allow both adjusting the value of the torque setting on the wheel and automatic acceleration of the electric locomotive to a given speed with its further maintenance without direct torque setting. However, in view of the fact that the greatest operating time of traction rolling stock is in the range from 0 to 40–60 km/h (with a limitation on the clutch), it is advisable to control them adjacent. Thus, the control system for the traction drive will completely provide the realization of traction properties of a locomotive subject to achieve and automatically maintain specified speed until the construction regardless of the profile path with an acceleration due to the task utilization of time on the wheel.

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