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Computing the Stability of a Nonlinear Control System of a Locomotive Multi-Motor Electric Drive

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Abstract.

The paper considers the problem of figuring out the stability of the control system of a multi-motor electric drive of a TE33A series locomotive produced and operated within the railway network of the Republic of Kazakhstan. To determine the stability of the nonlinear control system of a multi-motor electric drive of a TE33A series locomotive, the authors developed a program in the MATLAB system, which allowed solving a system of algebraic equations in symbolic form. The stability of the system is determined by the static torque of the traction motors $M_C = 0$ and $M_C \neq 0$. The stability check and speed matching of traction motors of the automated electric drive of a TE33A series diesel locomotive was carried out using a virtual model in the MATLAB system.

Keywords: locomotive, TE33A, asynchronous drive, system stability, modeling, MATLAB.

I. INTRODUCTION

The railway industry of the Republic of Kazakhstan is a link of the integral economic system and has a strategic importance. One of the main factors for increasing the carrying capacity and ensuring high-quality transport work is the task of updating the fleet of the traction rolling stock. As a result, it was decided to launch a new production of locomotives and create a subsidiary of the “Locomotive Kurastyru Zauyty” joint-stock company [1].

The main goal of the company is to provide a high-quality and timely product – TE33A diesel locomotive for domestic consumers and export to foreign markets.

The TE33A locomotive was developed on the basis of the Evolution ES44ACi locomotives of GE Transportation [2] and the main technical characteristics of this locomotive are presented in [3].

On the Kazakhstan railway, the TE33A diesel locomotive is to a greater extent used in the traction of freight trains, providing high throughput and carrying capacity at non-electrified railway sections.

The TE33A locomotive is a type of a locomotive that has an autonomous power plant in the form of a diesel generator that feeds (with electric current) traction motors.

These days electric traction is used more widely than other forms of traction because it helps achieve hyperbolic tractional effort characteristics and a possibility of controlling a traction system in a broad range of various operating conditions. The wide-ranging traction system control has been available due to the introduction of the new generation of power semiconductor devices and control management based on microprocessor technology for varied AC–AC and AC–DC topologies of traction. New engineering decisions allow processing complex algorithms on locomotive control systems including real-time traction and braking operational modes. The traction coefficients achieved on modern rail traction vehicles make up to 50%. The existing rolling stock uses four types of topologies for electric traction: DC, AC–DC, AC–AC with variable frequency and DC–AC [4].

A typical electric traction scheme of a TE33A locomotive is shown in Fig. 1. This locomotive belongs to the AC–AC topology with an individual wheelset traction control system.

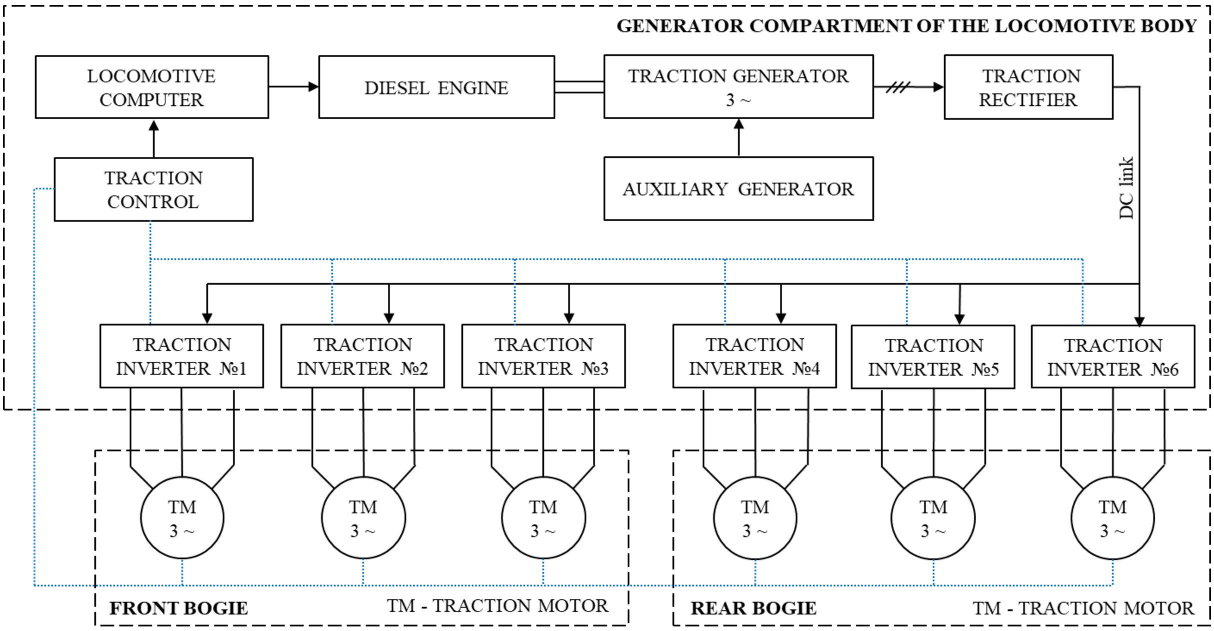

Fig. 1. An electric traction scheme for TE33A diesel locomotive with individual wheelset traction control.

II. MATERIALS AND METHODS

The above said defines as one of the priority tasks of designing a nonlinear control system for a multi-motor AC electric drive of a TE33A locomotive the calculating the stability of the control system. This problem can be solved by known methods of determining the stability of the control system [5, 6].

However, this problem can be successfully solved using the MATLAB mathematical system [7, 8].

To date, the MATLAB system has been widely used for the study of electrical machines. For example, some papers use it for modelling asynchronous motors [9] and for optimizing the control system of the multi-motor electric drive of the conveyor belt [10].

The block diagram of a multi-motor asynchronous electric drive of a TE33A locomotive with the proposed control system, which provides high-quality transient processes of motor speeds and their coordination is shown in Fig. 2.

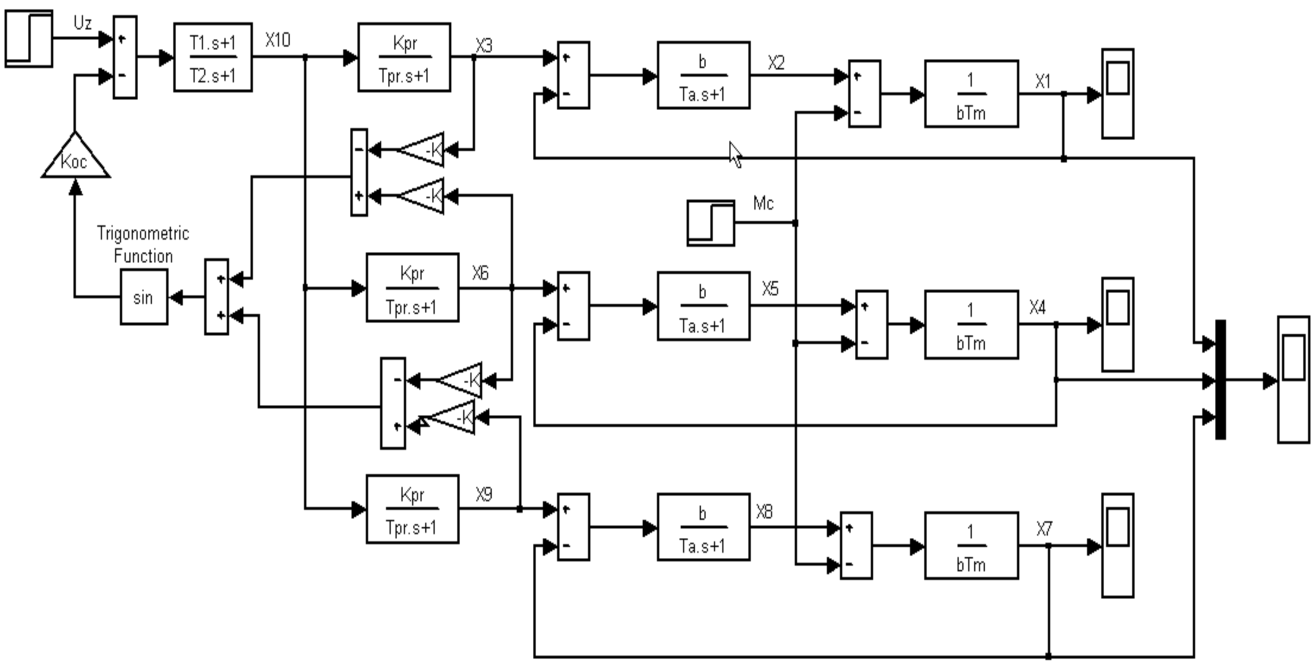

Fig. 2. Block diagram of a three-motor asynchronous electric drive with a continuous control system.

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According to its design, the TE33A locomotive has two three-axle bogies, where one asynchronous traction motor of the 5GEB30 type is installed on each wheel pair (Fig. 3).

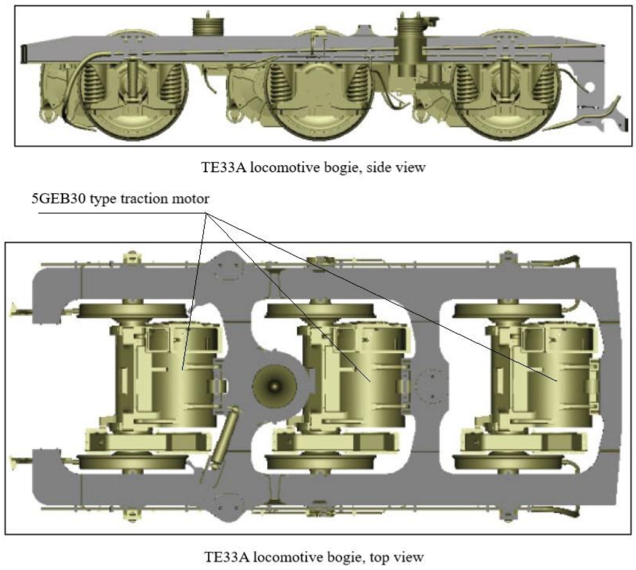

Fig. 3. Location of the traction motor in the bogie.

The block diagram shown in Fig. 2 is made up for one truck of the TE33A diesel locomotive, and where each asynchronous traction motor with a short-circuited rotor is represented by a linearized block diagram [11, 12] with transfer functions $W_1(s) = 1/(bTm)$ и $W_2(s) = b/(T_a s + 1)$ covered by feedback on the speed of the frequency converters (FC) with the transmission function $W_3(s) = K_{PR}/(T_{PR}s + 1)$, and a speed controller with transfer function $W_{10}(s) = (T_1 s + 1)/(T_2 s + 1)$. To ensure the process of matching the speeds of the motors we introduced a feedback voltage from each frequency converter. The nonlinear link with the function (y=sin(x)) provides sufficient quality of transient processes of speed and moments of the electric drive. The following designations are accepted on the scheme [13]:

$b -$ rigidity modulus of the linearized mechanical characteristic of an asynchronous motor (AM);

$Tm -$ electromechanical time constant;

$Ta -$ electromagnetic time constant of the AM stator and rotor circuit;

$Kpr -$ the frequency converter transmission coefficient;

$Tpr -$ the time constant of the frequency converter control circuit.

To determine the stability of the nonlinear control system of a multi-motor electric locomotive drive using the MATLAB system, it is necessary, on the basis of the transfer functions of the block diagram in Fig. 2, to obtain algebraic equations in the symbolic form.

Algebraic equations in symbolic form have the following form:

$$\begin{aligned}
&X_1 - W_1 X_2 = 0,\\
&X_1 + (1/W_2)X_2 - X_3 = 0,\\
&X_3 - W_3 X_{10} = 0,\\
&X_4 - W_4 X_5 = 0,\\
&X_4 + (1/W_5)X_5 - X_6 = 0,\\
&X_6 - W_6 X_{10} = 0,\\
&X_7 - W_7 X_8 = 0,\\
&X_7 + (1/W_8)X_8 - X_9 = 0,\\
&X_9 - W_9 X_{10} = 0,
\end{aligned} \tag{1}$$

Where $W_i -$ transfer functions of asynchronous motors and frequency converters; X_1, X_4, $X_7 -$ angular velocity of asynchronous motors; X_2, X_5, $X_8 -$ electromagnetic torque of asynchronous motors; X_3, X_6, $X_9 -$ voltage from the output of frequency converters.

The constraint equation in symbolic form between the speed controller and a multi-motor electric drive, taking into account the replacement of the nonlinear link $y = sin(x)$ by the two elements of the Taylor power series $(x - (1/6) \cdot x^3)$ [14], can be written in the following form:

$$\begin{aligned}
&(1/w_{10}) * x_{10} = U - k_{fdbk} \cdot sign((k_2 x_9 - k_1 x_3) -\\
&- q \cdot (k_2 x_9 - k_1 x_3)\hat{}3)
\end{aligned} \tag{2}$$

From the point of view of convenience of solving the problem of stability of the control system using MATLAB, equation (2) is represented by the equation as:

$$\begin{aligned}
&(1/w_{10}) * x_{10} + k_{fdbk} \cdot sign((k_2 x_9 - k_1 x_3) -\\
&- q \cdot (k_2 x_9 - k_1 x_3)\hat{}3) - U = 0
\end{aligned} \tag{3}$$

Where k_2, $k_1 -$ coefficients, $k_{fdbk} -$ feedback coefficient, $q -$ coefficient of the second member of Taylor power series ($q = 0.166$), $U -$ control input and $x_{10} -$ the output voltage of the speed control device.

III. RESULTS AND DISCUSSION

The transition process of coordinated rotation of the traction motors of the TE33A locomotive is shown in Fig. 4.

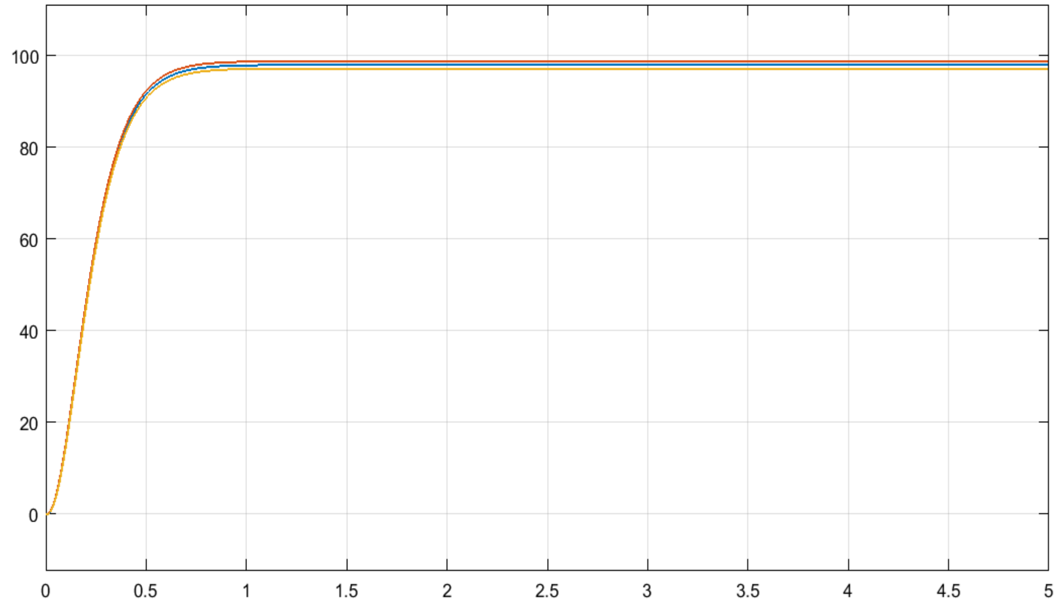

Fig. 4. The transient process of conformal rotation of traction motors.

The program for determining the stability of the control system of the electric locomotive drive, using equations (1) and (3) in symbolic form, is shown in Fig. 5.

```
1    function USTOI
2 -  syms w1 w2 w3 w4 w5 w6 w7 w8 w9 w10
3 -  f1=sym('(1/w1)*x1-x2');
4 -  f2=sym('x1+(1/w2)*x2-x3');
5 -  f3=sym('(1/w3)*x3-x10');
6 -  f4=sym('(1/w4)*x4-x5');
7 -  f5=sym('x4+(1/w5)*x5-x6');
8 -  f6=sym('(1/w6)*x6-x10');
9 -  f7=sym('(1/w7)*x7-x8');
10 - f8=sym('x7+(1/w8)*x8-x9');
11 - f9=sym('(1/w9)*x9-x10');
12 - f10=sym('Koc*sign((k2*x9-k1*x3)-q*(k2*x9-k1*x3)^3)+(1/w10)*x10-U');
13 - [x1,x2,x3,x4,x5,x6,x7,x8,x9,x10]=...
14       solve(f1,f2,f3,f4,f5,f6,f7,f8,f9,f10);
15 - b=25; Tm=0.2; a1=1/(b*Tm); Ta=0.05;
16 - Kp=10; Tp=0.001; T1=0.02;  T2=0.08;
17 - q=0.166; Koc=0.1; k1=0.1; k2=0.1; U=10;
18 -  w1=tf([a1],[1 0]); w2=tf([b],[Ta 1]);
19 -  w3=tf([Kp],[Tp 1]); w4=tf([a1],[1 0]);
20 -  w5=tf([b],[Ta 1]); w6=tf([Kp],[Tp 1]);
21 -  w7=tf([a1],[1 0]); w8=tf([b],[Ta 1]);
22 -  w9=tf([Kp],[Tp 1]); w10=tf([T1 1],[T2 1]);
23 -  R1=eval(x1); Wc=minreal(R1);
24 -  p=pole(Wc)
25 -   end
```

Fig. 5. The program for determining the stability of the control system.

In Fig. 5, character objects with names from W_1 to W_{10} (transfer function symbols) are entered in the 2nd line of the program. In lines 3 to 12 of the program, the system of symbolic equations (1) and equation (3) are introduced.

The solution of the system of equations in symbolic form is carried out by the MATLAB solve function (program line 14), which forms (calculates) a transfer function for each variable. Lines 15, 16, and 17 of the program show the motor parameters and control system coefficients. Lines 18 through 22 show the transfer functions of the block diagram in Fig. 2. The transfer function of the system and the roots of the characteristic equation are shown in Fig. 6.

```
Transfer function:
                    2.475e006 s + 1.237e008
---------------------------------------------------------
s^4 + 1033 s^3 + 3.285e004 s^2 + 3.512e005 s + 1.25e006


p =

  1.0e+003 *

  -1.0000
  -0.0125
  -0.0100 + 0.0000i
  -0.0100 - 0.0000i

>>
```

Fig. 6. The transfer function and the roots of the characteristic equation.

The roots of the characteristic equation of the transfer function of the system (automated electric drive of the TE33A locomotive), as a result of the calculation, were obtained with a negative real part – the system is stable [15, 16]. It is noted that the stability of the system is determined with the static torque of the motors is equal to zero $M_C = 0$.

However, the program for determining the stability of the system allows to calculate the stability of the system at $M_C \neq 0$ also. In this case, the stability program will look as the following (Fig. 7):

The transfer function of the system and the roots of the characteristic equation of the transfer function with the account of the static moment of the electric locomotive motors are shown in Fig. 8.

```
function USTOI
syms w1 w2 w3 w4 w5 w6 w7 w8 w9 w10
f1=sym('(1/w1)*x1-x2=Mc');
f2=sym('x1+(1/w2)*x2-x3');
f3=sym('(1/w3)*x3-x10');
f4=sym('(1/w4)*x4-x5=Mc');
f5=sym('x4+(1/w5)*x5-x6');
f6=sym('(1/w6)*x6-x10');
f7=sym('(1/w7)*x7-x8=Mc');
f8=sym('x7+(1/w8)*x8-x9');
f9=sym('(1/w9)*x9-x10');
f10=sym('Koc*sign((k2*x9-k1*x3)-q*(k2*x9-k1*x3)^3)+(1/w10)*x10-U');
[x1,x2,x3,x4,x5,x6,x7,x8,x9,x10]=...
    solve(f1,f2,f3,f4,f5,f6,f7,f8,f9,f10);
b=25; Tm=0.2; a1=1/(b*Tm); Ta=0.05;
Kp=10; Tp=0.001; T1=0.02;  T2=0.08;
q=0.166; Koc=0.1; k1=0.1; k2=0.1; U=10; Mc=50;
 w1=tf([a1],[1 0]); w2=tf([b],[Ta 1]);
 w3=tf([Kp],[Tp 1]); w4=tf([a1],[1 0]);
 w5=tf([b],[Ta 1]); w6=tf([Kp],[Tp 1]);
 w7=tf([a1],[1 0]); w8=tf([b],[Ta 1]);
 w9=tf([Kp],[Tp 1]); w10=tf([T1 1],[T2 1]);
 R1=eval(x1); Wc=minreal(R1)
 p=pole(Wc)
  end
```

Fig. 7. The program for determining the stability of the control system with the account of the static moment.

```
Transfer function:
    10 s^3 + 1.032e004 s^2 + 2.803e006 s + 1.262e008
---------------------------------------------------------
s^4 + 1032 s^3 + 3.285e004 s^2 + 3.512e005 s + 1.25e006


p =

  1.0e+003 *

  -1.0000
  -0.0125
  -0.0100 + 0.0000i
  -0.0100 - 0.0000i

>>
```

Fig. 8. The transfer function and the roots of the characteristic equation with the account of the static moment.

Fig. 8 shows the roots of the characteristic equation of the transfer function of the system with the negative real part, which proves the stability of the control system of the multi-motor electric drive of the TE33A locomotive.

It should be noted that the numerators of transfer functions shown in Fig. 5 and Fig. 7 are different in terms of the number of derivatives. At solving control problems, when the setting effect is not constant, that is $U \neq const$, then the static moment in the equations of the system dynamics should be taken into account. The check of the stability and coordination of the motor speeds of the TE33A locomotive automated electric drive can be carried out using a virtual model of an electric drive of the locomotive.

Fig. 9 shows a model of a multi-motor asynchronous electric drive of the TE33A locomotive using the blocks from the Sim Power Systems MATLAB library.

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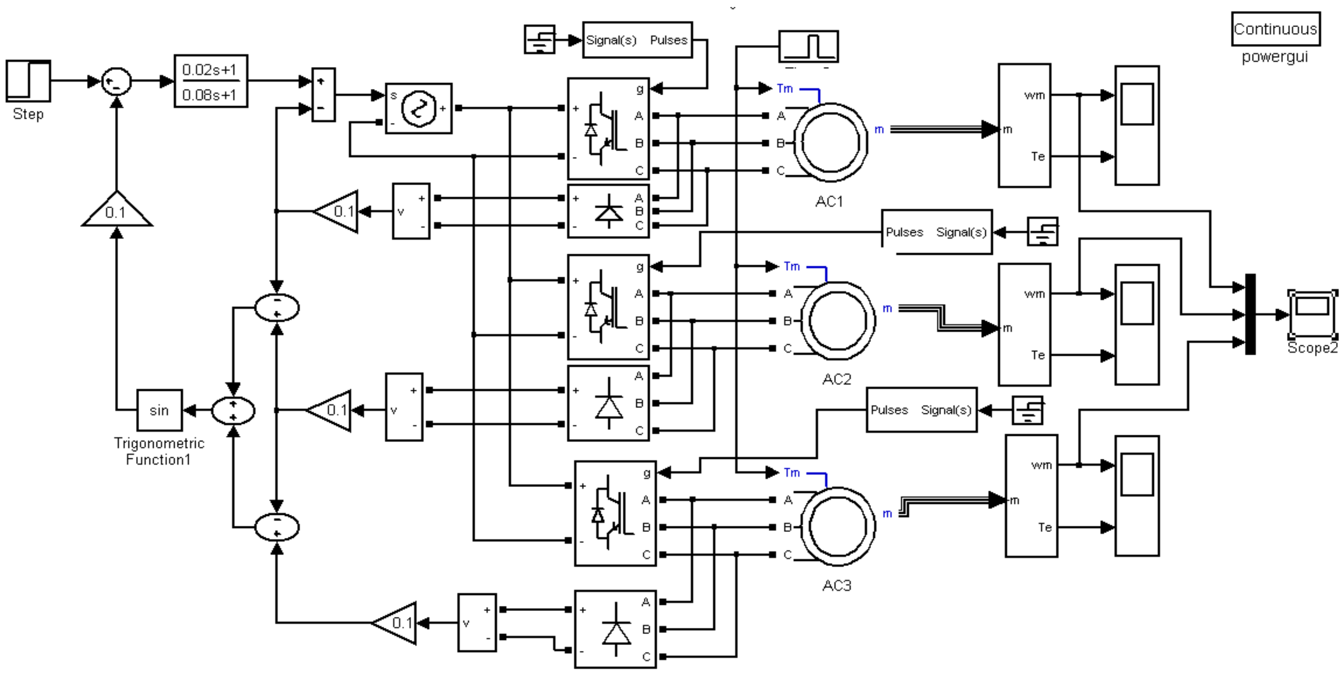

Fig. 9. Virtual model of a multi-motor electric drive of the TE33A locomotive.

The virtual model shown in Fig. 9 consists of asynchronous motors with a short-circuited rotor (three motors mounted on a bogie of the TE33A locomotive (See. Fig. 1 and Fig. 3)). The power for the motors is supplied from an autonomous inverter. All inverters receive voltage from a controlled voltage source. An inertial – integrating dynamic link is used as a speed controller. To ensure the coordination of speeds of the motor's voltage feedback is introduced. Voltmeters are used as voltage feedback sensors in the virtual model of the electric drive.

Transient processes of speeds of asynchronous motors of the electric locomotive drive are shown in Fig. 10.

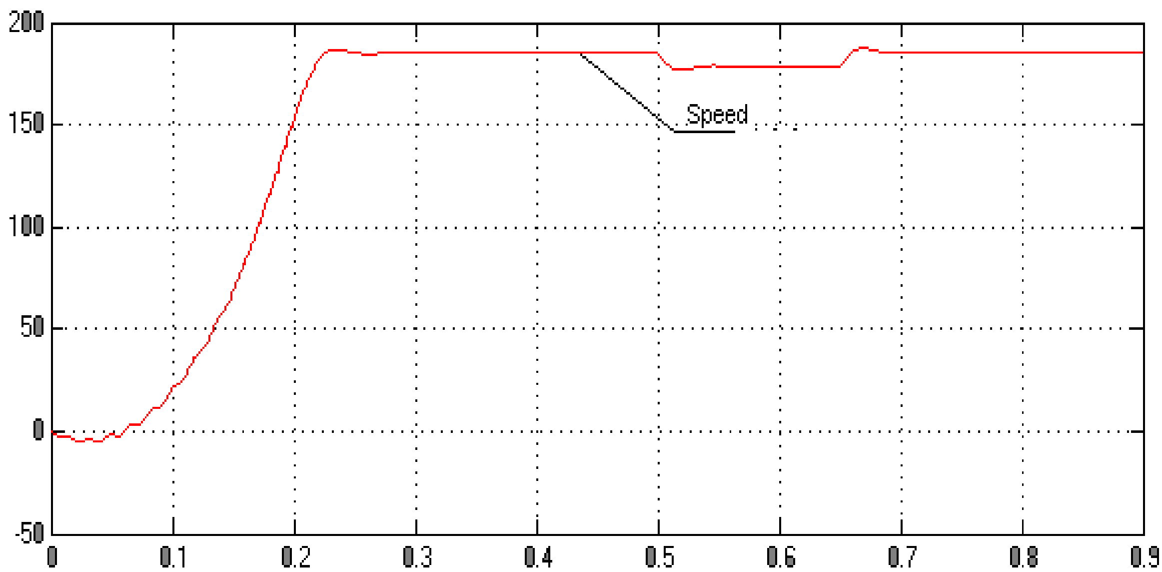

Fig. 10. Transient processes of speeds of traction motors of the TE33A locomotive electric drive.

As can be seen from Fig. 10, the velocity graphs are represented by a single velocity transition curve. In addition, it should be noted that according to the graph of the transition process of speeds, the movement of the automated asynchronous electric drive is stable. With the load surge, the reduction of speeds takes place in a coordinated fashion.

The problems considered in this paper are relevant, similar issues, but related to improving the energy efficiency of rail vehicles equipped with a multi-motor electrical traction are discussed in [17] and control issues of the consensus-based total-amount cooperative tracking control (TACTC) for multi-motor locomotive traction system in [18].

IV. CONCLUSIONS

As a result of the conducted research, a block diagram of the TE33A multi-motor asynchronous electric drive with the proposed control system was developed. The control system provides high-quality transient processes of traction motor speeds and their coordination. A virtual model in the MATLAB system with an optimal acceleration curve of the TE33A multi-motor electric drive was built.

The obtained results in the form of graphs of speed transient processes of electric drive traction motors and the roots of the characteristic equation of the transfer function of the system with and without the account for the static moment of the motors, with a negative real part, confirm the correctness of the obtained model.

The resulting model provides synchronous rotation and smooth start of traction motors of the 5GEB30 type, thereby ensuring their long service life and the optimization of the traction characteristics of the TE33A locomotive.

In their turn, the locomotives with the best traction characteristics are the key to ensuring high throughput and carrying capacity of the railway section.

REFERENCES

[1] AOLKZ., 2020, About the company and product, http://www.aolkz.kz/ru/product

[2] GE., 2009, GE Transportation Celebrates First Evolution® Series Locomotive Assembled in Kazakhstan Plant, https://www.genewsroom.com/press-releases/ge-transportation-celebrates-first-evolution%C2%AE-series-locomotive-assembled-kazakhstan

[3] TL., 2020, GE ES44AC, https://www.trains-and-locomotives.fandom.com/wiki/GE_ES44AC

[4] Spiryagin, M., Cole, C., Sun, Y. Q., McClanachan, M., Spiryagin, V., and McSweeney, T., 2014, Design and Simulation of Rail Vehicles, CRC Press, Boca Raton, FL, USA.

[5] Popov, E. P., 1961, The Dynamics of Automatic Control Systems, 1st Edn., Pergamon Press, Oxford, UK.

[6] Netushil, A., 1973, Theory of Automatic Control, Mir Publishers, Moscow, Russia.

[7] Moler, C., 2011, Experiments with MATLAB, Electronic edition published by MathWorks, Inc, MA, USA.

[8] Chaturvedi, D.K., 2009, Modeling and Simulation of Systems Using MATLAB and Simulink, CRC Press, Boca Raton, FL, USA.

[9] Gong, Y., 2011, "Modeling and simulation of asynchronous motor based on MATLAB/Simulink," 2011 International Conference on Electrical and Control Engineering, IEEE, Yichang, China, pp: 2338-2341.

[10] Sagitov, P. I., Akpanbetov, D. B., Almuratova N. K., and Toygozhinova, Zh. Zh., 2019, "Mathematical Modeling and Optimization of the Control System for Multi-Motor Electric Drive of Conveyor Belt," International Journal of Engineering Research and Technology, vol. 12, no. 6, pp. 899-911.

[11] Krishnan R., 2001, Electric motor drives: modelling, analysis and control, Prentice Hall, NJ, USA.

[12] Terekhov V. N., and Osipov, O. I. 2006, Electric drive control systems, Academy, Moscow, Russia.

[13] André Veltman, Duco Pulle W. J., and De Doncker, R. W., 2016, Fundamentals of Electrical Drives, Power Systems, 2nd Edn., Springer International Publishing, Cham, Switzerland.

[14] Kaczor W. J., and Nowak, M.T., 2001, Problems in Mathematical Analysis II: Continuity and Differentiation (Student Mathematical Library, Vol. 12), 1st Edn., American Mathematical Society, Providence, USA.

[15] Golnaraghi F., and Kuo, B., 2009, Automatic Control Systems, John Wiley & Sons, Hoboken, NJ, USA.

[16] Besekersky V. A., and Popov, E. P., 2003, Theory of automatic control systems, Professiya, Moscow, Russia.

[17] Zarifyan, A., Zarifyan, A., Grebennikov, N., Talakhadze, T., Romanchenko, N., and Shapshal, A., 2019, "Increasing the Energy Efficiency of Rail Vehicles Equipped with a Multi-Motor Electrical Traction Drive," 2019 26th International Workshop on Electric Drives: Improvement in Efficiency of Electric Drives (IWED), Moscow, Russia, pp. 1-5.

[18] Zhang, C., Lin, Z., Liu, J., He, J., Wu, H., and Li, P., 2019, "Consensus-based total-amount cooperative tracking control for multi-motor locomotive traction system," Journal of The Franklin Institute-Engineering and Applied Mathematics, vol. 356, no. 2, pp. 819-834.