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doi:10.15199/48.2023.04.21

Simulation model of traction electric drive of AC electric locomotive equipped with collector electric motors

***Abstract**. An approach to simulation modeling of traction electric drives of electric locomotives with collector engines is proposed which based on taking into account the nonlinear nature of the magnetic characteristic in electric motors, the inductances of the armature and the excitation winding of the electric motor, the nonlinearity of the volt-amperage characteristics of the rectifier unit and the features of the operation of the stage control system of the electric drive.*

***Streszczenie.** Zaproponowano podejście do modelowania symulacyjnego elektrycznych napędów trakcyjnych lokomotyw elektrycznych z silnikami kolektorowymi, oparte na uwzględnieniu w silnikach elektrycznych nieliniowości charakterystyki magnetycznej, indukcyjności twornika i uzwojenia wzbudzenia silnika elektrycznego, nieliniowości charakterystyki napięciowo-napięciowej zespołu prostownikowego oraz cech działania układu sterowania stopniowego napędu elektrycznego.(**Model symulacyjny trakcyjnego napędu elektrycznego lokomotywy prądu przemiennego wyposażonej w kolektorowe silniki elektryczne**)*

Keywords: traction collector electric motor, traction drive, power factor, efficiency factor
Słowa kluczowe: silnik elektryczny kolektora trakcyjnego, napęd trakcyjny, współczynnik mocy, współczynnik sprawności.

Introduction

The urgency of the task of evaluating the efficiency of technological processes and technical systems is caused by the global trend of constant growth in energy prices [1].

Optimization algorithms based on the evaluation of the efficiency of technological processes will allow to reduce both mechanical and electrical losses [2]. This fact will allow to reduce the power consumption of technical systems during the execution of technological processes. The most energy-intensive element of modern technological processes is an electric drive [3]. In addition to high power consumption caused by losses in the elements of the electric drive, during the execution of the technological process, the electric drive introduces distortion into the power supply network [4]. This fact is caused by a number of factors. Among such factors, first of all, the phase shift angle between the supply voltage and the load current of the traction electric drive, and the nonlinear nature of the characteristics of its elements [5-7] should be attributed.

As a traction drive on electric rolling stock of railways of Ukraine and Eastern Europe, an electric drive with collector motors is used [8, 9]. In such types of traction electric drive, the deterioration of the power factor, in addition to the phase shift angle between the supply voltage and the load current, is affected by the higher harmonic components of the traction current. They are caused by the nonlinearity of the volt-ampere characteristic of the rectifier and the nonlinearity of the Weber-ampere characteristics of the smoothing reactor, traction transformer, and excitation winding of the traction motor [10, 11]. These factors lead to the fact that the traction electric drive of the electric locomotive, in addition to consuming electrical energy, consumes reactive energy from the contact network, decreasing the quality indicators of the traction power supply system [12, 13].

According to JSC "Ukrzaliznytsia" (Ukraine), in 2021, the total utilization factor of active capacity was 0.733 [14]. Taking into account the fact, that electricity consumption for train traction makes up 70...80% of the total electricity consumption of Ukrzaliznytsia, it can be argued that such an indicator of the use of active power is caused precisely by low-quality energy consumption by electric rolling stock. At the same time, considering the requirements of the National Commission, which carries out state regulation in the fields of energy and communal services (Ukraine), the power factor of consumers must be at least 0.9 [15]. That is, the operation of the existing electric rolling stock leads to a decrease in the power factor of the electric traction system below the normative value.

In order to increase the power factor of electric rolling stock, reactive power compensators are used on it [16, 17]. In order to develop a reactive power compensator and optimize its operation, taking into account the operation modes of the traction electric drive, electrodynamic processes in the traction electric drive of the electric rolling stock should be investigated. The most convenient method of studying electrodynamic processes in the traction electric drive system of electric rolling stock is simulation modeling of its operation, in view of the operating modes of the electric drive. Therefore, the development of a simulation model of the traction electric drive of an AC electric locomotive equipped with collector electric motors is an urgent task.

When modeling a traction drive with pulsating current electric motors (PCM) of series excitation, a rectifier and a step control system, an important task is to develop a model of all its components, including the peculiarities of their functioning. At the same time, at this stage of the research, we consider it sufficient to study the processes of the traction electric drive in the established modes of its operation. This assumption allows to simplify the simulation model of the electric drive, taking into account only the key features of its components. Thus, when modeling motors with pulsating current of series excitation, the main problem is the reproduction of the dependence of the magnetic flux on the currents of the excitation winding and the armature, which implies the presence of an adequate model of the Weber-ampere characteristic. In connection with this factor, models that take into account the nonlinearity of the magnetic characteristic and the influence of eddy currents and magnetic losses in the magnetic circuit of the electric motor are in demand [18].

Since PCM always work in the loaded mode, the electrodynamic processes in the electric motor should also be modeled taking into account the load. In work [18], this factor was not taken into account.

The solution to this problem can be found in the work [19], where the authors show the relationship between the nature of the load and the mechanical characteristics of the PCM. And in the other works [20, 21], where the influence of the load on the magnetic characteristic of the electric motor is shown, in turn, the electromagnetic characteristics of the PCM also depend on it. But in these works, the transition from mathematical models to their implementation in simulation models is not shown. Also, when developing a traction electric drive model, it should be taken into account that with a change in the mode of operation of the electric locomotive (moving, traction mode, braking mode, braking mode, skidding, etc.), the frequency of rotation of the traction motor shaft changes [10], which leads to a change in magnetic losses in the PCM [22-24]. The determination of magnetic losses in steel as a function of the frequency of rotation of the electric motor shaft can be found in the study [25]. hich the authors, basing on the analysis of existing methods, determined and proposed a more accurate approach to the calculation and modeling of instantaneous magnetic losses in the steel of a DC traction motor, an example of the NB- 418K6.

Considering the mentioned factors, such as the nonlinearity of the magnetic characteristic and the effect on it of eddy currents and magnetic losses in the magnetic circuit of the electric motor, as a function of the frequency of rotation of the motor shaft, in the article [26] the authors proposed a model of the NB-418K6 motor.

There are many scientific works devoted to the development of the traction electric drive model of electric locomotives with collector engines [27-29]. But these works are devoted to the modeling of the drive with controlled installations. Uncontrolled rectifiers are used in electric locomotives of the VL80T, VL80T, ChS4, ChS8 series. A simulation of an uncontrolled rectifier drive can be found in [30], but this paper does not show the step control system. The model of the traction electric drive with the control system is important in the study of electrodynamic processes in the traction electric drive system during the transition from one mode of operation of the electric locomotive to another. On the indicated series of electric locomotives, a group electric contactor is used as a control system, the model of which is given in [31]. But in this work, the model of only the group electric contactor is given, and not the model of the traction electric drive as a whole.

In this paper, in the MATLab/Simulink software environment, a simulation model of the traction electric drive of an electric locomotive with an uncontrolled rectifier was developed using ready-made simulation models of a collector traction electric motor and a group electric contactor. The simulation model of the traction electric drive is supplemented by the simulation model of the uncontrolled rectifier. The developed simulation model will allow to study the electrodynamic processes in the traction electric drive system and can be the basis for the development of an effective reactive power compensation system taking into account the operation modes of the electric locomotive. The article has the following structure: in the second chapter, the object of research is chosen and the use of a mathematical model of the collector engine is justified, taking into account the magnetic losses in its steel. In the third section, the simulation model of the traction drive is implemented in the MATLab software environment. Time diagrams of motor shaft rotation frequency, currents and voltages and primary and secondary windings of the traction transformer were obtained on the simulation model. Amplitude-frequency spectra of currents and voltages in the primary and secondary windings of the traction transformer are constructed for the stable mode. The fourth section compares the obtained results with the engine's passport data. The conclusions are given at the end of the work.

Determination of the Object of Research and Justification of the Choice of a Mathematical Model of a Pulsating Current Electric Motor

Definition of the Object of Research

In the course of the research, the spectral components of the current and voltage on the primary and secondary windings of the traction transformer and their influence on the power factor of the electric locomotive are determined. When determining the object of research, it is advisable to choose the same type of traction electric motor of the electric locomotive. Since a number of studies have already been carried out for it, in particular the study of its operation taking into account magnetic losses in the steel of the traction electric motor and features of the operation of the traction electric drive control system. In the following works [26,31], the mentioned studies were carried out for the traction electric drive of the VL80К,T series electric locomotive. Therefore, it is logical to choose the specified traction electric drive as an object of research.

Technical characteristics of the traction drive of the ВЛ80К electric locomotive are given in Table 1 [32].

Table 1. Technical characteristics of the traction drive of the VL80K electric locomotive

Parameter	Value
The full power of the primary (mains) traction winding of the transformer, S_1, kVA	4485
Nominal voltage of the primary winding of the traction transformer, U_1, V	25000
Nominal current of the primary traction winding, I_1, A	245
Supply voltage frequency, f, Hz	50
Nominal voltage of the secondary traction winding of the transformer, U_2, V	1218
Nominal current of the secondary winding of the traction transformer (1 section) in long-term mode, I_2, A	1750
The number of traction electric motors in one section, k	4
Nominal frequency of rotation of the motor shaft, n, rpm	915
The nominal power factor of the electric locomotive, taking into account the drive of auxiliary machines, k_p	0,866
Nominal coefficient of useful action, taking into account the drive of auxiliary machines η , %	84

Other parameters of the traction drive are not given, since a ready-made simulation model of the traction electric motor was used. More complete information about the parameters of this electric motor is given in [26].

Justification of the Choice of the Mathematical Model of the Pulsating Current Traction Electric Motor

In the next work [27], an approach to modeling a collector electric motor is applied, taking into account magnetic losses in its steel. In this model, the electrical part of the electric motor is made in the form of electrical elements of the MATLab/Simulink software environment, and the magnetic and mechanical part - in the form of structural elements. In addition, in this model, the magnetic losses are a function of the frequency of rotation of the electric motor shaft. This makes it possible to carry out research in different operating modes of the electric locomotive. Therefore, the model presented in the study [26] was adopted as a mathematical model of the traction motor.

In the study [31], a simulation model of the stepped control system of the traction electric drive of an electric locomotive with an uncontrolled rectifier unit was developed. In this study, the algorithm for switching the contactors of the group electric contactor when moving from one position of the driver's controller to another was implemented.

This makes it possible to carry out research when switching from one operating mode of an electric locomotive to another. Therefore, the model given in the study [31] was adopted as the model of the group electric contactor. The model [31] contains transient reactors that are used on a real electric locomotive.

Development of a Simulation Model of a Traction Electric Drive with Collector Motors and an Uncontrolled Rectifier

Mathematical Model of an Uncontrolled Rectifier

A simplified diagram of the power circuit of one section of the VL80K electric locomotive is shown in Fig. 1 [32].

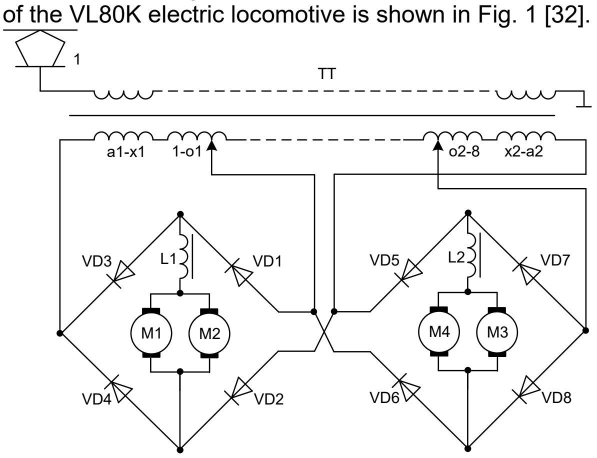

Fig.1. A simplified diagram of the power circuit of one section of the VL80K electric locomotive: M1-M4 – traction motors, VD1-VD8 – rectifier's diodes, TT – traction transformer, 1 - pantograph, L1, L2 – smoothing reactors, a1-x1, a2-x2 – uncontrolled sections of the secondary winding of the traction transformer, o1-1, o2-8 – controlled sections of the traction transformer.

The equations describing the processes in the diagram in Fig. 1, have the form

(1) $$e_{TT} = e_{20} \cdot sin(2 \cdot \pi \cdot f \cdot t),$$

(2) $$\frac{di_{TT}}{dt} = \frac{1}{L_{TT} + \left[L_a(i_d) + L_{sr} \cdot (i_d)\right] \cdot G_1} \cdot \Big(e_{TT} \cdot G_2 - \left[e_{TT} - (r_{sr} + r_a) \cdot i_d - r_{sh} \cdot (i_d - i_r) - r_{TT} \cdot i_{TT}\right] \cdot G_1\Big),$$

(3) $$\frac{di_d}{dt} = \frac{1}{L_{TT} \cdot G_1 + L_a(i_d) + L_{sr} \cdot (i_d)} \cdot \Big((e_{TT} - r_{TT} \cdot i_{TT}) \cdot G_2 - \left[r_{sh} \cdot (i_d - i_r) - (r_{sr} + r_d) \cdot i_d \cdot G_1\right] \cdot G_1\Big),$$

(4) $$\frac{di_k}{dt} = \frac{1}{L_k} \cdot (-e_k - r_k \cdot i_k) \cdot G_3,$$

(5) $$\frac{di_r}{dt} = \frac{1}{L_f(i_d)} \cdot \big(r_r \cdot i_r - r_k \cdot (i_d - i_r)\big),$$

where i_{TT}, i_d, i_k, i_r – the current of the secondary winding of the transformer, the traction motor, the commutation of the rectifier, the excitation winding, respectively; r_{sr}, r_a, r_f, r_k, r_{sh}, r_d, r_{TT} – active resistances of the smoothing reactor, the traction motor, the excitation winding of the traction motor, the commutation circuit, the shunt resistor, the secondary winding of the traction transformer, respectively; e_{TT} – EMF of the secondary winding of the transformer; L_a, L_f, L_{sr}, L_{TT}, L_k – inductance of the armature winding of the traction motor, the excitation winding of the traction motor, the smoothing reactor, the secondary winding of the traction transformer and the commutation circuit, respectively; G_1, G_2, G_3 – logical variables that determine the current state of the circuit, at the moment of switching, or at the moment of direct conduction of the gates.

The rectifier is modeled using standard diode models from the SimPowerSystems library. The volt-ampere characteristic in the model is presented in the form of a simplified linear function (Fig. 2).

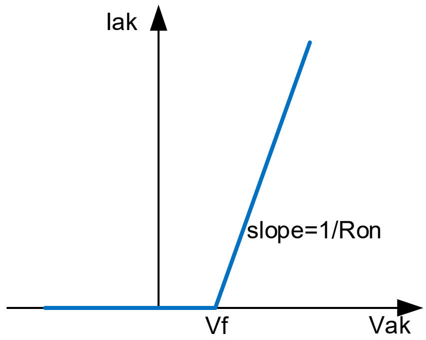

Fig.2. A linear function, with the help of which the volt-ampere characteristic of the rectifier is simulated: V_f – potential barrier voltage; R_{on} – diode resistance in the forward direction

From the theory of nonlinear electric circuits, it is known that a certain number of nonlinear resistances connected in series or in parallel can be replaced by one, while in the case that the elements are connected in series, the I-V characteristics of the elements must be graphically added by voltage, and in the case of parallel connection - by current. In the rectifier unit of VL80K,T electric locomotives, one arm has 12 parallel branches, each of which includes 4 diodes in series. In the model, each arm is replaced by an equivalent diode VD1-VD8.

Model of Smoothing Reactor, Electric Contactor of Group and Traction Transformer

Smoothing reactors L1, L2 are built using a standard RLC branch block, which in this case models active-inductive resistance. Since the smoothing reactor has a ferromagnetic core, its magnetic characteristic will usually be nonlinear, but in our case, the simulation was carried out at currents within which the inductance can be assumed to be linear.

As it was mentioned above, on electric locomotives of the ВЛ80К series, a group electric contactor is used as a traction electric drive control system, the model of which is given in the article [29].

A simplified diagram of electric traction drive control circuits is shown in Fig. 3. The algorithm for switching contactors of a group electric contactor is given in [31].

The traction transformer of the ОДЦЭ-5000/25Б series electric locomotive is modeled by a standard unit of a multi-winding transformer Multi-winding transformer (in the "Traction transformer" model). The full power and frequency at which the transformer operates, the primary and secondary winding voltages, active resistances and dissipation inductances of the windings, as well as the parameters of the magnetization circuit are entered for simulation. The mathematical and simulation model of the traction transformer of the ОДЦЭ-5000/25Б series, taking into account the non-linear nature of the dependence of the inductance of its windings on the load current, is given in [31]. In the same work, a model of the electric contactor of the EKG-8 group series is given. The EKG-8 group electrical contactor is represented by the "Group electrical contactor" block.

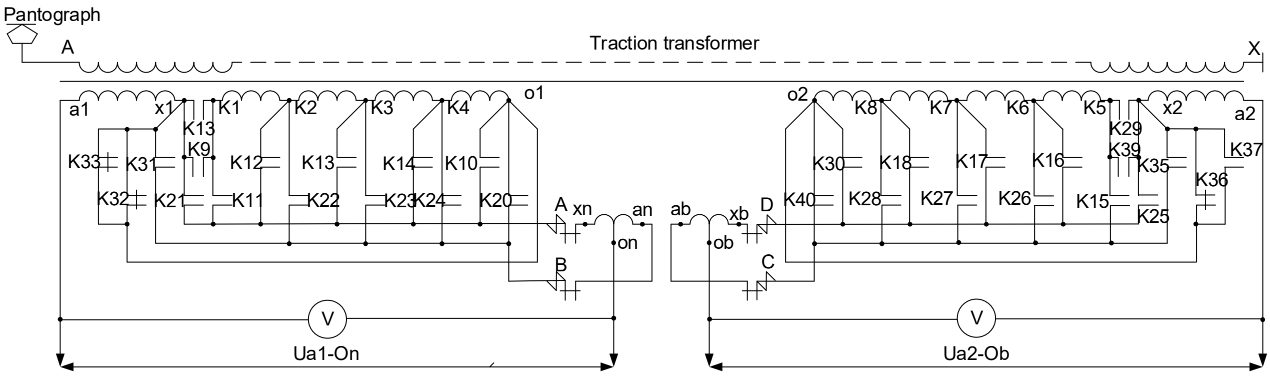

Fig.3. A simplified diagram of the control circuits of the traction drive of the VL80K electric locomotive

Traction Power Supply System Model

The traction substation is made in the form of an alternating voltage source with parameters U=38885 V (amplitude), f=50Hz, and is marked as "Traction substation". It should be noted that instantaneous values of voltages and currents were used when modeling the traction electric drive. When building a contact network model suitable for further research, it is advisable to take it as a basic model, in the form of an L-shaped substitution scheme. In addition, it is necessary to take into account that when modeling the operation of an AC electric locomotive with traction electric motors of pulsating current, the contact network should be considered as a chain with distributed parameters, as indicated in the paper [30] (Fig. 4).

The following parameter values were used in the modeling of the catenary section [31]: Δx=40 km, f=50Hz, r_0=9.346 Sm/km, r=0.107 Ω/km, L=0.819·10^{-3} H/km, C_0=29·10^{-9} H/km.

The section of the contact network is made in the form of a "Line" block, which simulates the operation of a "long line", from the SimPowerSystems library and is marked "Catenary".

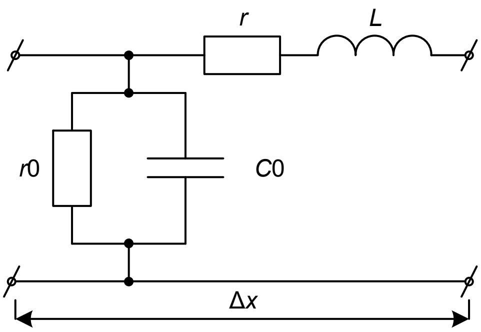

Fig.4. Scheme of replacement of an elementary section of the catenary: Δx – the length of the catenary section being modeled; r_0, C_0 – active resistance and capacity of the parallel branch of the circuit per unit length; r, L – active resistance and inductance of the series circuit branch per unit length.

Traction Electric Motor Model

The mathematical model of the pulsating current traction motor of the НБ-418К6 series, taking into account the influence of eddy currents of magnetic losses, the nonlinear nature of the dependence of the excitation winding inductance on the excitation current, and its implementation in the MATLab software environment is given in the study [26]. In this regard, consideration of the mathematical model of the pulsating electric traction motor in this study is inappropriate. The traction electric motor model is combined into the "Traction motor" unit.

Simulation Model of Traction Electric Drive

Taking into account the models of the elements of the traction electric drive system of the electric locomotive, given above, a model of the traction drive of the VL80K electric locomotive was developed in the MATLab/Simulink software environment (Fig. 5).

To set one or another position of the electric locomotive driver controller, the "Position" block has been added to the traction drive model. The simulation was performed for the nominal mode of operation of the traction electric drive of the electric locomotive. Position 28 of the driver's controller corresponds to the nominal operating mode of the traction drive.

Modeling the Traction Drive of an Electric Locomotive with an Uncontrolled Rectifier and Analysis of the Obtained Results

During the simulation, the following parameters were monitored: traction electric motor shaft rotation frequency n, traction motor armature current Ia, armature voltage Ua (devices for displaying these parameters are not shown in Fig. 5, as they are included in the "Traction Motor 1" unit), primary winding current I1, the current of the secondary winding I2 of the traction transformer, the voltage of the primary winding U1 and the voltage of the secondary winding of the traction transformer U2. The specified parameters were taken for the established mode of operation of the traction electric drive.

As a result of the simulation, time diagrams of the rotation frequency of the shaft of the traction electric motor (Fig. 6), the current of the primary winding of the traction transformer (Fig. 7), the voltage on the primary winding of the traction transformer (Fig. 8), the current of the secondary winding of the traction transformer (Fig. 9), voltage on the secondary winding of the traction transformer (Fig. 10) were obtained.

The amplitude and phase harmonic components of the currents and voltages of the primary and secondary windings of the traction transformer were calculated on the basis of the data obtained during the simulation to calculate such parameters of the traction electric drive as the drive power factor, the drive efficiency factor, and similar parameters of the electric locomotive. Calculations were performed using the fast Fourier transform [33].

(6) $$X_k = \sum_{n=0}^{N-1} x_n \cdot e^{-j\cdot\frac{2\cdot\pi\cdot n\cdot k}{N}}, \quad k = 0,...,N-1,$$

where X_k - k-th component of the fast Fourier transform; k - fast Fourier transform index in the frequency domain; x_n - sequence of input counts; n - time index of incoming counts; N - the number of counts.

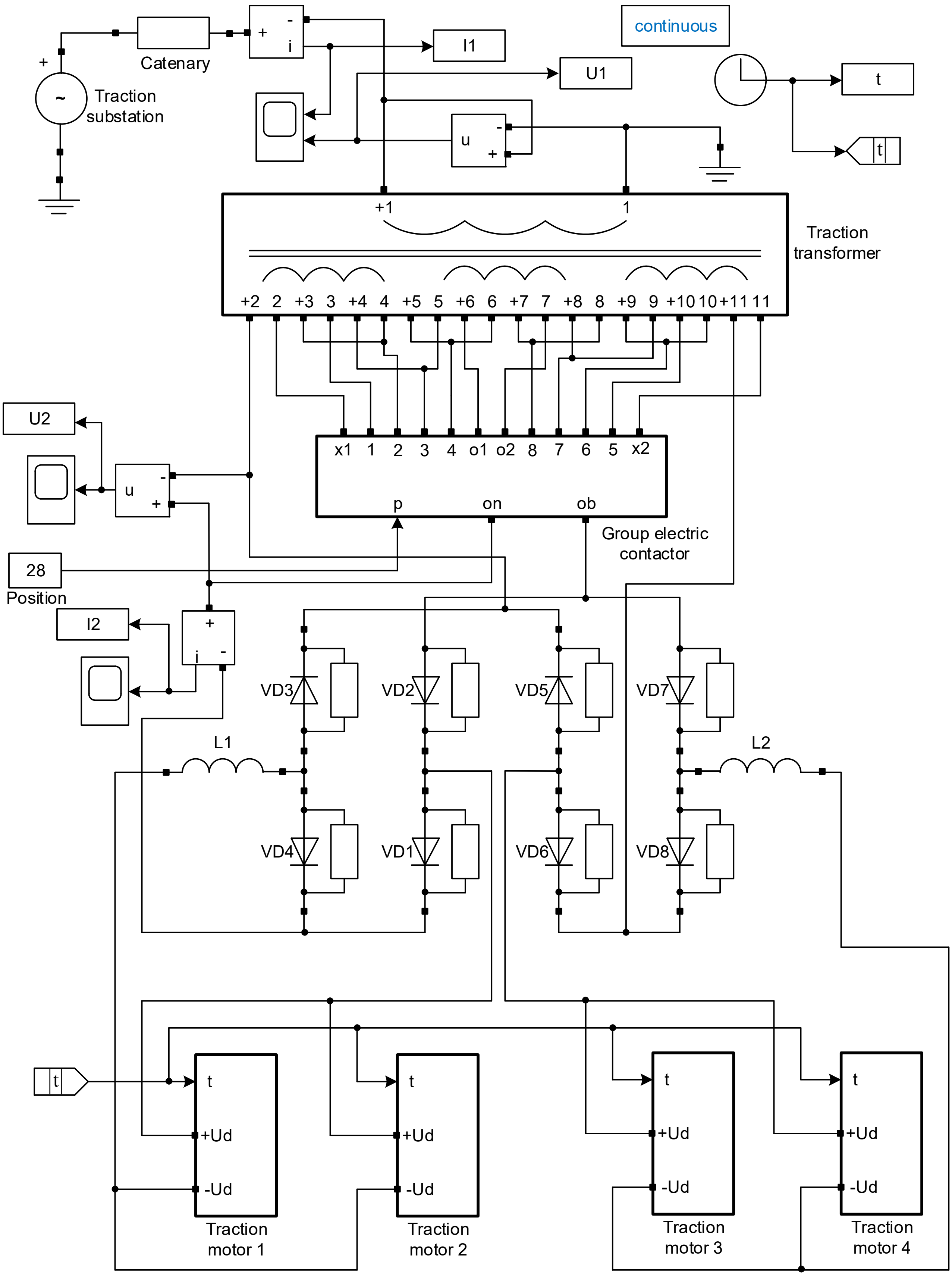

Fig.5. Simulation model of traction electric drive of electric locomotive VL80K

Table 2. Results of calculations of amplitude-frequency components of controlled quantities

No. of the harmonic component	Frequency, Hz	Parameter			
		The current of the primary winding of the traction transformer I1, A	Voltage on the primary winding of the traction transformer U1, V	The current of the secondary winding of the traction transformer I2, A	Voltage on the secondary winding of the traction transformer U2, V
0	0	0	0	0	0
1	50	218.11	25171.165	1746.4	1199.654
2	100	1.1815	251.392	51.907	14.695
3	150	46.631	1324.252	426.876	115.774
4	200	1.2393	138.11	49.994	9.591
5	250	24.3746	1106.264	219.101	97.64
6	300	0.8806	64.222	42.387	6.359
7	350	14.1049	890.247	122.728	78.284
8	400	0.5661	21.474	33.577	4.927
9	450	7.9424	655.223	65.909	56.058
10	500	0.2669	55.731	23.741	6.353
11	550	4.5118	476.181	32.302	39.721
12	600	0.2975	38.894	15.448	5.593
13	650	2.7625	371.479	15.596	28.711
14	700	0.4845	83.802	9.441	8.417
15	750	2.0876	391.58	12.91	28.798
16	800	0.4947	54.3	5.781	6.204
17	850	1.8071	398.151	14.168	29.466
18	900	0.3315	80.206	4.53	7.62
19	950	1.5079	426.119	13.709	29.527
20	1000	0.204	72.489	4.927	6.636

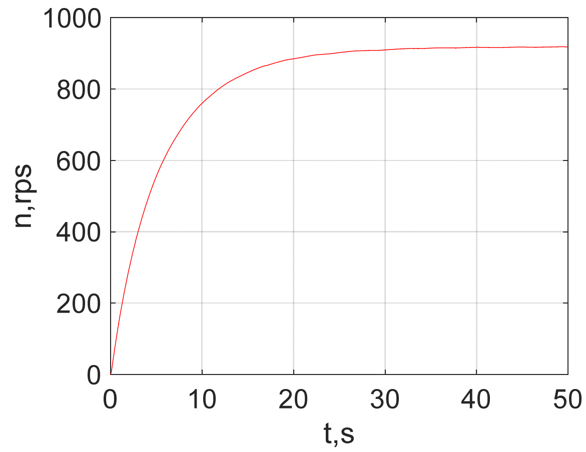

Fig.6. Timing diagram of the rotation frequency of the traction motor shaft

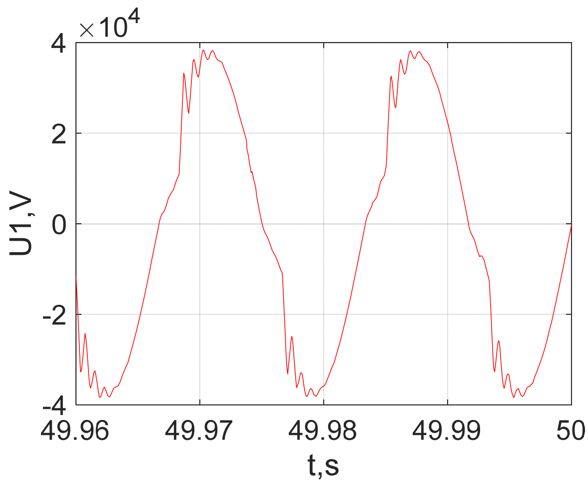

Fig.8. Time diagram of the voltage on the primary winding of the traction transformer

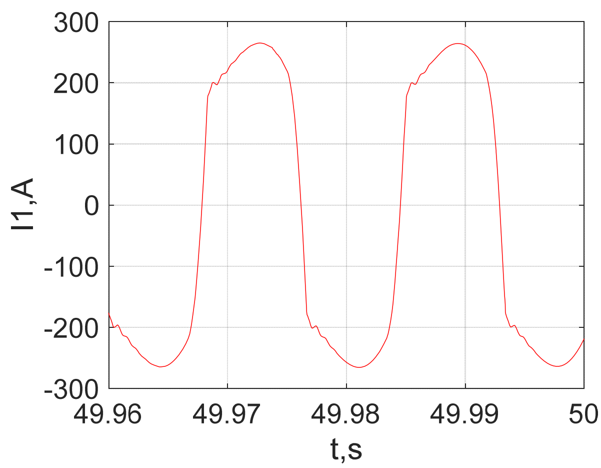

Fig.7. Time diagram of the current of the primary winding of the traction transformer

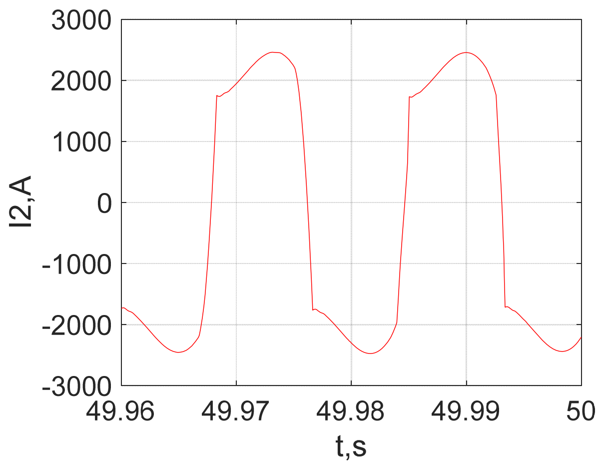

Fig.9. Time diagram of the current of the secondary winding of the traction transformer

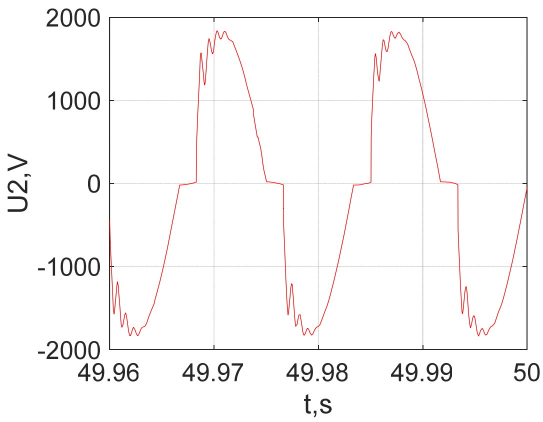

Fig.10. Time diagram of the voltage on the secondary winding of the traction transformer

Harmonic components of the amplitude-frequency spectrum of currents and voltages of the primary and secondary windings of the traction transformer are calculated according to formula (7) [34]

(7) $$A(k \cdot f) = \sqrt{\left(Re\left(X_k\right)\right)^2 + \left(Im\left(X_k\right)\right)^2},$$

where $Re(X_k)$ - the real part of the kth component of the fast Fourier transform;
$Im(X_k)$ - imaginary part of the kth component of the fast Fourier transform.

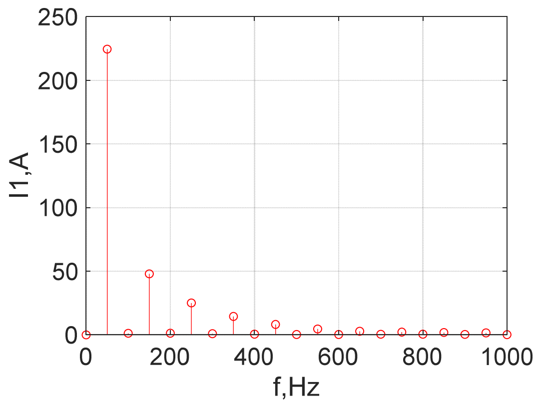

Fig.11. Amplitude-frequency current spectrum of the primary winding of the traction transformer

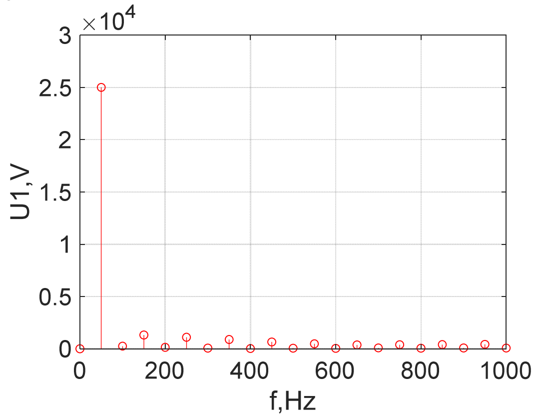

Fig.12. Amplitude-frequency spectrum of the voltage on the primary winding of the traction transformer

When calculating the spectral components of the controlled values, only the first 20 harmonic components were taken into account, since the values of the other components are so small that they can be neglected. The results of the calculations of the amplitude-frequency components of the controlled values are listed in Table 2.

As a result of the calculations, the amplitude-frequency spectra of the current of the primary winding of the traction transformer (Fig. 11), the voltage on the primary winding of the traction transformer (Fig. 12), the current of the secondary winding of the traction transformer (Fig. 13) and the secondary winding of the traction transformer (Fig. 14) were obtained.

The results of modeling and all calculations are summarized in Table 3.

The error of determining the controlled parameters was determined by the expression

(8) $$\sigma = \left|\frac{A_{data} - A_{calc}}{A_{data}}\right| \cdot 100\%,$$

where A_{data} - passport value of the parameter; A_{calc} - calculated parameter value.

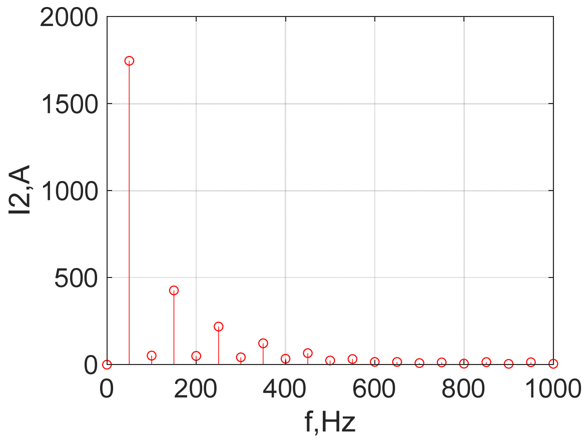

Fig.13. Amplitude-frequency current spectrum of the secondary winding of the traction transformer

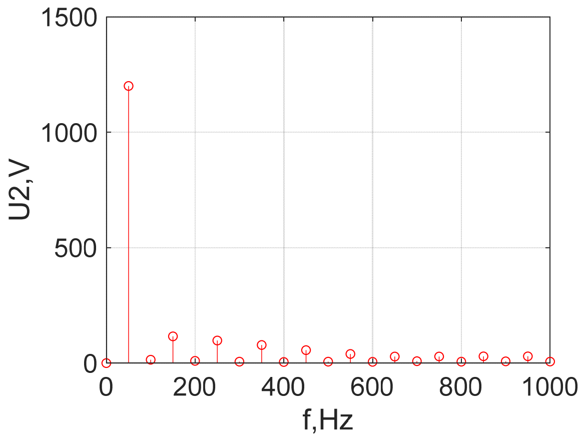

Fig.14. Amplitude-frequency spectrum of the voltage on the secondary winding of the traction transformer

The results of the calculations are listed in Table 3.

The analysis of the errors of the controlled parameters (table 3) shows that the error of determination as a result of the simulation of the controlled parameters did not exceed 8%. This indicates the high reliability of the simulation results.

To determine the power factor of the electric locomotive with the drive of the auxiliary machines turned off, the phase-frequency spectra of the current in the primary winding of the traction transformer and the voltage on the primary winding of the traction transformer were calculated

(Table 4). Since only the first 20 harmonic components were taken into account when calculating the amplitude-frequency spectra of the controlled quantities, only the first 20 harmonic components were also considered when calculating the phase-frequency spectra.

According to the results of Table 4, the phase-frequency spectrum of the current in the primary winding of the traction transformer (Fig. 15) and the voltage on the primary winding of the traction transformer (Fig. 16) were constructed.

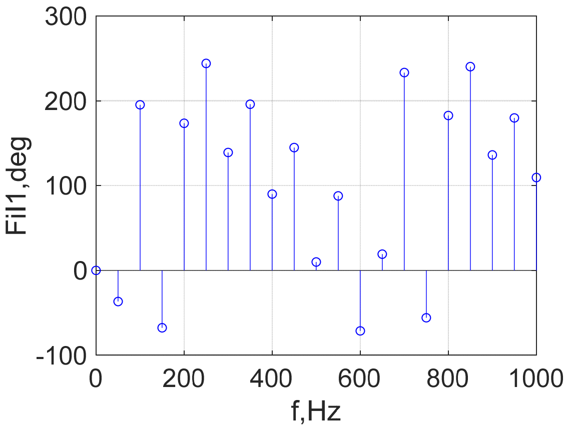

Fig.15. Phase-frequency current spectrum of the primary winding of the traction transformer

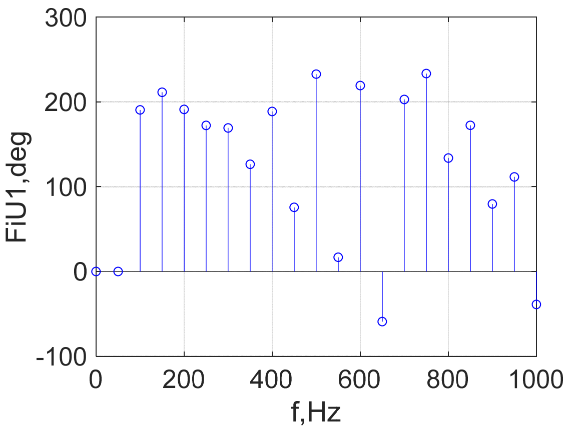

Fig.16. Phase-frequency spectrum of the voltage on the primary winding of the traction transformer

The power factor of the electric locomotive with the drive of the auxiliary machines turned off was determined by the formula [35]

(9) $$k_p = \frac{P_{1(1)}}{S},$$

where $P_{1(1)}$ – active power consumed by the primary winding of the traction transformer at the main frequency of the contact network;
S – total power consumed by the primary winding of the traction transformer.

Active power consumed by the traction transformer at the main frequency of the catenary network [35]

(10) $$P_{1(1)} = I_{1(1)} \cdot U_{1(1)} \cdot cos\left(\varphi_{U_{1(1)}} - \varphi_{I_{1(1)}}\right),$$

$I_{1(1)}$ – the amplitude of the first harmonic of the current in the primary winding of the traction transformer; $U_{1(1)}$ - the amplitude of the first harmonic of the voltage on the primary winding of the traction transformer; $\varphi_{U1(1)}$ – the phase of the first harmonic voltage component on the primary winding of the traction transformer; $\varphi_{I1(1)}$ - phase of the first harmonic component of the current in the primary winding of the traction transformer.

The total power consumed by the traction transformer was determined by the formula [35]

11) $$S = \sum_{i=0}^{N} \sqrt{\left(P_{1(i)}\right)^2 + \left(Q_{1(i)}\right)^2},$$

where $P_{1(i)}$ – active power of the i-th harmonic component consumed by the primary winding of the traction transformer;
$Q_{1(i)}$ - reactive power of the i-th harmonic component consumed by the primary winding of the traction transformer.

The active power of the i-th harmonic component consumed by the primary winding of the traction transformer is calculated according to the formula [35]

12) $$P_{1(i)} = U_{1(i)} \cdot I_{1(i)} \cdot cos\left(\varphi_{1(i)}\right),$$

The active power of the i-th harmonic component consumed by the primary winding of the traction transformer is calculated according to the formula [35]

13) $$Q_{1(i)} = U_{1(i)} \cdot I_{1(i)} \cdot sin\left(\varphi_{1(i)}\right),$$

$U_{1(i)}$ – amplitude of the i-th harmonic voltage component on the primary winding of the traction transformer;
$I_{1(i)}$ – the amplitude of the i-th harmonic component of the current in the primary winding of the traction transformer;
$\varphi_{1(1)}$ – phase shift between the first harmonic components of voltage and current of the primary winding of the traction transformer;
N - the number of harmonic components of voltage and current of the primary winding of the traction transformer.

The phase shift between the first harmonic components of the voltage and current of the primary winding of the traction transformer was determined by the formula [35]

14) $$\varphi_{1(i)} = \varphi_{U1(i)} - \varphi_{I1(i)}.$$

The results of the calculations are listed in Table 4.

The value of the power factor of the electric locomotive with the drive of the auxiliary machines turned off, the value of which was kp=0.85. The obtained value of the power factor, even when the drive of auxiliary machines is turned off, does not meet the requirements of the National Commission, which carries out state regulation in the fields of energy and communal services (Ukraine) [15]. This fact indicates the need to develop measures aimed at compensating the reactive power in the traction drive of the electric locomotive.

Conclusion

The application of the group electric controller block in the traction electric drive model of the electric locomotive makes it possible to study the electrodynamic processes in the traction electric drive system during the change of operating modes of the electric locomotive. A comparison of the controlled parameters in the steady state with the passport data of the electric locomotive showed a high degree of reliability of the simulation results. Thus, the errors in determining the controlled parameters did not exceed 8%.

Table 3. Simulation results and analysis of the obtained results

№ п/п	Controlled parameter	Passport value	The value obtained as a result of calculations or simulations	Definition error σ, %
1	Motor shaft rotation frequency n, rpm	915	931.1	1.76
2	Torque on the motor shaft T_2, N·m	7727	7500	2.93
3	Voltage on the secondary winding of the traction transformer U_2, V	1218	1200	1.48
4	The current of one section of the secondary winding of the traction transformer I_2, A	1750	1746.4	0.21
5	Voltage on the primary winding of the traction transformer U_1, V	25000	25165	0.66
6	The current of the primary winding of the traction transformer I_1, A	235	218.11	7.19

Table 4. The results of the calculation of the harmonic components of the active and reactive power of the primary winding of the traction transformer

No. of the harmonic component	Frequency, Hz	Parameter						
		The current of the primary winding of the traction transformer I1, A	Voltage on the primary winding of the traction transformer U1, V	Current phase of the primary winding of the traction transformer φI1, deg.	Voltage phase on the primary winding of the traction transformer φ_{U1}, deg.	Phase shift between the voltage and current of the primary winding of the traction transformer φ, deg.	Active power P1, W	Reactive power Q1, VAr
0	0	0	0	0	0	0	0	0
1	50	218.11	25171.165	0	0	31.692	4674776.471	2886299.172
2	100	1.1815	251.392	-31.692	190.502	-9.766	292.7123	-50.382
3	150	46.631	1324.252	200.268	211.360	274.053	4364.525	-61596.745
4	200	1.2393	138.11	-62.693	191.09	12.547	167.073	37.183
5	250	24.3746	1106.264	178.543	172.246	-76.749	6180.788	-26246.813
6	300	0.8806	64.222	248.995	169.29	25.247	51.1512	24.121
7	350	14.1049	890.247	144.043	126.489	-74.447	3366.86	-12097.042
8	400	0.5661	21.474	200.936	188.729	93.728	-0.79	12.131
9	450	7.9424	655.223	95.001	75.651	-74.225	1414.773	-5008.04
10	500	0.2669	55.731	149.876	232.745	217.821	-11.75	-9.121
11	550	4.5118	476.181	14.924	16.806	-76.079	516.879	-2085.331
12	600	0.2975	38.894	92.885	219.2	285.519	3.096	-11.149
13	650	2.7625	371.479	-66.319	-59.097	-83.269	120.28	-1019.138
14	700	0.4845	83.802	24.172	202.881	-35.389	33.101	-23.514
15	750	2.0876	391.58	238.27	233.338	284.194	200.446	-792.505
16	800	0.4947	54.3	-50.856	133.797	-53.844	15.848	-21.689
17	850	1.8071	398.151	187.641	172.369	-72.828	212.425	-687.425
18	900	0.3315	80.206	245.197	79.595	-61.5880000	12.651	-23.3867732
19	950	1.5079	426.119	141.1830000	111.57	-73.225	185.4484818	-615.202
20	1000	0.204	72.489	184.795	-38.799	-153.375	-13.22	-6.627

The proposed approach to modeling the traction electric drive of an electric locomotive will make it possible to apply this model in the development of a reactive power compensation scheme, to simulate processes in solving the traction and braking problem, etc.

The presence of a unit for determining magnetic losses in a traction electric motor makes it possible to more correctly investigate dynamic processes in the traction electric drive system of an electric locomotive. Especially it is applied to those studies where, for example, it is necessary to determine the harmonic composition of voltages and currents in the traction electric drive system, considering the modes of operation of the electric locomotive.

The calculated power factor of the electric locomotive with the drive of auxiliary machines turned off, the value of which was kp=0.85, which does not meet the requirements of the National Commission, which carries out state regulation in the fields of energy and communal services (Ukraine). This fact indicates the need to develop measures aimed at compensating the reactive power in the traction drive of the electric locomotive.

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

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