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# Research on the energy efficiency of a traction induction electric drive for a shunting locomotive

**Ievgen Riabov***
Assistant Professor
National Technical University "Kharkiv Polytechnic Institute"
61002, 2 Kyrpychov Str., Kharkiv, Ukraine
https://orcid.org/0000-0003-0753-514X

**Yevhen Lysenko**
Postgraduate Student
National Technical University "Kharkiv Polytechnic Institute"
61002, 2 Kyrpychov Str., Kharkiv, Ukraine
https://orcid.org/0009-0007-1263-7446

**Bagish Yeritsyan**
Assistant Professor
National Technical University "Kharkiv Polytechnic Institute"
61002, 2 Kyrpychov Str., Kharkiv, Ukraine
https://orcid.org/0000-0003-0579-3882

**Iryna Bilokon**
Director
Kremenchuk Vocational College
of Transport Infrastructure and Technologies
39600, 14 Yuri Ruf Str., Kremenchuk, Ukraine
https://orcid.org/0000-0002-4675-3994

**Anton Zhukov**
Independent Researcher
LLC "Kharkiv Electric Machine-Building Plant"
61037, 199 Heroiv Kharkova Ave., Kharkiv, Ukraine
https://orcid.org/0009-0001-5229-1685

**Abstract.** The modernisation of the fleet of locomotives used on Ukrainian railways for shunting operations is essential to improve the reliability of rail transport, reduce fuel and energy costs, and minimise the negative impact on the environment. The aim of this work was to investigate the energy efficiency of an induction traction drive for a shunting locomotive, which influences the locomotive's traction and energy performance. The ChME3 shunting diesel locomotive was selected for the study, for which the energy efficiency indicators of the traction drive with 140 kW induction electric motors were determined through mathematical modelling. The results of the calculations showed that the ChME3 diesel locomotive can utilise an induction traction drive with either four or six electric motors. For both variants, calculations of the tangential power were performed at various positions of the driver's controller, and it was determined that both variants exhibit high energy performance. At the same time, the six-motor traction induction electric drive provided an increase in tangential tractive force compared to a traction electric drive with commutator motors. A comparison was made of the efficiency of the traction induction electric drive and a standard electric drive with commutator motors. It has been determined that the efficiency of the traction induction drive is higher across the entire load range, confirming the feasibility of using a traction induction electric drive on shunting locomotives. The findings of this study can be utilised in the development of new shunting locomotives and the modernisation of existing ones at domestic and foreign enterprises

**Keywords:** energy effectiveness; energy and resource saving; induction electric motor; power; rolling stock

## Introduction

Improving the efficiency of rail transport is a key priority, the achievement of which requires a comprehensive approach and involves streamlining the organisational management of the transport process, upgrading technical transport infrastructure, advancing digitalisation for rail logistics tasks, and so on. Rolling stock has a direct impact on the stability of rail transport, and therefore it is subject to strict requirements regarding traffic safety, the need for high operational performance, and low environmental impact, among other things. Currently, the technical condition of most railway rolling stock, particularly locomotives, is characterised as obsolete: locomotives built 40-50 years ago have poorer operational characteristics than modern locomotives.

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*Corresponding author (*yevhen.riabov@khpi.edu.ua*)

This makes it necessary to modernise the traction rolling stock and requires the search for technical solutions that will ensure high operational performance of the traction rolling stock.

Current regulations, such as Resolution of the Cabinet of Ministers of Ukraine No. 1550… (2024), provide for the modernisation of the railway rolling stock through the use of energy-efficient equipment and technologies. Currently, the technical characteristics of locomotives used for shunting operations at stations of JSC "Ukrzaliznytsia" do not meet modern requirements for energy efficiency and low environmental impact. This is due to the long service life of locomotives, which were created several decades ago using equipment available at that time. Another aspect is that locomotives were created as unified machines that can be used in different conditions. As a result, their characteristics do not correspond to the actual operating conditions, which leads to excessive consumption of fuel and energy resources. Given the long service life of the existing shunting locomotives, their modernisation is essential, and energy-saving technologies will be implemented in the process. Analysis shows that the main objective in this area is to reduce fuel and lubricant consumption, for which modern diesel engines or separate systems are being installed, as evidenced by the experience of modernising diesel locomotives at Mykolaiv Locomotive Repair Plant LLC (NTRZ, n.d.). J. Pagenkopf *et al.* (2022) and G. Bakyt *et al.* (2025) also point to reduced fuel consumption as the key factor in improving the efficiency of shunting locomotives, which determines the direction of improvements to outdated locomotives. More promising is the modernisation of diesel locomotives using modern diesel-generator sets, AC-DC electrical transmission, electric fan motors, etc. This allows for a reduction in diesel fuel consumption, lower maintenance and repair costs, and so on. In Ukraine, such work is carried out by Mykolaiv Diesel Locomotive Repair Plant LLC (NTRZ, n.d.), Poltava Locomotive Repair Plant LLC (TRZ, n.d.) and other enterprises.

However, almost all modernisation options involve retaining the standard brush-type electric motors. Yu. Syrotenko (2016), A. Falendysh *et al.* (2019) and D. Zaika (2024) are investigating precisely such modernisation options for shunting diesel locomotives. However, retaining commutator motors significantly limits the potential for improving the energy efficiency of the traction drive, as in operating modes requiring increased tractive force, the traction motors operate at higher currents. This significantly limits the possibility of increasing the energy efficiency of the traction electric drive, since in operating modes with increased traction force, traction electric motors operate with increased currents. In such modes, the efficiency of the traction electric drive is significantly reduced, and the risk of thermal damage to the electric motor components also increase. It is impossible to achieve a significant increase in traction properties while maintaining collector electric motors. Therefore, it is urgent to search and study ways to increase the traction and energy characteristics of shunting locomotives by improving their traction electric drive.

The purpose of the work was to study the energy efficiency of a traction induction electric drive for a shunting locomotive. The tasks of the work were to determine the energy efficiency indicators of a traction induction electric drive and compare it with a serial traction electric drive based on collector electric motors.

## Materials and Methods

For the study, the authors selected the ChME3 diesel locomotive, which is the main shunting locomotive of JSC "Ukrzaliznytsia", and is also used at many industrial enterprises for shunting and export operations. It is well known that the use of traction induction motors allows for an increase in the gear ratio of the traction gearbox. This, in turn, reduces the size of the induction motor, which has a positive effect on its layout within the wheel-motor unit. With this in mind, the authors have proposed a new wheel-motor unit with a traction gearbox having a gear ratio of 5.929. (the number of gear teeth is 83, the number of gear teeth is 14). A general view of the developed wheel-motor unit is shown in Figure 1. Traction induction motor – with axial rolling bearings. A coupling is used to compensate for the misalignment between the axes of the electric motor shaft and the input shaft of the traction gearbox.

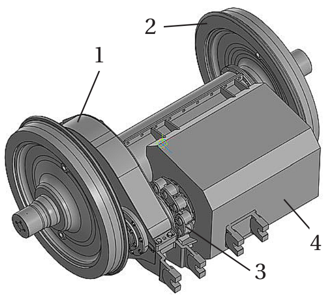


**Figure 1.** 3D sketch of the wheel-motor unit
**Note:** 1 – traction gear-box; 2 – wheel-set; 3 – clutch; 4 – traction motor
**Source:** created by the authors

Based on the power of the serial diesel locomotive ChME3, which is 1350 hp (992 kW), for a six-axle diesel locomotive it is necessary to use a traction electric motor with a power of 140 kW. The authors performed calculations and a sketch layout of such a traction induction electric motor. The calculations for the electric motor were carried out in accordance with the recommendations set out in D. Tsypenkov *et al.* (2020). In the calculations, it was assumed that the traction electric drive should provide a continuous traction force of 360 kN and operate at rated power up to a speed of 60 km/h. The maximum speed of the locomotive is 90 km/h. According to the results of the calculations, an eight-pole three-phase electric motor with a short-circuited rotor winding was selected. The calculated parameters of the electric motor are given in Table 1. To assess energy efficiency, the parameters of the traction induction electric motor were determined. The calculations were performed with a sinusoidal power supply. The calculation did not take into account losses due to higher-order harmonics in current and voltage, nor losses in semiconductor converters. For the purposes of this study, the omission of these losses does not introduce significant errors, but it does significantly simplify the calculation model. Calculations of the parameters of losses in electric motors and the parameters necessary for their calculation were performed using the algorithm below, based on the recommendations V. Bezruchenko *et al.* (2003) and I. Riabov *et al.* (2025). The calculation algorithm involved performing the following calculations:

1) Set the power frequency and phase voltage;

2) Calculate the correction factor that takes into account the saturation of the magnetic core:

$$C_1 = \sqrt{\left(1 + \frac{X_1}{X_m}\right)^2 + \left(\frac{R_{1T}}{X_m}\right)^2}, \quad (1)$$

where $X_1 = 2\pi f_1 L_1$ – inductive resistance of the stator; $X_m = 2\pi f_1 L_m$ – inductive resistance of the magnetising circuit; $R_{1T}$ – active resistance of the stator winding in a heated state; $f_1$ – fundamental voltage harmonic frequency.

3) Calculate the equivalent active resistance of an electric motor:

$$R_{eq} = C_1 \left(R_{1T} + C_1 \frac{R'_{2T}}{s}\right), \quad (2)$$

where $R'_{2T}$ – the active resistance of the rotor winding in the heated state is given; $s$ – relative slip.

To calculate energy efficiency indicators, the power distribution by the positions of the controller of the serial locomotive driver was used (Table 2).

**Table 1.** Design parameters of a traction induction electric motor

| Parameter name/unit of measurement | Value |
|---|---|
| Mode of operation | continued |
| Power, kW | 140 |
| Nominal linear voltage, V | 315 |
| Maximum linear voltage, V | 460 |
| Phase current, A | 342 |
| The largest phase current at start-up, A | 450 |
| Nominal torque, Nm | 5,500 |
| Starting torque, Nm | 7,700 |
| Nominal frequency, Hz | 16.8 |
| Maximum frequency, Hz | 130 |
| Nominal rotation speed, s-1 (rpm) | 243 |
| Maximum rotation speed (at a speed of 90 km/h), s-1 (rpm) | 3,000 |
| Rotational speed range when operating at rated power, rpm | 244…2,040 |
| Efficiency in nominal mode when powered by sinusoidal voltage, % | 90.6 |
| Power factor in nominal mode, p.u. | 0.82 |
| Multiplicity of maximum torque at a speed of 2,040 rpm, rated power and rated line voltage, p.u. | 1.2 |
| Cooling air flow rate, m³/s | 0.3 |
| Number of phases | 3 |
| The number of pairs of poles | 8 |

**Source:** developed by the authors

**Table 2.** Characteristics of the diesel locomotive ChME3

| Driver controller position | Power supplied to traction motors, kW | Traction force during start, kN |
|---|---|---|
| 0 | - | - |
| 1 | 28 | 90 |
| 2 | 98 | 180 |
| 3 | 220 | 246 |
| 4 | 310 | 312 |
| 5 | 410 | 360 |
| 6 | 530 | 360 |
| 7 | 720 | 360 |
| 8 | 880 | 360 |

**Source:** developed by the authors based on Ukrzaliznytsia (n.d.)

4) Calculate the equivalent inductive resistance of an electric motor:

$$X_{eq} = C_1(X_1 + C_1 X'_2), \quad (3)$$

where $X'_2 = 2\pi f_1 L'_2$ – reduced inductive resistance of the rotor winding.

5) Calculate the equivalent resistance of an electric motor:

$$Z_{eq} = \sqrt{R_{eq}^2 + X_{eq}^2}, \quad (4)$$

6) Calculate the reduced rotor current:

$$I'_2 = \frac{C_1 U_{1ph}}{Z_{eq}}, \quad (5)$$

where $U_{1ph}$ – effective value of the first harmonic phase voltage.

7) Calculate the active component of the stator current:

$$I_{1a} = I_{0a} + \frac{U_{1ph}}{Z_{eq}} cos\,\varphi'_2, \tag{6}$$

where $I_{0a}$ – active component of the no-load current; $\varphi'_2$ – the angle between the vectors $I'_2$ and $U_{1ph}$. At the same time $cos\,\varphi'_2 = \frac{R_{eq}}{Z_{eq}}$.

8) Calculate the active component of the no-load current:

$$I_{0a} = \frac{P_{st1} + mI_\mu^2 R_{1T}}{mU_{1ph}}, \tag{7}$$

where $P_{st1}$ – losses in the stator magnetic circuit at voltage $U_{1ph}$ and frequency $f_1$ (are calculated for (14)); $I_\mu$ – magnetising current at voltage $U_{1ph}$ and frequency $f_1$; $m$ – number of phases of the electric motor.

9) Calculate the reactive component of the stator current:

$$I_{1r} = I_\mu + \frac{U_{1ph}}{Z_{eq}} sin\,\varphi'_2, \tag{8}$$

where $sin\,\varphi'_2 = \frac{X_{eq}}{Z_{eq}}$.

10) Calculate the effective value of the stator phase current according to the first harmonic:

$$I_{1ph} = \sqrt{{I_{1a}}^2 + {I_{1r}}^2}. \tag{9}$$

11) Calculate the power factor of an electric motor:

$$cos\,\varphi = \frac{I_{1a}}{I_{1ph}}. \tag{10}$$

12) Calculate the active power taken from the source

$$P_1 = mU_{1ph}I_{1a}. \tag{11}$$

13) Compare the power value calculated by the (11), with the power value supplied to the electric motor $P_{1M} = \frac{P_{DC}}{N_M}$. In this expression $P_{DC}$ – power supplied to the traction electric drive; $N_M$ – number of traction motors.

Calculations according to expressions (1)-(11) are carried out until the value calculated according to (11) does not differ significantly (no more than 5%) from the specified power value $P_{1M}$. To do this, change the supply frequency $f_1$ and phase voltage $U_{ph1}$. When the electric drive operates in the first zone – with constant torque – the ratio between the supply frequency and voltage must correspond to the proportional law $\frac{U}{f} = const$, which approximately corresponds to operation with constant flux linkage $\Psi = const$. When operating in the second zone – with constant power – the supply voltage does not change ($U = const$), and changing the supply frequency leads to a weakening of the flux linkage. After determining the operating parameters of the electric motor, the losses and efficiency of the electric motor are determined using the model below.

Stator winding losses:

$$P_{e1} = mI_{1ph}^2 R_{1T}. \tag{12}$$

Rotor winding losses:

$$P_{e2} = m(I'_2)^2 R'_{2T}. \tag{13}$$

Losses in the magnetic core:

$$P_{st1} = P_{stnom}\left(\frac{\psi_1}{\psi_{1nom}}\right)^2 \left(\frac{f_1}{f_{1nom}}\right)^{1,5}, \tag{14}$$

where $P_{stnom}$ – losses in the magnetic core (all types of magnetic losses) at rated voltage and frequency; $\psi_1$ – flux linkage under voltage $U_{1ph}$ and frequency $f_1$:

$$\psi_1 = \frac{U_{1ph}}{4.44 f_1}, \tag{15}$$

$\psi_{1nom}$ – nominal flux linkage:

$$\psi_{1nom} = \frac{U_{1phnom}}{4.44 f_{1nom}}, \tag{16}$$

$U_{1phnom}$ – rated phase voltage, $f_{1nom}$ – nominal frequency.

Mechanical losses:

$$P_{mech} = P_{mechnom}\frac{n_2}{n_{2nom}}, \tag{17}$$

where $P_{mechnom}$ – mechanical losses at rated speed .

Rotor speed:

$$n_2 = \frac{60 f_1}{p}(1 - s), \tag{18}$$

where $p$ – number of pole pairs of an electric motor.

Additional losses (excluding losses from higher voltage harmonics):

$$P_{add} = 0.005 P_{1nom}\left(\frac{I_{1ph}}{I_{1phnom}}\right)^2. \tag{19}$$

Losses in an electric motor:

$$\Delta P = P_{e1} + P_{e2} + P_{st1} + P_{mech} + P_{add}. \tag{20}$$

Efficiency of the electric motor:

$$\eta = 1 - \frac{\Delta P}{P_1}. \tag{21}$$

Shaft power:

$$P_2 = P_1 - \Delta P. \tag{22}$$

Moment on the shaft:

$$M_2 = \frac{30}{\pi}\frac{P_2}{n_2}. \tag{23}$$

Traction power of the locomotive:

$$F_k = N_M \frac{2M_2}{D_k}\mu_{gb}\eta_{gb}, \tag{24}$$

where $\mu_{gb}$ – gear ratio of the drive reduction gear; $\eta_{gb}$ – gearbox efficiency, equal to 0.98.

Locomotive speed (in km/h):

$$V = \frac{3.6\pi D_k}{\mu_{gb}} n_2. \tag{25}$$

Power at the wheel rim (tractive power):

$$P_k = \frac{F_k V}{3.6}. \qquad (26)$$

Thus, model (1)-(26) allowed for calculations of the characteristics of a locomotive equipped with a traction induction electric drive. To perform the calculations, a script has been developed in the Matlab environment for calculating the characteristics. I. Riabov *et al.* (2025) shown that it is advisable to regulate the voltage of the electric motor depending on its power. This leads to an increase in the efficiency of the electric motor and the power factor, which affects the efficiency of the traction converter. The smallest voltage value is chosen from the condition of ensuring the stability of the induction machine at the highest speed in the rated power mode. Based on this, based on the Kostenko law for frequency-controlled electric motors, the following expression was obtained, which determines the linear voltage depending on the power:

$$U_1 = U\sqrt{\frac{P_2}{P_{2nom}}}_{1max}, \qquad (27)$$

where $U_{1max}$ – the highest value of line voltage at rated power; $P_2$ – specified motor power; $P_{2nom}$ – rated power of the electric motor.

Calculations were made for the speed range corresponding to operation on the hyperbolic part of the traction characteristic. The minimum speed is determined by the starting traction force at the given position of the driver's controller according to Table 2. It was worth noting that in models (1)-(11) and (12)-(26) the losses in the traction converter and the losses in the induction electric motors from higher harmonics of current and voltage were not taken into account, since for their determination it is necessary to know the algorithms of voltage modulation. Considering that such losses constitute several percent of the total power of the electric drive, they are not taken into account in this study.

## Results and Discussion

Below are the results of calculations of the characteristics of the electric motor and the locomotive. The calculations were carried out for the variants of the traction induction electric drive with six and four electric motors for 1-6 driver controller positions and six electric motors for 7 and 8 driver controller positions. Tractive power was chosen as the criterion:

$$P_l = P_s \eta, \qquad (28)$$

where $P_s$ – power supplied to the traction electric drive at a given position of the driver's controller; $\eta$ – traction motor efficiency.

Table 3-10 show the results of the calculations.

**Table 3.** Design characteristics for 1 driver controller positions (DCP) (supplied power 28 kW)

| Number of electric motors | Parameters | Value | | | | |
|---|---|---|---|---|---|---|
| 4 | Tractive power, kW | 20 | 23 | 24 | 24 | 26 |
| | Efficiency, % | 67.2 | 79.4 | 83.2 | 85.6 | 81.6 |
| | Speed, km/h | 1.2 | 5.0 | 10.0 | 20.0 | 30.0 |
| | Traction force, kN | 90 | 25.2 | 12.6 | 6.3 | 4.2 |
| 6 | Tractive power, kW | 18 | 21 | 22.8 | 22.2 | 21 |
| | Efficiency, % | 60.0 | 72.7 | 83.2 | 80.8 | 75.5 |
| | Speed, km/h | 0.7 | 5.0 | 10.0 | 20.0 | 30.0 |
| | Traction force, kN | 90 | 25.2 | 8.5 | 4.2 | 2.9 |

**Source:** developed by the authors

**Table 4.** Design characteristics for 2DCP (supplied power 98 kW)

| Number of electric motors | Parameters | Value | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 4 | Tractive power, kW | 62 | 84 | 90 | 88 | 88 | 88 | 86 | 84 | 82 |
| | Efficiency, % | 64.4 | 87.5 | 92.4 | 92.5 | 92.1 | 90.8 | 89.3 | 87.5 | 85.5 |
| | Speed, km/h | 1.2 | 5.0 | 10.0 | 15.0 | 20.0 | 30.0 | 40.0 | 50.0 | 60.0 |
| | Traction force, kN | 180 | 59.3 | 29.6 | 20.7 | 15.5 | 10.3 | 7.7 | 6.1 | 4.9 |
| 6 | Tractive power, kW | 63 | 84 | 87 | 87 | 87 | 87 | 84 | 81 | 78 |
| | Efficiency, % | 67.3 | 87.0 | 91.8 | 91.8 | 91.0 | 89.1 | 86.8 | 83.7 | 81.0 |
| | Speed, km/h | 1.3 | 5.0 | 10.0 | 15.0 | 20.0 | 30.0 | 40.0 | 50.0 | 60.0 |
| | Traction force, kN | 180 | 59.1 | 29.6 | 19.8 | 14.8 | 9.9 | 7.4 | 5.3 | 4.3 |

**Source:** developed by the authors

**Table 5.** Design characteristics for 3DCP (supplied power 220 kW)

| Number of electric motors | Parameters | Value | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 4 | Tractive power, kW | 168 | 192 | 204 | 208 | 208 | 208 | 204 | 204 | 200 |
| | Efficiency, % | 75.9 | 87.2 | 93.1 | 93.9 | 94.0 | 93.6 | 93.0 | 92.2 | 91.3 |
| | Speed, km/h | 2.4 | 5.0 | 10.0 | 15.0 | 20.0 | 30.0 | 40.0 | 50.0 | 60.0 |
| | Traction force, kN | 246.0 | 135.6 | 71.5 | 48.9 | 36.7 | 24.4 | 18.0 | 14.4 | 11.7 |

**Table 5.** Continued

| Number of electric motors | Parameters | Value | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 6 | Tractive power, kW | 174 | 192 | 204 | 210 | 210 | 204 | 204 | 204 | 198 |
| | Efficiency, % | 79.0 | 86.0 | 92.9 | 93.5 | 93.4 | 92.7 | 91.7 | 90.6 | 89.2 |
| | Speed, km/h | 2.5 | 5.0 | 10.0 | 15.0 | 20.0 | 30.0 | 40.0 | 50.0 | 60.0 |
| | Traction force, kN | 246.0 | 134.5 | 71.5 | 49.3 | 36.7 | 23.9 | 18.0 | 14.4 | 11.6 |

**Source:** developed by the authors

**Table 6.** Design characteristics for 4DCP (supplied power 310 kW)

| Number of electric motors | Parameters | Value | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 4 | Tractive power, kW | 232 | 272 | 288 | 292 | 292 | 292 | 290 | 288 | 288 |
| | Efficiency, % | 74.9 | 87.3 | 93.0 | 94.1 | 94.3 | 94.1 | 93.7 | 93.2 | 92.5 |
| | Speed, km/h | 2.6 | 5.0 | 10.0 | 15.0 | 20.0 | 30.0 | 40.0 | 50.0 | 60.0 |
| | Traction force, kN | 310 | 190 | 100 | 68.5 | 51.5 | 34.0 | 25.7 | 20.3 | 16.9 |
| 6 | Tractive power, kW | 246 | 270 | 291 | 294 | 294 | 291 | 288 | 288 | 282 |
| | Efficiency, % | 80.0 | 87.1 | 93.1 | 93.8 | 93.9 | 93.5 | 92.8 | 92.0 | 91.0 |
| | Speed, km/h | 2.8 | 5.0 | 10.0 | 15.0 | 20.0 | 30.0 | 40.0 | 50.0 | 60.0 |
| | Traction force, kN | 310 | 190 | 100 | 69.1 | 51.9 | 34.5 | 25.4 | 20.3 | 16.6 |

**Source:** developed by the authors

**Table 7.** Design characteristics for 5DCP (supplied power 410 kW)

| Number of electric motors | Parameters | Value | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 4 | Tractive power, kW | 312 | 354 | 378 | 386 | 388 | 388 | 386 | 384 | 382 |
| | Efficiency, % | 76.1 | 86.4 | 92.3 | 94.2 | 94.5 | 94.4 | 94.2 | 93.8 | 93.3 |
| | Speed, km/h | 3.0 | 5.0 | 10.0 | 15.0 | 20.0 | 30.0 | 40.0 | 50.0 | 60.0 |
| | Traction force, kN | 360 | 249 | 131.8 | 91.2 | 67.7 | 45.5 | 34.2 | 27.1 | 22.9 |
| 6 | Tractive power, kW | 330 | 357 | 381 | 384 | 384 | 384 | 381 | 378 | 375 |
| | Efficiency, % | 80.5 | 87.4 | 93.1 | 93.7 | 93.8 | 94.0 | 93.5 | 92.9 | 92.2 |
| | Speed, km/h | 3.2 | 5.0 | 10.0 | 15.0 | 20.0 | 30.0 | 40.0 | 50.0 | 60.0 |
| | Traction force, kN | 360 | 250 | 133 | 90.5 | 67.7 | 45.0 | 33.8 | 26.6 | 21.8 |

**Source:** developed by the authors

**Table 8.** Design characteristics for 6DCP (supplied power 530 kW)

| Number of electric motors | Parameters | Value | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 4 | Tractive power, kW | 436 | 452 | 492 | 500 | 500 | 506 | 504 | 504 | 500 |
| | Efficiency, % | 82.3 | 84.3 | 92.5 | 93.6 | 93.8 | 94.8 | 94.6 | 94.4 | 94.0 |
| | Speed, km/h | 4.3 | 5.0 | 10.0 | 15.0 | 20.0 | 30.0 | 40.0 | 50.0 | 60.0 |
| | Traction force, kN | 360 | 319 | 173.5 | 117.4 | 88.2 | 59.5 | 44.3 | 34.7 | 29.4 |
| 6 | Tractive power, kW | 441 | 459 | 489 | 498 | 498 | 498 | 498 | 498 | 498 |
| | Efficiency, % | 84.7 | 87.0 | 92.6 | 94.0 | 94.5 | 94.4 | 94.0 | 93.6 | 93.0 |
| | Speed, km/h | 4.3 | 5.0 | 10.0 | 15.0 | 20.0 | 30.0 | 40.0 | 50.0 | 60.0 |
| | Traction force, kN | 360 | 320 | 172.4 | 116.9 | 87.5 | 58.4 | 43.9 | 34.7 | 28.9 |

**Source:** developed by the authors

**Table 9.** Design characteristics for 7DCP (supplied power 720 kW)

| Number of electric motors | Parameters | Value | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 6 | Tractive power, kW | 642 | 666 | 678 | 681 | 678 | 678 | 678 | 672 |
| | Efficiency, % | 88.6 | 92.5 | 94.3 | 94.7 | 94.7 | 94.5 | 94.2 | 93.8 |
| | Speed, km/h | 6.2 | 10.0 | 15.0 | 20.0 | 30.0 | 40.0 | 50.0 | 60.0 |
| | Traction force, kN | 360 | 234.2 | 159.2 | 119.0 | 79.5 | 59.7 | 47.4 | 39.1 |

**Source:** developed by the authors

**Table 10.** Design characteristics for 8DCP (supplied power 880 kW)

| Number of electric motors | Parameters | Value | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 6 | Tractive power, kW | 738 | 810 | 831 | 834 | 834 | 834 | 831 | 810 |
| | Efficiency, % | 89.7 | 91.9 | 94.3 | 94.6 | 94.7 | 94.5 | 94.2 | 93.9 |
| | Speed, km/h | 7.3 | 10.0 | 15.0 | 20.0 | 30.0 | 40.0 | 50.0 | 60.0 |
| | Traction force, kN | 360 | 289.3 | 197.5 | 147.7 | 98.6 | 74.1 | 58.7 | 48.7 |

**Source:** developed by the authors

Analysis of the data in Table 3-8 shows that at speeds above 10 km/h, the efficiency of the traction electric drive with six and four traction induction electric motors does not differ significantly. At higher speeds, the four-motor electric drive has higher efficiency. This is explained by lower magnetic losses in the electric motors. However, when working with high traction forces, the six-motor electric drive has higher efficiency. This is explained by the fact that the electric motors operate with lower current, which causes lower electrical losses. It is worth noting that the proposed wheelset unit and traction induction motor provide traction properties of the serial diesel locomotive ChME3 when using a traction electric drive with four electric motors. However, to achieve high starting traction force, it is necessary to increase the axial load. In the case of using a six-motor traction electric drive, the locomotive can achieve a traction force of 450...540 kN, depending on the axial load.

A common way to increase the traction and energy performance of shunting locomotives is to use unit modules: separate sections of locomotives equipped with a traction electric drive and, as a rule, a power plan. A. Falendysh & V. Gatchenko (2013) investigate the use of shunting locomotives as a system comprising multiple traction units. This allows for increased traction and reduced fuel consumption. Similar traction units are used for heavy shunting work, on complex profiles, and hilly work. Serial locomotives are used for medium and light shunting work. This approach involves increasing the locomotive fleet, which requires significant capital expenditures. However, as demonstrated by C. Bulucea *et al.* (2016), such traction units exhibit low electric drive efficiency under partial load conditions. To eliminate this, it is proposed and justified the feasibility of disconnecting traction electric motors when operating in partial load modes. However, it is worth noting that the use of traction commutator electric motors limits the possibilities for improving traction and energy indicators. Commutator electric motors have insufficiently high specific torque indicators, and the presence of a commutator-brush apparatus reduces reliability. In addition, for high-quality control of traction electric motors, it is necessary to use semiconductor converters, as a result of which capital costs for modernisation increase. Therefore, to ensure high traction performance and energy efficiency, it is necessary to use an electric drive system based on AC motors. This conclusion is supported by studies S. de Pancorbo *et al.* (2015), C. Bulucea *et al.* (2016), Y. Cho *et al.* (2021). Studies by A. Abouzeid *et al.* (2020) and S. Semenov *et al.* (2025) show that the use of AC electric motors enables effective control, achieving maximum torque under specified conditions of wheel-rail adhesion.

A. Abouzeid *et al.* (2020) and W. Jibin *et al.* (2022) note that, the most common type of traction motor used in modern rolling stock, particularly in new shunting locomotives, is the induction motor This is due to their high specific indicators, which allows to achieve a traction force of one axle of 70…80 kN. Also important is the reduction of maintenance and high reliability of traction induction electric motors. In addition, traction induction electric motors have higher energy efficiency indicators compared to collector electric motors. N. Zhao & N. Schofield (2016) demonstrated that optimal performance of the wheel-motor unit can be achieved through the co-design of its main components – the traction gearbox and the traction induction motor. Ensuring high energy performance of the traction electric drive is achieved not only by its optimal design, but also by using rational control algorithms. S. Wang *et al.* (2019) proved that the use of vector control algorithms in an induction motor increases its energy efficiency and improves its dynamic performance, which is important when applying traction forces at the slip threshold. Despite the large number of rolling stock units equipped with induction traction motors, specific studies are required to assess the feasibility of their use under the specific operating conditions of a locomotive. This explains the relevance of this study.

In order to compare the energy efficiency of the proposed induction traction electric drive with that of the standard electric drive of the ChME3 diesel locomotive, calculations were carried out for the standard electric drive of the ChME3 diesel locomotive. Both six-motor and four-motor electric drives were considered. The results of studies obtained in V. Shayda *et al.* (2024), Y. Lysenko & Y. Riabov (2025) were used to calculate the data for the standard electric drive. As a criterion for comparison, the tangential power at a fixed power supplied to the traction electric drive was chosen. Figures 2-9 show the dependence of the tractive power on the speed of movement for all positions of the driver's controller for both variants of the electric drive. The data on the traction induction electric drive correspond to Tables 4-10.

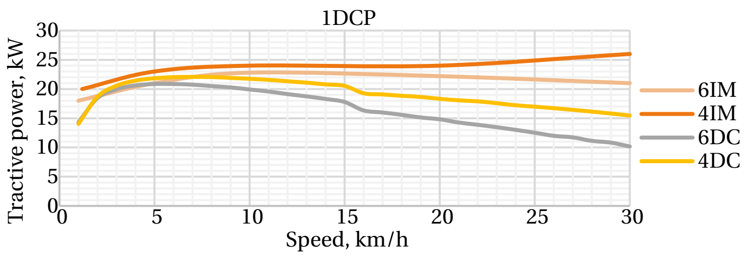


**Figure 2.** Dependence of tractive power on speed at 1DCP

**Note:** 6IM – traction electric drive with six induction electric motors; 4IM – traction electric drive with four induction electric motors; 6DC – serial electric drive with six direct current electric motors TE006; 4DC – traction electric drive with four direct current electric motors TE006

**Source:** developed by the authors

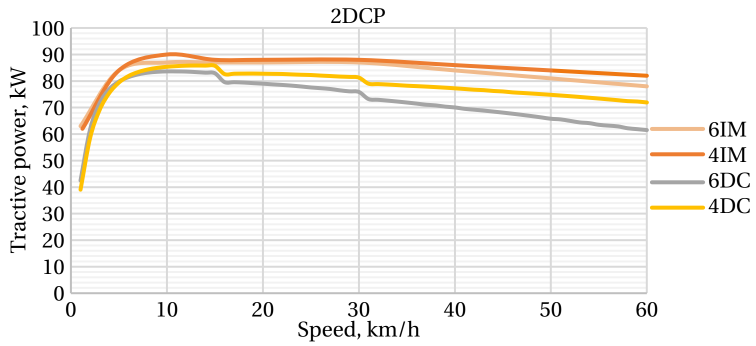


**Figure 3.** Dependence of tractive power on speed at the second position of the driver's controller

**Note:** 6IM – traction electric drive with six induction electric motors; 4IM – traction electric drive with four induction electric motors; 6DC – serial electric drive with six direct current electric motors TE006; 4DC – traction electric drive with four direct current electric motors TE006

**Source:** developed by the authors

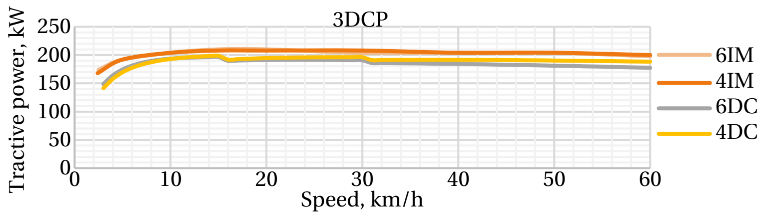


**Figure 4.** Dependence of tractive power on speed at the third position of the driver's controller

**Note:** 6IM – traction electric drive with six induction electric motors; 4IM – traction electric drive with four induction electric motors; 6DC – serial electric drive with six direct current electric motors TE006; 4DC – traction electric drive with four direct current electric motors TE006

**Source:** developed by the authors

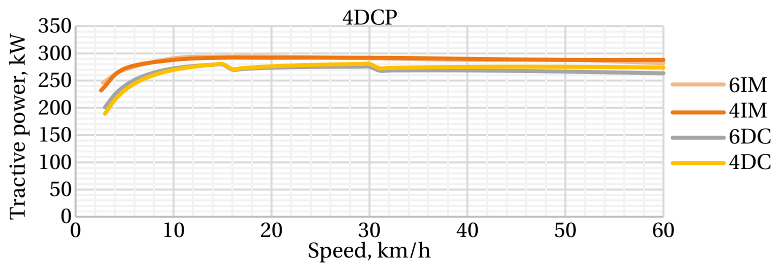


**Figure 5.** Dependence of tractive power on speed at the fourth position of the driver's controller

**Note:** 6IM – traction electric drive with six induction electric motors; 4IM – traction electric drive with four induction electric motors; 6DC – serial electric drive with six direct current electric motors TE006; 4DC – traction electric drive with four direct current electric motors TE006

**Source:** developed by the authors

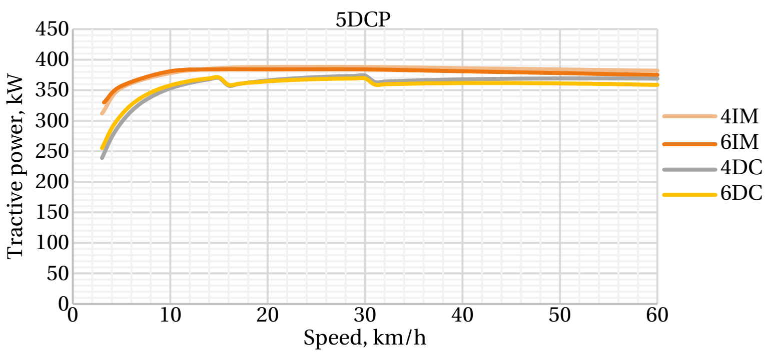


**Figure 6.** Dependence of tractive power on speed at the fifth position of the driver's controller

**Note:** 6IM – traction electric drive with six induction electric motors; 4IM – traction electric drive with four induction electric motors; 6DC – serial electric drive with six direct current electric motors TE006; 4DC – traction electric drive with four direct current electric motors TE006

**Source:** developed by the authors

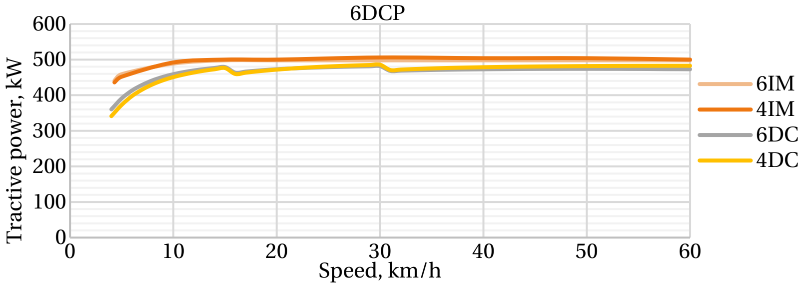


**Figure 7.** Dependence of tractive power on speed at the sixth position of the driver's controller

**Note:** 6IM – traction electric drive with six induction electric motors; 4IM – traction electric drive with four induction electric motors; 6DC – serial electric drive with six direct current electric motors TE006; 4DC – traction electric drive with four direct current electric motors TE006

**Source:** developed by the authors

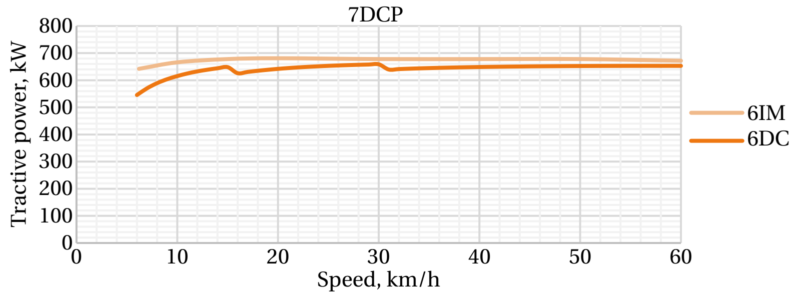


**Figure 8.** Dependence of tractive power on speed at the seventh position of the driver's controller

**Note:** 6IM – traction electric drive with six induction electric motors; 4IM – traction electric drive with four induction electric motors; 6DC – serial electric drive with six direct current electric motors TE006; 4DC – traction electric drive with four direct current electric motors TE006

**Source:** developed by the authors

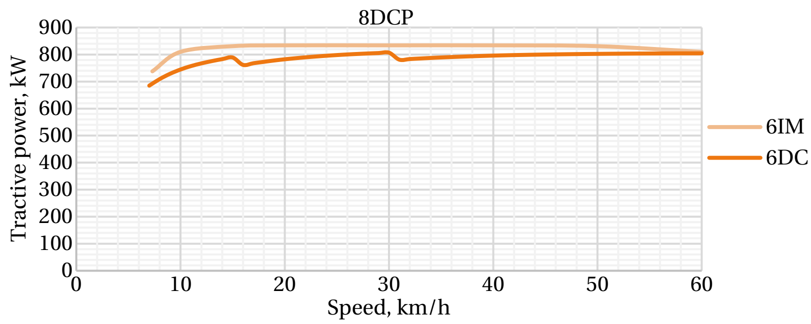


**Figure 9.** Dependence of tractive power on speed at the eighth position of the driver's controller

**Note:** 6IM – traction electric drive with six induction electric motors; 4IM – traction electric drive with four induction electric motors; 6DC – serial electric drive with six direct current electric motors TE006; 4DC – traction electric drive with four direct current electric motors TE006

**Source:** developed by the authors

Analysis of the dependencies shown in Figures 2-9 shows that the traction induction drive provides higher values of tractive traction force at all positions of the driver's controller. A certain exception is the first position, where the six-motor induction electric drive at low speeds has slightly lower performance than the serial traction collector electric drive. At higher positions of the driver's controller, consistently higher values of tangential power are observed in the case of using induction electric motors. In the zone of high traction forces, the increase in tractive force reaches 25% at higher positions of the driver's controller. With increasing speed, the magnitude of tractive force when using induction electric motors is higher by 5-10%. In summary, the results obtained indicate that the use of induction electric traction drives in shunting and transport locomotives will improve their traction and energy efficiency characteristics. According to studies S. Buryakovskiy *et al.* (2019), S. Buryakovskiy *et al.* (2020), S. Goolak *et al.* (2024) this has a positive impact on the parameters and indicators characterising the operation of shunting locomotives, increases the intensity of auxiliary operations at railway stations, and contributes to the stability of the railway transport system as a whole.

## Conclusions

Updating the rolling stock used for shunting operations is a pressing task that involves choosing technical solutions to ensure high traction and energy characteristics and performance of locomotives. The article considers the use of a traction induction electric drive based on induction electric motors. The use of a three-phase eight-pole induction electric motor with a squirrel-cage winding with a capacity of 140 kW and a wheel-motor unit using this electric motor are proposed. A mathematical model has been developed and calculations of the characteristics of the traction electric drive with the proposed electric motor have been carried out. Variants of a six- and four-motor electric drive have been considered. According to the results of the calculations, it has been determined that the energy indicators of both variants of the electric drive are practically the same. It has been determined that a four-motor induction electric drive provides the traction characteristics of a serial six-axle shunting locomotive. A six-motor traction induction electric drive is recommended for a significant increase in traction performance.

A comparison of the traction and energy indicators of the induction electric drive and the serial electric drive of the ChME3 diesel locomotive equipped with collector electric motors was made. It was determined that in the zone of high traction efforts, the tangential traction force of the induction electric drive is higher by 25% and more percent than the traction force of the collector at the same supplied power. With increasing speed, the magnitude of the tractive traction force when using induction electric motors is higher by 5-10% than the traction force of the collector at the same supplied power. The obtained results confirm that the use of a traction induction electric drive substantially improves the traction and energy characteristics of shunting locomotives. This advancement positively impacts the performance of shunting and removal operations. At the same time, the study highlights important directions for future research, including full-scale experimental verification, development of advanced vector control systems, and detailed evaluation of the economic efficiency and reliability of induction-based modernisation projects.

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## Conflict of Interest

None.

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# Дослідження енергетичної ефективності тягового асинхронного електропривода маневрового локомотива

**Євген Рябов**
Доцент
Національний технічний університет «Харківський політехнічний інститут»
61002, вул. Кирпичова, 2, м. Харків, Україна
https://orcid.org/0000-0003-0753-514X

**Євген Лисенко**
Аспірант
Національний технічний університет «Харківський політехнічний інститут»
61002, вул. Кирпичова, 2, м. Харків, Україна
https://orcid.org/0009-0007-1263-7446

**Багіш Єріцян**
Доцент
Національний технічний університет «Харківський політехнічний інститут»
61002, вул. Кирпичова, 2, м. Харків, Україна
https://orcid.org/0000-0003-0579-3882

**Ірина Білоконь**
Директор
Кременчуцький фаховий коледж транспортної інфраструктури та технологій
39600, вул. Юрія Руфа,14, м. Кременчук, Україна
https://orcid.org/0000-0002-4675-3994

**Антон Жуков**
Незалежний дослідник
ТОВ «Харківський електро-машинобудівний завод»
61037, пр. Героїв Харкова, 199, м. Харків, Україна
https://orcid.org/0009-0001-5229-1685

**Анотація.** Модернізація парку локомотивів, які використовуються на залізницях України для виконання маневрової роботи, є вкрай важливою для підвищення надійності залізничного транспорту, зниження паливно-енергетичних витрат і мінімізації негативного впливу на навколишнє середовище. Метою цієї роботи було дослідження енергетичної ефективності асинхронного тягового привода маневрового локомотива, яка впливає на його тягові та енергетичні показники. Об'єктом дослідження було обрано маневровий тепловоз ЧМЕ3, для якого за допомогою математичного моделювання визначено показники енергетичної ефективності тягового привода з асинхронними електродвигунами потужністю 140 кВт. Результати розрахунків показали, що на тепловозі ЧМЕ3 може бути застосований асинхронний тяговий привод із чотирма або шістьма електродвигунами. Для обох варіантів виконано розрахунки дотичної потужності на різних позиціях контролера машиніста та встановлено, що обидва варіанти демонструють високі енергетичні показники. Водночас шестимоторний тяговий асинхронний електропривод забезпечив збільшення дотичної сили тяги порівняно з тяговим електроприводом із колекторними двигунами. Проведено порівняння коефіцієнта корисної дії (ККД) тягового асинхронного електропривода та стандартного електропривода з колекторними двигунами. Визначено, що ККД тягового асинхронного привода є вищим у всьому діапазоні навантажень, що підтверджує доцільність використання тягового асинхронного електропривода на маневрових локомотивах. Результати цього дослідження можуть бути використані при розробці нових маневрових локомотивів та модернізації існуючих на вітчизняних і зарубіжних підприємствах

**Ключові слова:** енергетична ефективність; енерго- та ресурсозбереження; асинхронний електродвигун; потужність; рухомий склад