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THE ASPECT OF VECTOR CONTROL USING THE ASYNCHRONOUS TRACTION MOTOR IN LOCOMOTIVES

Lionginas Liudvinavičius¹, Leonas Povilas Lingaitis²,
Stasys Dailydka³, Virgilijus Jastremskas⁴

Dept of Railway Transport, Vilnius Gediminas Technical University,
J. Basanavičiaus g. 28, 03224 Vilnius, Lithuania
E-mails: ¹liong@vgtu.lt; ²leonasl@vgtu.lt; ³s.dailydka@litrail.lt,
⁴v.jastremskas@litrail.lt

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Abstract. The article examines curves controlling asynchronous traction motors increasingly used in locomotive electric drives the main task of which is to create a tractive effort-speed curve of an ideal locomotive $F_k = f(v)$, including a hyperbolic area the curve of which will create conditions showing that energy created by the diesel engine of diesel locomotives (electric locomotives and in case of electric trains, electricity taken from the contact network) over the entire range of locomotive speed is turned into efficient work. Mechanical power on wheel sets is constant $P_k = F_k v = \text{const}$, the power of the diesel engine is fully used over the entire range of locomotive speed. Tractive effort-speed curve $F_k(v)$ shows the dependency of locomotive traction power F_k on movement speed v . The article presents theoretical and practical aspects relevant to creating the structure of locomotive electric drive and selecting optimal control that is especially relevant to creating the structure of locomotive electric drive using ATM (asynchronous traction motor) that gains special popularity in traction rolling stock replacing DC traction motors having low reliability. The frequency modes of asynchronous motor speed regulation are examined. To control ATM, the authors suggest the method of vector control presenting the structural schemes of a locomotive with ATM and control algorithm.

Keywords: inverter, traction converter, vector control, locomotive, asynchronous traction motor, encoder.

1. Introduction

When fuel (usually diesel fuel) is burnt in the cylinders of the internal combustion engine in locomotives, the chemical energy of fuel combustion is transformed into mechanical work of crankshaft. Then, the energy of the internal combustion engine is transferred over power transmission (mechanical, hydraulic, electric) to wheel pairs where transformed into locomotive traction power. Locomotive traction power F_k must change in inverse proportion to movement speed v . When the tractive effort-speed curve is hyperbolic, then the locomotive is used optimally over the entire speed range, i.e. the power of the diesel engine is used fully. To solve this task, it is necessary to change the curves of the diesel engine in a drive part not satisfying the theoretical requirements of traction. Fig. 1 shows the structural scheme of the locomotive using the diesel engine and the input and transformed output parameters of the system in a graphic form.

To create traction force, three energy converters are used: a diesel engine, drive and moving wheel pairs.

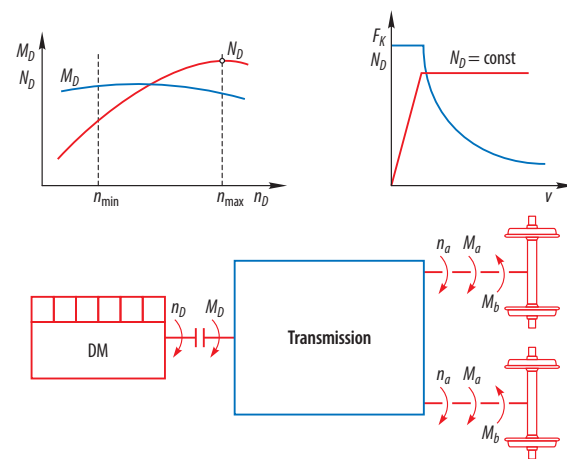


Fig. 1. The structural scheme of the composition and characteristics of the locomotive:

DM – diesel engine; M_D , n_D – parameters of diesel engine crankshaft; M_a , n_a – transformed parameters of drive per wheel sets; M_D – diesel engine torque; N_D – diesel engine power; M_b – torque of dynamic braking

The dependency of diesel engine crankshaft power $N_D = f(n_D)$ and torque $M_D = f(n_D)$ on the speed of crankshaft shows that the torque of the diesel engine does not depend much on crankshaft speed and the maximum power of the diesel engine is achieved at maximum rotations of crankshaft. The type of tractive effort-speed curve $F_k = f(v)$ allows assessing locomotive losses in the traction mode. Taking into consideration that the diesel engine power in locomotives with electric drive is from 800 kW to 6 000 kW, the issues of energy economy in electric locomotives with power up to 10 000 kW and more are of high importance. In practice, because of the insolvable technical problems of creating the tractive effort-speed curve in the ideal locomotive, energy losses often reach 15–20% and more. The practical tractive (Inarida *et al.* 2001) effort-speed curves of the locomotives are different from theoretical requirements. This task is being solved in the compositions of the locomotive electric drives of all types. The authors suggest using vector control for adjusting the ATM speed of the locomotive in order to create the tractive effort-speed curve of the ideal locomotive. The technical task has not yet fully solved. The leading global transport companies BOMBARDIER, SIEMENS, ALSTOM, MITSUBISHI ELECTRIC, HITACHI (Kaneko *et al.* 2004) etc. intensively search for the principles controlling ATM speed and torque to carry out tests. The authors examine the theoretical issues of controlling DC and AC electric drives of the locomotive and suggest practical schemes for controlling electric drive.

2. Problems of Making Artificial Tractive Effort-Speed Curves in the Diesel-Electric Locomotive Having DC/DC system

In order to create the tractive effort-speed curves of the required type in diesel-electric locomotives with DC traction generators and DC traction motors, one has to look for a compromise technical solution and to evaluate all possible options of interconnecting the exciting winding and armature winding of a traction generator. The type of the natural curves of DC traction generators (see Fig. 2) depends on the manner of interconnecting exciting winding and armature winding.

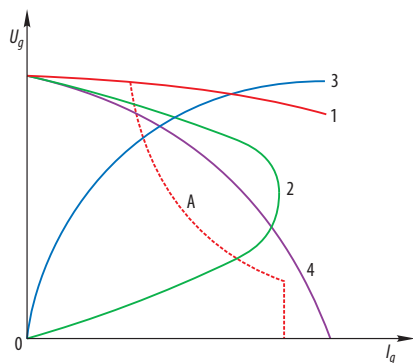


Fig. 2. Natural curve $U_g = f(I_g)$ of DC traction generators: 1 – separately excited shunt – wound DC generator; 2 – self-excited shunt-wound DC generator; 3 – series- wound DC generator; 4 – variable compound DC generator

These curves show that depending on load current, the voltage of generators $U_g = f(I_g)$ varies differently. To achieve proportional reduction in traction force at an increase in locomotive speed, it is necessary that the voltage of traction generator U_g at an increase in load current I_g should vary according to the law of hyperbole. Only in this case, the power of traction generator over the entire range of locomotive speed will be constant $P_g = U_g I_g = \text{const}$ (thus achieving the most economic mode of the diesel engine and the entire diesel locomotive). This technical problem can be solved by the separately excited shunt – wound DC traction generator and by the artificially changing natural type of the curve using automatic control systems (ACS) creating the areas of hyperbole, maximum voltage and current limitation within it. DC traction generator curve A of the type changed using ACS systems is shown in Fig. 2 using the dotted line. Control task for ACS system is formed by the locomotive driver who changes the positions of locomotive control by LV. The obtained artificial traction generator curves of the diesel-electric locomotive with DC/DC system are shown in Fig. 3.

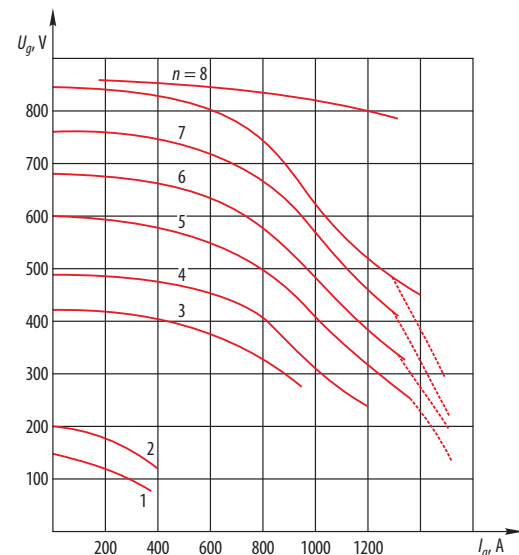


Fig. 3. Artificial traction generator curves $U_g = f(I_g)$ of the diesel-electric locomotive with DC/DC system at different positions of locomotive control

The curves shown in Fig. 3 demonstrate that analogous automatic control systems do not accurately create the part of hyperbole, where $P_g = \text{const}$ (most economic part of diesel engine operation). The ‘distorted’ hyperbole shows that the power of the diesel engine of such type is not fully used which increases fuel consumption and deteriorates the general economic indices of the diesel locomotive.

3. Problems of Making Artificial Tractive Effort-Speed Curves in the Diesel- Electric Locomotive Having AC/AC System

In order to make the required tractive effort-speed curves for electric drives with asynchronous traction motors of AC/AC system in diesel-electric locomotives, it is necessary to look for the optimum way of control-

ling traction motor. The speed-torque natural curve of asynchronous motor $n = f(M)$ is shown in Fig. 4. The speed-torque natural curve of asynchronous motor does not satisfy traction requirements and can only be used up to point B, i.e. the pull-out torque. Furthermore, ATM loses stability; moreover, its type must be changed in order to create the tractive effort-speed curve of the ideal locomotive.

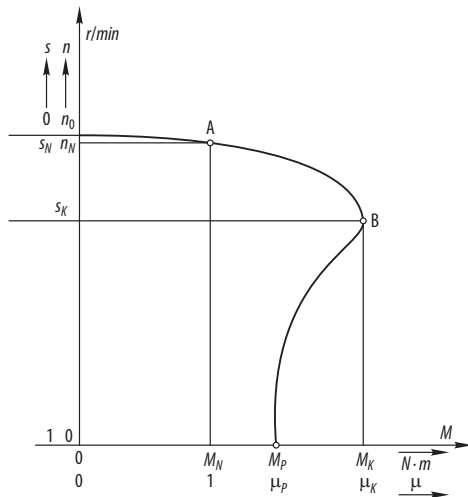


Fig. 4. Speed-torque natural curve $n = f(M)$ of asynchronous traction motor: s_k – at pull-out torque slip; M_N – the rated torque of asynchronous motor; M_p – starting torque; M_k – pull-out torque

Controlling the rotor rotation speed of asynchronous traction motor n_2 can be made (i.e. artificial speed-torque curves can be obtained) as follows:

- by changing the frequency of supply voltage f_1 (frequency control). It is possible to evenly adjust the speed of rotating magnetic field n_1 ;
- by changing the value of voltage supply U_1 . Variations in artificial speed-torque curves can be characterised by the fact that the motor-developed torque is proportional to the square of supply voltage and does not vary at pull-out torque slip s_k .

The general principles of the locomotive with control over the parameters of asynchronous traction motors (Lingaitis and Liudvinavičius 2006) can be calculated as:

$$\frac{U_1}{U_1'} = \frac{V_1}{V_1'} \sqrt{\frac{M_1}{M_1'}} \quad \text{or} \quad \frac{U_1}{U_1'} = \frac{V_1}{V_1'} \sqrt{\frac{F_k}{F_k'}}, \quad (1)$$

where: locomotive movement speed V_1 and traction force F_1 correspond to frequency f_1 and supply voltage U_1 and locomotive movement speed V_1' and traction force F_k' correspond to frequency f_1' and supply voltage U_1' .

In order to maintain constant power condition for asynchronous traction motor, it is necessary to change supply voltage in proportion to the square root of its frequency.

In order to maintain the stability of locomotive speed, the value of supply voltage must be changed in proportion to the square root of traction force.

A respective tractive effort-speed curve $F_k(V)$ of the locomotive obtained using asynchronous traction motor in electric drive varies according to the law of square hyperbole, i.e. analogously as when using DC series-wound traction motor. By the simultaneously changing value of supply voltage U_1 and its frequency f_1 and depending on the selected law on adjusting the rotation speed of asynchronous traction motor, it is possible to obtain any type tractive effort-speed curves of the locomotive.

4. Vector Control Using Asynchronous Traction Motor in the Diesel-Electric Locomotive

Theoretical aspects. The quality of the parameters of ATM speed and torque control is determined by the voltage of the components of frequency converter output and the principle of amplitude control (Liudvinavičius and Lingaitis 2007). These components determine the current and magnetic field of asynchronous traction motor the interaction of which results in the torque determining the speed of the motor (Yamaguchi 2006). Presently, control over ATM of locomotive electric drives is widely performed using scalar controlled voltage inverters suitable only for locomotive control systems that do not require high accuracy. To take control over ATM, the authors suggest using a vector control system of frequency electric drive that will allow autonomously (separately) controlling the current and magnetic field of ATM in the static and dynamic mode and to obtain tractive effort-speed curves of the desired type close to those of DC electric drives.

The components of ATM stator currents and magnetic field (Geleževičius et al. 1990) are transformed from a static to synchronously rotating system of coordinates. ATM control impacts are formed in the system of coordinates x, y rotating at the speed of rotating magnetic field and drive parameters are measured and adjusted in the fixed system of coordinates α, β related to motor stator winding. Therefore, in addition to the usual regulators of the parameters of electric drive, this system will need special modules (arithmetic functional converters) that will recalculate the values of control parameters from one system of coordinates to another. When designing the resultant vectors of ATM currents i_1, i_2' (i_1 – a resultant vector of the current in stator windings; i_2' – a resultant vector of rotor current), field Ψ_1, Ψ_2 and stator phase-type voltage (u_1) to x, y axes of the rectangular rotating system of coordinates, a system of scalar equations is obtained and reflects electromagnetic processes in the frequency-controlled ATM. To determine the algorithm of optimal control over ATM, we present mathematical expressions of electromagnetic processes according to the resultant scheme of ATM as shown in Fig. 5.

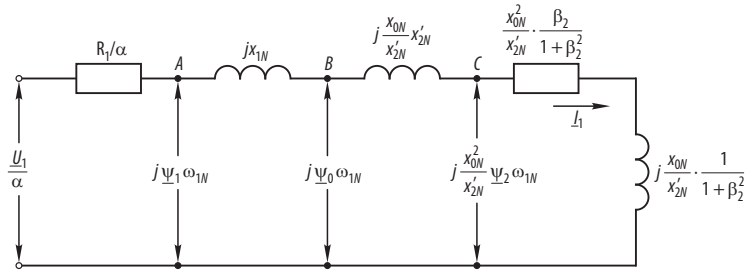


Fig. 5. One-line resultant scheme of asynchronous traction motor

$$\begin{cases}
 u_{1x} = i_{1x}R_1 + \frac{d\psi_{1x}}{dt} - \omega_1\psi_{1y}, \\
 u_{1y} = i_{1y}R_1 + \frac{d\psi_{1y}}{dt} - \omega_1\psi_{1x}, \\
 0 = i'_{2x}R'_2 + \frac{d\psi_{2x}}{dt} - (\omega_1 - p_p\Omega_V)\psi_{2y}, \\
 0 = i'_{2y}R'_2 + \frac{d\psi_{2y}}{dt} - (\omega_1 - p_p\Omega_V)\psi_{2x}, \\
 \psi_{1x} = L_1i_{1x} + L_0i'_{2x}, \\
 \psi_{1y} = L_1i_{1y} + L_0i'_{2y}, \\
 \psi_{2x} = L_0i_{1x} + L'_2i'_{2x}, \\
 \psi_{2y} = L_0i_{1y} + L'_2i'_{2y},
 \end{cases} \quad (2)$$

where: ψ_1 – stator magnetic field vector, ψ_2 – a vector of magnetic field bound with rotor winding.

ATM torque can be expressed via the projections of currents and the field to x and y axes:

$$M_V = \frac{3}{2} p_p \frac{L_0}{L'_2} (i_{1y}\psi_{2x} - i_{1x}\psi_{2y}). \quad (3)$$

Suppose that electromagnetic processes in the motor are established, i.e. $\frac{d\psi_{1x}}{dt} = 0$; $\frac{d\psi_{1y}}{dt} = 0$; $\frac{d\psi_{2x}}{dt} = 0$; $\frac{d\psi_{2y}}{dt} = 0$.

Moreover, we will assume that axis x of the rotating system of coordinates coincides with the resultant vector of the rotor flow, i.e. $\psi_{2x} = \psi_{2m}$, $\psi_{2y} = 0$.

Then, from equations '3' and '7' of equation system (2), $i'_{2x} = 0$ and $\psi_{2x} = L_0i_{1x}$ follow. Considering that voltage supply frequency $\omega_1 = \omega_{1s}p_p$, we obtain a system of equations reflecting electromagnetic processes in the frequency-controlled ATM:

$$\begin{cases}
 u_{1x} = i_{1x}R_1 - p_p\omega_{1s}\psi_{1y}, \\
 u_{1y} = i_{1y}R_1 - p_p\omega_{1s}\psi_{1x}, \\
 0 = i'_{2y}R'_2 + p_p(\omega_{1s} - \Omega_V)\psi_{2m}, \\
 \psi_{1x} = L_1i_{1x}, \\
 \psi_{1y} = L_1i_{1y} + L_0i'_{2y}, \\
 \psi_{2x} = \psi_{2m} = L_0i_{1x}, \\
 M_V = \frac{3}{2} p_p \frac{L_0}{L'_2} i_{1y}\psi_{2m}.
 \end{cases} \quad (4)$$

The obtained system of equations shows that in the rotor field-oriented system of coordinates, the ATM rotor flow depends only on component i_{1x} of the stator resultant current vector and by maintaining $i_{1x} = \text{const}$, it is possible to stabilise module ψ_{2m} of the field vector bound to motor rotor. In the stabilised ATM rotor-bound field ($\psi_{2x} = \psi_{2m} = \text{const}$), ATM torque depends only on component i_{1y} of the stator resultant current vector. This is the essence of the principle of vector control.

After creating two independent circuits of the control component of the resultant current vector of the stator in the ATM control system, according to the preferred law, it is possible to stabilise or change ATM rotor-bound field ψ_2 and to adjust ATM torque M and speed at the same time.

5. Automatic Vector Control System Used in the Asynchronous Traction Motor of the Diesel- Electric Locomotive

The authors suggest forming a vector control system of locomotive ATM with the structural scheme shown in Fig. 6. The power part of the drive comprises frequency converter UZ and ATM- M and its control system consist of coordinate changing units $U1$ and $U2$, regulators of current vector components $A3$ and $A4$, speed regulator $A1$, rotor magnetic field regulator $A2$, functional summing and division devices and stator current, ATM magnetic field in the air gap and traction motor rotation speed sensors.

Coordinate changing unit $U1$ transforms current and magnetic field vectors from system coordinates α, β to rotating system coordinates x, y . Input signals are the currents of two windings of traction motor stator including i_{1A}, i_{1B} and magnetic field in the air gap – ψ_{0A}, ψ_{0B} . The output signals of coordinate changing unit $U1$ are the components of the stator current vector in the rotating system of coordinates – i_{1x}, i_{1y} , rotor magnetic field module ψ_{2m} , the systems of synchronously rotating coordinates with field vector ψ_2 and position-describing parameters – $\cos\phi_\psi$ and $\sin\phi_\psi$ (where ϕ_ψ – an argument for the motor rotor current vector in the fixed system of coordinates α, β).

Coordinate changing unit $U1$ consists of four arithmetic functional modules. The output signals of coordinate changing unit $U1$ are the module of rotor magnetic field ψ_{2m} and the projections of the current vector in the system of coordinates x, y used as feedback signals in the channels of magnetic field and torque

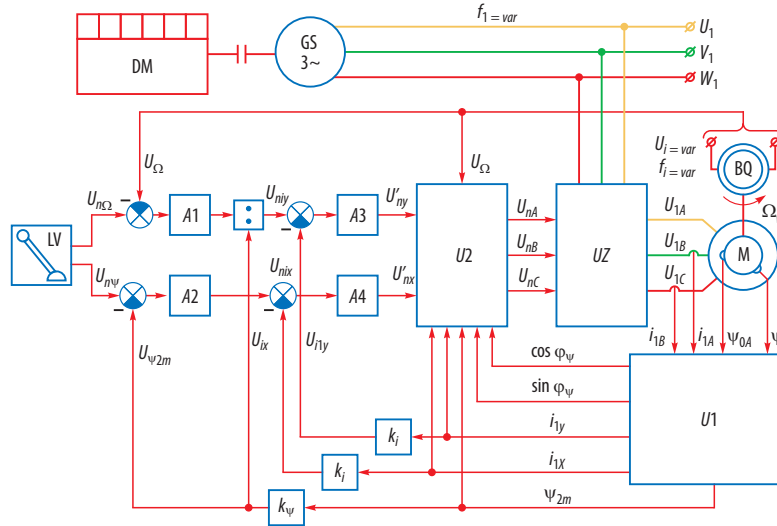


Fig. 6. The structural scheme of ATM vector control: GS – traction generator; UZ – frequency converter; M – asynchronous traction motor; U1, U2 – coordinate changing units, A3, A4 – regulators of current vector components, A1 – speed regulator, A2 – rotor magnetic field regulator; BQ – sensor of rotor speed and position (encoder)

control. A magnetic field control channel is intended to stabilise a rotor field at the set level. The required value of the field is set by signal $U_{n\psi}$ that is compared with the signal proportional to rotor field module $U_{\psi 2m}$. The obtained deviation signal makes impact on the input of field regulator A2. The latter forms control impact U_{nix} on the adjustment circuit of current vector projection- i_{1x} . The regulator of circuit A4 forms signal U'_{nx} according to stator voltage vector projection to axis x . The ATM torque control channel consists of the circuit of the internal speed control system. Control impact on this circuit is made using speed regulator A1 at the input of which speed deviation signal $U_{\Delta} = U_{n\Omega} - U_{\Omega}$ acts. At the output of current regulator A3, signal U'_{ny} is obtained, according to which, the projection of the stator voltage vector to axis y of the rotating system of coordinates is formed. Agreeing with the obtained signals U'_{nx} and U'_{ny} , in the rotating system of coordinates x, y , it is necessary to perform reverse transformation and to form the signals of three-phase stator voltage system U_A, U_B, U_C in the fixed system of coordinates α, β . Before making reverse transformation, it is necessary to assure control autonomy of the projections of setting voltage vector u_n in the system of rotating coordinates u_{nx}, u_{ny} . The equation in the system:

$$\begin{cases} U_1 = i_1 R_1 + \frac{d\psi_1}{dt} + j\omega_1 \psi_1, \\ 0 = i_2' R_2' + \frac{d\psi_2}{dt} + j(\omega_1 - p_p \Omega_V) \psi_2, \\ \psi_1 = L_1 i_1 + L_0 i_2', \\ \psi_2 = L_0 i_1 + L_2' i_2'. \end{cases} \quad (5)$$

Following the expression of current and field vectors by the integral components and subsequently, identifying the real axis of the rotating system of coordinates with the rotor field vector, we obtain $\psi_{2x} = \psi_{2m}$,

$\psi_{2y} = 0$. Having designed the axis of the rotating system of coordinates x, y , we obtain the following system of scalar equations:

$$\begin{cases} \frac{d\psi_{2m}}{dt} + \frac{R_2'}{L_2'} \psi_{2m} = \frac{L_0}{L_2'} R_2' i_{1x}, \\ p_p (\omega_{1s} - \Omega_V) \psi_{2m} = \frac{L_0}{L_2'} R_2' i_{1y}, \\ L_1^* \frac{di_{1x}}{dt} + \left[R_1 + \left(\frac{L_0}{L_2'} \right)^2 R_2' \right] i_{1x} = u_{1x} + \Sigma u_{kx}, \\ L_1^* \frac{di_{1y}}{dt} + \left[R_1 + \left(\frac{L_0}{L_2'} \right)^2 R_2' \right] i_{1y} = u_{1y} - \Sigma u_{ky}. \end{cases} \quad (6)$$

From equations '3' and '4' of system (6), we can see that in order to autonomously control the components of resultant current vector i_{1x} and i_{1y} , it is necessary to compensate signals Σu_{kx} and Σu_{ky} .

One of the functions of coordinate changing unit U2 is to ensure conditions for the autonomy of the control channels of current resultant vector components. Coordinate changing unit U2 replaces the projections of the voltage resultant vector in the system of coordinates x, y with the projections of the vector in the system of coordinates α, β and determines the components of the vector in three-phase system U_{1A}, U_{1B}, U_{1C} .

Unit U2 is used for reverse changing of the coordinate system and for compensating cross links. The unit consists of the cross link compensation module and two arithmetic functional modules.

The arithmetic functional module forms signals proportional to the components of the resultant voltage vector in three-phase A, B, C system (under the CIE standard, they are respectively marked as U, V, W). The formed signals u_{nA}, u_{nB}, u_{nC} are the periodic functions of

time – control frequency converter forming system supply voltages U_{1A} , U_{1B} , U_{1C} of the traction motor stator.

After compensation for the impact of mutual connections between current adjustment circuits and flow ψ_{2m} on the operation of the circuits of adjusting the current vector components – i_{1x} , i_{1y} and taking into consideration the fact that $p_p \omega_{1s} \cong p_p \Omega_V$, we obtain new equations representing the electromagnetic processes of asynchronous traction motor:

$$\begin{cases} \frac{d\psi_{2m}}{dt} + \frac{R'_2}{L'_2} \psi_{2m} = \frac{L_0}{L'_2} R'_2 i_{1x}, \\ L_1^* \frac{di_{1x}}{dt} + \left[R_1 + \left(\frac{L_0}{L'_2} \right)^2 R'_2 \right] i_{1x} = u_{1x}, \\ L_1^* \frac{di_{1y}}{dt} + \left[R_1 + \left(\frac{L_0}{L'_2} \right)^2 R'_2 \right] i_{1y} = u_{1y}. \end{cases} \quad (7)$$

The obtained system of equations is identical with the equations of DC drive when DC traction motor exciting field and the voltage of its armature are changed. The examined system of the parameters controlling ATM is similar to DC traction motors.

The elements of ATM vector control. To perform the most complex elements of the coordinate changing unit function, the authors suggest using unified functional modules implementing them by means of microprocessors. To measure ATM rotation speed and the coordinates of position, the authors suggest using an encoder installed inside traction motor (see Fig. 7). The encoder is an analogous or digital converter, at the output of which an analogous signal or a certain number of pulses proportional to rotation speed or the angle of inclination is received.

It is suggested to use the encoder in the ATM vector control system (Smilgevičius 2005). The encoder consists of light source, mask, code disc and sensors. The code disc has artificial gaps providing translucent and

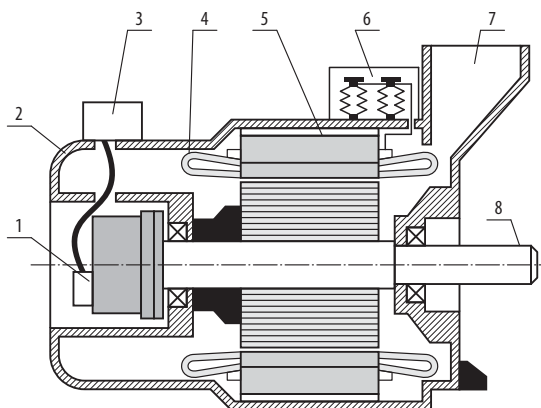


Fig. 7. ATM with the internally installed encoder:

- 1 – encoder; 2 – ATM stator; 3 – encoder connection box;
- 4 – ATM stator windings; 5 – ferromagnetic; 6 – ATM stator windings connection box; 7 – ventilating opening;
- 8 – ATM rotor shaft

non-translucent segments. Behind the code disc, light-sensitive sensors are installed. The scheme of the optic encoder is shown in Fig. 8.

The scheme of processing absolute encoder signals is presented in Fig. 9.

After the installation of the encoder in the ATM vector control system as suggested by the authors, it will be possible to obtain digital information about ATM rotation speed and thus to create a digital (microprocessor) automatic control system for locomotive electric drive. The codes including binary code, Gray code and Gray-express code would be used in the encoder.

The characteristics of ATM vector control. The application of ATM vector control, depending on locomotive control task, allows obtaining artificial curves just as in locomotive drives with DC traction motors. A type of the artificial speed-torque curve of ATM can be changed by the frequency of supply voltage control. Locomotive tractive effort-speed curve $F_k(V)$ obtained using ATM vector control in electric drive changes according to the law of square hyperbole, i.e. in the analogous way using a traditional serial excited DC motor in locomotive electric drive. When supply voltage is stable and its frequency is changed in reverse proportion to traction force

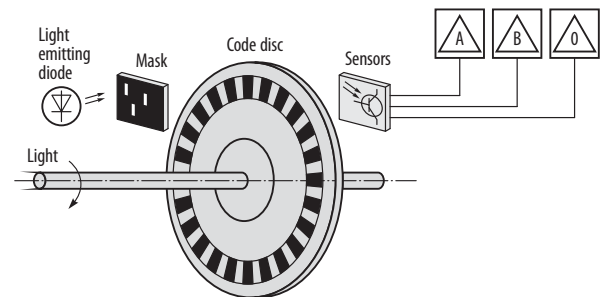


Fig. 8. The scheme of the optic encoder

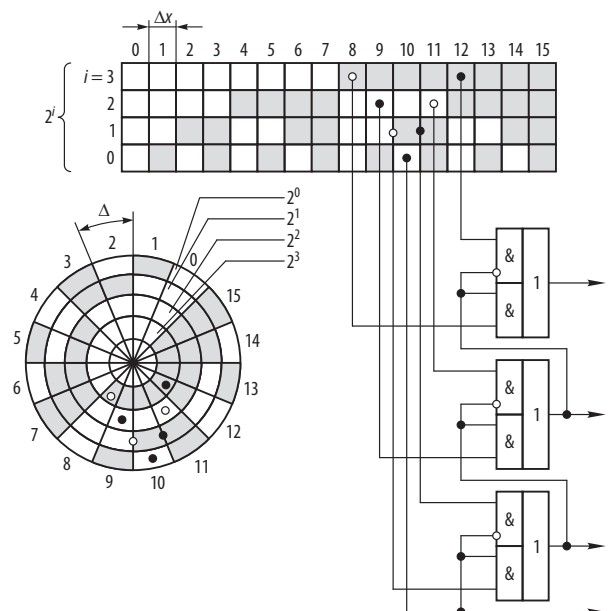


Fig. 9. The system processing absolute encoder signals

(Стрекопытов и др. 2003), we obtain a soft speed-torque curve of ATM motor maintaining conditions for minimum losses and a permanent overload factor, high efficiency of motor η , high $\cos \varphi$ and ATM stability reserve over the entire range of control over the locomotive (see the curves in Fig. 10).

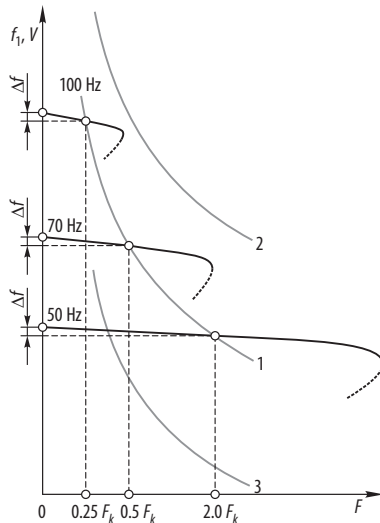


Fig. 10. Artificial locomotive tractive effort-speed curves using the methods of ATM vector control

6. Conclusions

1. The obtained system of equations (7) is identical with the equations of serial excited DC traction motor drive. This proves that by improving complex micro-processor control over ATM, it is possible to obtain curves identical with DC traction motors, which, due to comparatively simple control, were indispensable in traction rolling stock.
2. The application of ATM vector control allows forming locomotive tractive effort-speed curves of the required type;
3. The artificial tractive effort-speed curves obtained when applying ATM vector control are close to the tractive effort-speed curve of the ideal locomotive.
4. The application of ATM control system allows stabilising or changing ATM rotor-related magnetic field Ψ_2 and under the law preferred, to controlling ATM torque M and speed n .
5. When vector control is applied, the accuracy of ATM torque and speed parameters will achieve some 0.001% of locomotive traction and electrodynamic braking mode.
6. When vector control of ATM is applied, traction creation energy is fully used over the entire range of locomotive speed.
7. When vector control is applied, it is always possible to preserve conditions for ATM stability reserve and minimum losses.
8. During the process of control, voltage drop in the active resistance of ATM stator windings is fully compensated.

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