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CALCULATION OF TRACTION AND ENERGY CHARACTERISTICS ELECTRIC ROLLING STOCK WITH ASYNCHRONOUS TRACTION ELECTRIC DRIVE

The issue of determining the traction and energy characteristics of electric rolling stock with asynchronous traction drive is considered. It is noted that such rolling stock can work at any point of the traction area, resulting in the need to determine the characteristics of the rolling stock for the entire traction area. The calculation of the characteristics of the traction induction motor, which are the basis for determining the traction and energy characteristics of the electric rolling stock, is considered in detail. A procedure based on the calculation of the replacement circuit of an induction motor is proposed. The calculation of power losses due to higher harmonic voltages and currents is considered. An example of calculation of traction and energy characteristics of an DC electric shunting locomotive with a traction asynchronous electric drive is given.

Keywords: *traction asynchronous electric drive, electric rolling stock, induction motor, traction characteristics*

Introduction. Resolution of the Cabinet of Ministers of Ukraine "On approval of the National Economic Strategy for the period up to 2030" [1] defines decarbonization as a priority for the country's development. Improving the energy efficiency of transport is part of the process of implementing decarbonisation initiatives. One of the directions of this is the use of energy-optimal modes of vehicles movement with minimal energy consumption to perform the train task [2, 3]. To solve such problems, the characteristics of rolling stock are used, which are given in the Rules of traction calculations for train operation [4, 5]. At the same time, rolling stock with an asynchronous electric traction drive is becoming more and more widely used on the railways of Ukraine. Data on traction and energy characteristics of this rolling stock are not provided in the technical documentation. That is why the task of determining the characteristics is important.

Analysis of recent research and problem statement. Traction and braking characteristics of rolling stock are used while solving traction problems. Current characteristics that are necessary for the calculations of the traction power supply system are also important for the electric rolling stock. The use of an asynchronous traction electric drive on a rolling stock ensures its operation with any value of traction force and speed within the traction area. However, in the technical documentation, for example, [5], only the limit traction characteristics are given, which leads to the need to apply assumptions about the behavior of traction characteristics for operating modes whose parameters do not meet the limit. Therefore, the definition of traction and current characteristics for the entire traction area is relevant. The characteristics of traction electric machines and the characteristics of auxiliary equipment are basic for determining the traction and current characteristics of rolling stock. In this paper, only traction asynchronous electric motors in the traction mode of rolling stock are considered in detail.

The traction asynchronous motor is a frequency-controlled electric machine with a wide range of load and speed changes. The calculation of their characteristics is important for determining the energy efficiency of rolling stock. In [6] the method of calculation of the traction asynchronous electric motor is given, and the method of characteristics calculation on the basis of data on geometrical sizes of active parts of a stator and a rotor and winding data is given. In [7, 8] detailed mathematical models of the traction asynchronous electric motor at power supply from a source of non-sinusoidal voltage, in particular, for calculation of losses from higher harmonics of tension and current are resulted. In [9], a model for calculating losses in a frequency-controlled induction motor is proposed. Work [10] contains a method for determining losses in a traction induction motor in solving traction problems. In [11] a comparison of the results of analytical and numerical calculations of losses in a traction induction motor is performed. The authors [12] proposed and investigated a new model of losses in electrical steel, which is used in the manufacture of electric motor cores. In [13], an algorithm for calculating losses by the finite element method is presented. In general, it should be noted that in the study of traction asynchronous motors are widely used specialized software [14-17]. Mathematical models of induction motors for asymmetric modes of operation have also been developed [18-20].

Thus, we can conclude about a significant study of electromechanical processes in traction induction motors. However, the direct application of the results of these studies to determine the traction and current characteristics for the entire traction area is labored, so we consider the task of calculating the above characteristics is relevant.

The purpose and objectives of the study. The purpose of the work is to develop a method for calculating the traction and current characteristics of electric rolling stock with asynchronous traction drive in traction mode. To achieve this goal it is necessary to adjust the existing methods of calculating the characteristics of traction induction motors and additions that take into account the features of the power supply system of electric motors.

Materials and methods of research. The procedure given in [20] can be used as a basis for the method of calculating the characteristics of an induction motor. The calculation formulas are based on the substitution scheme of an induction motor. Using them in the case of calculating the characteristics of the traction induction motor, it is necessary to use the parameters of the substitution circuit for the main harmonic voltage and current taking into account their change from saturation of the magnetic circuit, first of all, taking into account changes in magnetizing circuit inductance. The calculation should be performed for a winding temperature of 150 ° C in accordance with the requirements of DSTU GOST 2582 [21]. The sequence of calculation is given below.

The input data is the speed V and the tangential thrust force F_k.

Traction power

$$P_k = \frac{F_k V}{3,6}, \tag{1}$$

where the speed is set in km / h.

Motor rotor speed

$$n_2 = \frac{V \mu_{GB}}{3,6 \pi D_k}, \tag{2}$$

where D_k – the diameter of the drive wheel,

μ_{GB} – gear ratio of the traction gearbox.

Torque on the shaft of the traction motor

$$M_2 = \frac{F_k D_k}{2 n_{TM} \mu_{GB} \eta_{GB}}, \tag{3}$$

where n_{TM} – the number of traction motors (motorized axles),
η_{GB} – gear efficiency in the mode of operation with speed n_2 and torque M_2.
The efficiency of the gearbox can also be determined by the power on the motor shaft

$$P_2 = \frac{\pi M_2 n_2}{30} . \tag{4}$$

The dependences for this case are given in [22].
Electric rotor speed

$$f_r = \frac{p n_2}{60} \tag{5}$$

where p – the number of pole pairs of the motor.
The following calculations are performed in the following sequence.
Set the rotor current frequency f_2.
Supply voltage frequency

$$f_1 = f_r + f_2 \tag{6}$$

Using the dependence of the stator voltage on the frequency, we determine the phase voltage $U_{1ph} = U_{1l}/\sqrt{3}$ (U_{1l} – line voltage).
Flux linkage

$$\Psi_1 = \frac{1}{\pi\sqrt{2}} \frac{U_{1ph}}{f_1} \tag{7}$$

The obtained value of the flux coupling is determined by the inductance of the magnetizing circuit and the scattering inductance of the stator and rotor (in the case of taking into account the saturation of their values).

Correction factor that takes into account the saturation of the magnetic circuit

$$C_1 = \sqrt{\left(1 + \frac{X_1}{X_m}\right)^2 + \left(\frac{R_1}{X_m}\right)^2} , \tag{8}$$

where $X_1 = 2\pi f_1 L_1$ – inductive resistance of the stator (L_1 – the scattering inductance of the stator winding);
$X_m = 2\pi f_1 L_m$ – inductive resistance of the magnetizing circuit (L_m– inductance of the magnetizing circuit) ;
R_1 – active resistance of the stator winding phase in the heated state.
Relative slip

$$s = \frac{f_2}{f_1} \tag{9}$$

Equivalent active resistance of the electric motor

$$R_{eq} = C_1 \left(R_1 + C_1 \frac{R_2'}{s} \right) \tag{10}$$

where R_2' – the active resistance of the rotor winding in the heated state is given.
Equivalent inductive resistance of the electric motor

$$X_{eq} = C_1 \left(X_1 + C_1 X_2^{'} \right), \tag{11}$$

where $X_2' = 2\pi f_1 L_2'$ – the inductive resistance of the rotor winding is given (L_2' – the inductance of scattering of a rotor winding is resulted).

Equivalent resistance of the electric motor

$$Z_{eq} = \sqrt{R_{eq}^2 + X_{eq}^2} \tag{12}$$

The rotor current is reduced

$$I_2^{'} = \frac{C_1 U_{1ph}}{Z_{eq}} \tag{13}$$

Active component of the stator current

$$I_{1a} = I_{0a} + \frac{U_{1ph}}{Z_{eq}} cos\varphi_2^{'}, \tag{14}$$

where I_{0a} – active component of no-load current;

φ_2' – the angle between the vectors I_2' and U_{1ph}, with $cos\varphi_2^{'} = \frac{R_{eq}}{Z_{eq}}$

Active component of no-load current

$$I_{0a} = \frac{P_{st} + mI_{\mu}^2 R_1}{mU_{1ph}}, \tag{15}$$

where $P_{ст}$ – losses in the stator magnetic circuit at voltage U_{1ph} and frequency f_1;
I_μ – the magnetizing current, which is determined by the dependence of the flux linkage on the magnetizing current;
m – the number of phases of the motor.

Reactive stator current component

$$I_{1r} = I_{\mu} + \frac{U_{1ph}}{Z_{eq}} sin\varphi_2^{'}, \tag{16}$$

where $sin\varphi_2' = \frac{X_{eq}}{Z_{eq}}$.

The effective value of the phase current of the main harmonic

$$I_{1ph} = \sqrt{I_{1a}^2 + I_{1r}^2} \tag{17}$$

Power factor

$$cos\varphi = \frac{I_{1a}}{I_{1ph}} \tag{18}$$

Active power taken from the source

$$P_1 = mU_{1ph} I_{1ph} \tag{19}$$

Losses in the stator winding

$$P_{e1} = mI_{1ph}^2 R_1 \tag{20}$$

Losses in the rotor winding

$$P_{e2} = m\left(I_2^{'}\right)^2 R_2^{'} \tag{21}$$

Losses in the magnetic circuit

$$P_{st} = P_{st\,nom}\left(\frac{\Psi_1}{\psi_{1nom}}\right)^2\left(\frac{f_1}{f_{1nom}}\right)^{1,5}, \tag{22}$$

where $P_{st\,nom}$ – losses in the magnetic circuit (all types of magnetic losses) at rated voltage and frequency;
ψ_{1nom} – nominal flux linkage.

Nominal flux linkage

$$\Psi_{1nom} = \frac{U_{1ph\,nom}}{\pi\sqrt{2}f_{1nom}} \tag{23}$$

where $U_{1ph\,nom}$ – rated phase voltage,
f_{1nom} – nominal frequency.

Mechanical losses

$$P_{mech} = P_{mech\,nom}\frac{n_2}{n_{2nom}}, \tag{24}$$

where $P_{mech\,nom}$ – mechanical losses at rated speed n_{2nom}.

In the case of self-ventilating motors, mechanical losses must be added to the ventilation losses from the built-in fan, which can be calculated from the expression

$$P_{vent} = P_{vent\,nom}\left(\frac{n_2}{n_{2nom}}\right)^3, \tag{25}$$

where $P_{vent\,nom}$ – losses on ventilation at nominal speed.

Additional losses in accordance with the requirements of standard [21] (excluding losses from higher harmonics)

$$P_{add} = 0,005P_1\left(\frac{I_{1ph}}{I_{1ph\,nom}}\right)^2, \tag{26}$$

where $I_{1ph\,nom}$ – rated phase current.

Losses in the electric motor from the main harmonic

$$\Delta P_1 = P_{e1} + P_{e2} + P_{st} + P_{mech} + P_{vent} + P_{add} \tag{27}$$

Power on the motor shaft

$$P_2^{'} = P_1 - \Delta P_1\ . \tag{28}$$

Moment on the shaft

$$M_2^{'} = \frac{30}{\pi}\frac{P_2^{'}}{n_2} \tag{29}$$

The value of the moment M_2' compare with the value M_2, calculated by the formula (3). If the momentM_2 exceeds M_2', it is necessary to increase the frequencyf_2 (if on the contrary - the frequency must be reduced) and repeat the calculations by expressions (6)-(28). It is advisable to organize a cyclic calculation of the moment M_2', taking the initial frequency value f_2 equal to zero, corresponding to the idling mode. The criterion for completing the cycle is the deviation M_2' from M_2 by an amount not exceeding some error (absolute or relative). The values of the motor parameters obtained in the last step of the calculations are taken as the actual parameter values.

On modern rolling stock, traction asynchronous electric motors are powered by autonomous voltage inverters, the harmonic voltage spectrum of which contains, in addition to the main component, higher harmonics. It is believed that the currents caused by them do not create a useful moment on the shaft, but cause additional losses in the windings and magnetic circuit [6-8]. When calculating the losses from the higher harmonics, it is assumed that for the higher harmonics the motor "works" in the short-circuit mode.

The current of the highest harmonic (current value) is determined by the expression

$$I_h = \frac{U_{1h}}{\sqrt{\left(R_{1h} + R_{2h}^{'}\right)^2 + \left(X_{1h} + X_{2h}^{'}\right)^2}}. \tag{30}$$

where U_{1h} – the current value of the phase voltage of the highest harmonic,

R_{1h} – stator winding phase resistance in the heated state for higher harmonic taking into account current displacement;

R_{2h} – reduced resistance of the rotor winding in the heated state for a higher harmonic taking into account the displacement of the current;

X_{1h} – inductive resistance of the stator winding phase taking into account the current displacement;

X_{2h}' – the inductive resistance of the rotor is given taking into account the current displacement.

The procedure for determining the winding resistances for higher harmonics is given in [6, 9].

Losses in the stator winding from the flow of higher harmonic current

$$P_{e1h} = mI_h^2 R_{1h}. \tag{31}$$

Losses in the rotor winding from the flow of higher harmonic current

$$P_e 2h = mI_h^2 R_{2h}' \tag{32}$$

Losses in the magnetic circuit from higher harmonic voltages

$$P_{sth} = 0,02\frac{m_1 + m_2}{m_1}P_{st} \tag{33}$$

where m_1 – stator core weigth,

m_2 – rotor core weigth

Total losses from higher harmonics

$$\Delta P_h = \sum_{j=1}^{k}\left(P_{e1hj} + P_{e2hj}\right) + P_{sth} \tag{34}$$

k – number of harmonics.

Total losses in the electric motor

$$\Delta P = \Delta P_1 + \Delta P_h \tag{35}$$

Power consumed by the traction inverter

$$P_{TM} = P_2^{'} + \Delta P$$

Efficiency of the electric motor

$$\eta = \frac{P_2^{'}}{P_2^{'} + \Delta P} \tag{36}$$

Power consumed by the traction electric drive from the intermediate circuit (DC links)

$$P_{TS} = P_M + \Delta P_I, \tag{37}$$

where ΔP_I – total power losses in the traction converter.

Calculating the power loss in the traction converter is an independent task. Examples of analytical solutions can be found in [23, 24]. Methods for determining losses in the inverter, which are based on digital modeling, are proposed in [25, 26].

When calculating the power P_{TS} must take into account the power supply scheme of traction motors.

On modern rolling stock power supply of auxiliary systems is also carried out from the intermediate circuit. Therefore, the total power consumed in the intermediate circuit can be represented as

$$P_d = P_{TS} + P_{AUX} \tag{38}$$

whee P_{AUX} – the total capacity of consumers of auxiliary systems (including losses), which are fed from the intermediate circuit.

The current of the intermediate circuit is determined by the expression

$$I_d = \frac{P_d}{U_d}, \tag{39}$$

where U_d – intermediate circuit voltage.

For rolling stock that is powered by a DC catenary, the mains current is defined by the expression

$$I_c = \frac{\Sigma P_d + \Delta P_{IN}}{U_c}, \tag{40}$$

where ΣP_d – total power consumed by the load of intermediate circuits,
ΔP_{IN} – losses in input converters,
U_c – voltage in the catenary.

It should be noted that the use of the input converter on the rolling stock leads to the appearance of higher harmonics in the mains current, which must be taken into account when assessing the energy efficiency of the electric traction system. Formula (40) gives the value of the "useful" component of the mains current.

For rolling stock powered by AC mains, the active component of mains current is determined by the expression

$$I_A = \frac{1}{K_{TR}K_i}\frac{\Sigma P_d + \Delta P_{TR} + \Delta P_{IN} + \Delta P_F + \Delta P_R}{U_c}, \tag{41}$$

where ΔP_{TR} – losses in the traction transformer,
ΔP_F – losses in the dual frequency filter,
ΔP_R – losses in the mains choke,
$К_{TR}$ – traction transformer transformation coefficient,

K_i – coefficient that depends on the ratio of DC in the intermediate link and the input current 4QS-converter.

Since 4QS-converters operating with modulated voltage are used on rolling stock with asynchronous traction drive, higher harmonic voltages and currents must be taken into account when calculating losses in the transformer and mains choke.

As in the case of direct current, the mains current will be higher harmonic, due to the operation of 4QS-converters. They must be taken into account when assessing the energy efficiency of the electric traction system.

The main harmonic of the mains current

$$I_c = \sqrt{I_A^2 + I_R^2}, \tag{42}$$

where I_R^2 – reactive current, the value of which is set by the control system 4QS-converter.

The following indicators are used to assess energy efficiency in the standards for electric rolling stock:

efficiency – for all types of electric rolling stock;

power factor for the electric rolling stock of alternating current and dual power supply when working from the catenary of alternating current.

Efficiency of direct current electric rolling stock and dual power supply when working from a direct current network

$$\eta_{DC} = \frac{P_k}{U_c I_c} \tag{43}$$

Efficiency for electric rolling stock of alternating current and double power supply at work from a contact network of alternating current

$$\eta_{AC} = \frac{P_k}{U_c I_A} \tag{44}$$

Power factor

$$cos\varphi = \frac{I_A}{I_c} \tag{45}$$

Thus, the above algorithm allows to calculate the traction and energy characteristics of the electric rolling stock with asynchronous traction drive for the entire traction area.

To illustrate the operation of this algorithm, we calculate the traction and energy characteristics of the shunting electric locomotive, the applications of which have a number of advantages [27]. The data required for the calculation are given in table 1. Calculations are performed for the case of operation from a direct current catenary. Since the calculation of losses in the motor from higher harmonic voltage and current, as well as the calculation of losses in the inverter and input converter are quite complex, to simplify the test calculation, we assume that these losses are 2% of power on the motor shaft.

Table 1. **Input data for calculation**

Parameter	Unit of measurement	Value
Rated power of the traction motor	kW	200
Rated line voltage	V	290
The highest line voltage	V	530
Rated frequency	Hz	12,5
Nominal speed	rpm	240
Nominal moment	Nm	6500
Steel losses in nominal mode	kW	3,0

End of table 1

Mechanical losses in nominal mode	kW	0,5
Resistance of the stator winding at a temperature of 20 ° C	Om	0,0121
Inductance of the stator winding phase	mH	0,42
Resistance of the rotor	Om	0,0102
Iinductance of rotor scattering is given	mH	0,369
Nominal flux leankage	Wb	2,01
Intermediate circuit voltage	V	600
Contact network voltage	V	3000
Power of consumers' own needs	kW	80
Number of axles	–	2
Efficiency of a traction gearbox	%	98,0
Transmission ratio of the traction gearbox	–	5,067
Diameter of the drive wheel	v	1,05

The results of the calculations are shown in Fig. 1-3, which shows the limiting traction and current characteristics, as well as the dependence of the efficiency of the electric locomotive on speed. By performing the calculation of the above procedure, you can get the characteristics of the locomotive for any point of the traction area.

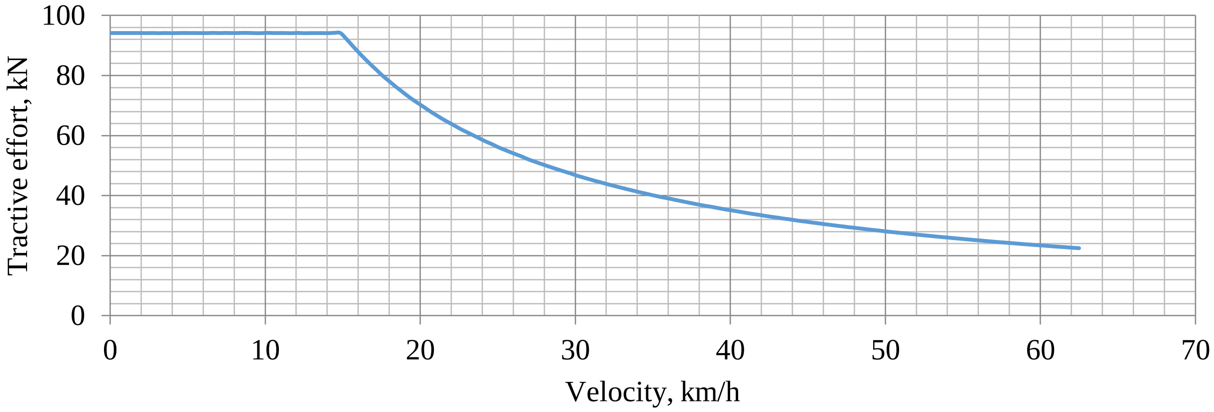

Fig. 1. **Traction characteristics of the electric locomotive**

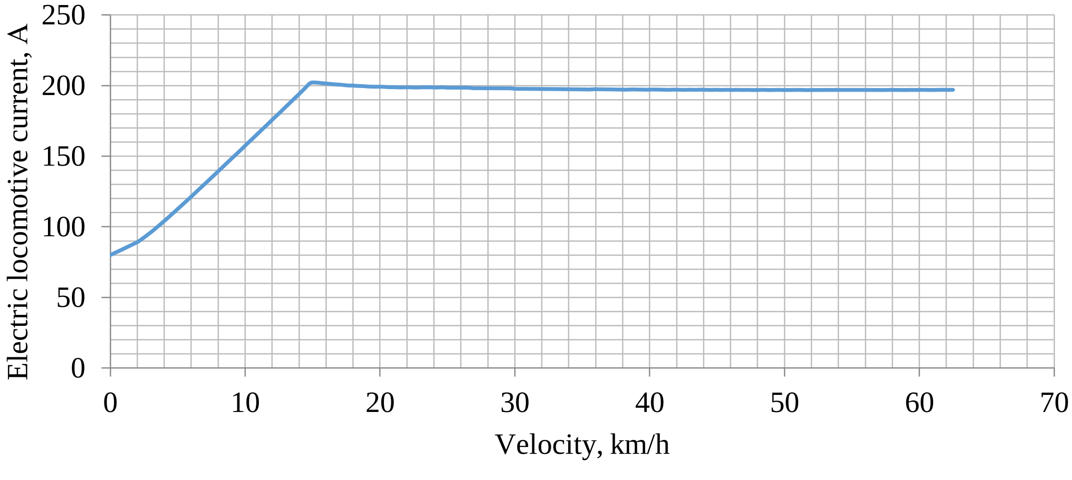

Fig. 2. **Current characteristics of the electric locomotive**

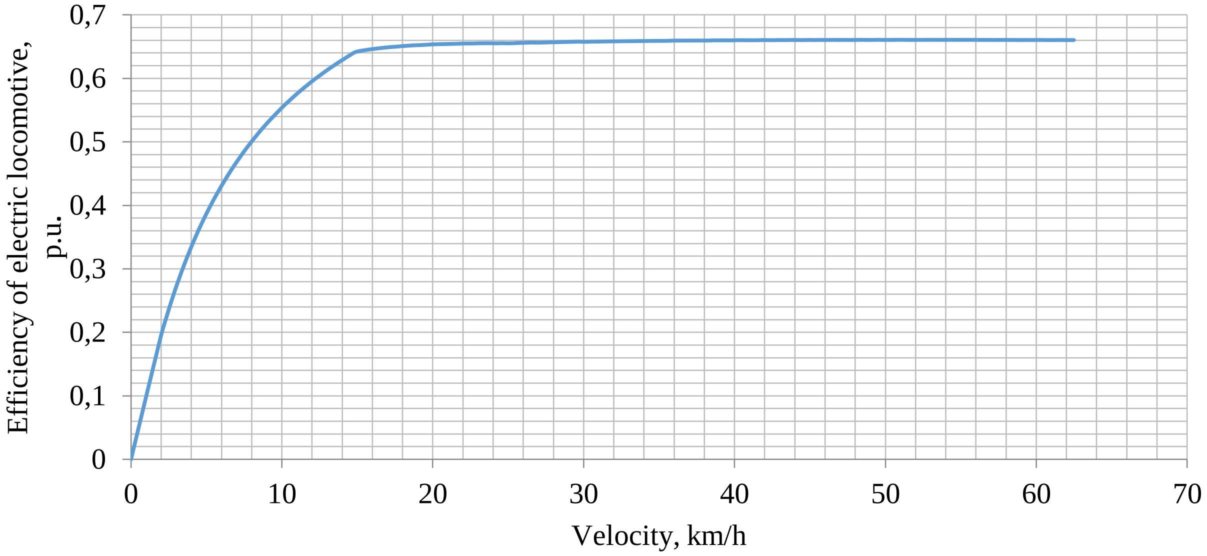

Fig. 3. **Dependence of electric locomotive efficiency on speed**

The analysis of the dependences in Fig. 1-3 shows that the characteristics have two parts, the limit of which is about a speed of 15 km / h. This speed corresponds to the transition from the zone of operation with a constant torque to the zone of operation with a constant power. This explains why in the second zone the current and efficiency of the electric locomotive do not change.

Conclusions. The algorithm for calculating the traction and energy characteristics of an electric rolling stock with an asynchronous traction drive is proposed in the article. The method is based on the calculation of electromechanical characteristics of asynchronous traction motor and calculations of power losses in the components of the traction drive. Further improvement of the proposed algorithm is associated with the refinement of the calculation of losses in semiconductor converters and traction transformers.

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РОЗРАХУНОК ТЯГОВО-ЕНЕРГЕТИЧНИХ ХАРАКТЕРИСТИК ЕЛЕКТРОРУХОМОГО СКЛАДУ З АСИНХРОННИМ ТЯГОВИМ ЕЛЕКТРОПРИВОДОМ

Розглянуто питання визначення тягово-енергетичних характеристик електрорухомого складу з асинхронним тяговим електроприводом. Відзначено, що такий рухомий склад може працювати у будь-якій точці тягової області, наслідком чого є необхідність визначення характеристик рухомого складу для у всій тяговій області. Детально розглянуто розрахунок характеристик тягового асинхронного електродвигуна, які є базовими для визначення тягово-енергетичних характеристик електрорухомого складу. Запропоновано процедуру, яка базується на розрахунку схеми заміщення асинхронного електродвигуна. Розглянуто розрахунок втрат потужності, обумовлених вищими гармонійними напруги та струму. Наведено приклад розрахунку тягово-енергетичних характеристик маневрового електровозу постійного струму з тяговим асинхронним електроприводом.

Ключові слова: *тяговий асинхронний електропривод, електрорухомий склад, асинхронний двигун, тягові характеристики.*