Comparative Analysis of Energy Performance of Induction Single-Motor and Multi-Motor Traction Electric Drive

Conference Paper · September 2021

DOI: 10.1109/KhPIWeek53812.2021.9570063

3 authors, including:

Vladimir Vodichev
Odessa National Polytechnic University
9 PUBLICATIONS **6** CITATIONS
SEE PROFILE

Alexander Kalinin
National Academy of Sciences of Ukraine
3 PUBLICATIONS **2** CITATIONS
SEE PROFILE

Comparative analysis of energy performance of induction single-motor and multi-motor traction electric drive

Vladimir Voytenko
Institute of Electromechanics and Energy Management
Odessa Polytechnic State University
Odessa, Ukraine
elektrik.wa@gmail.com

Alexandre Kalinin
Institute of Electromechanics and Energy Management
Odessa Polytechnic State University
Odessa, Ukraine
agk@opu.ua

Vladimir Vodichev
Institute of Electromechanics and Energy Management
Odessa Polytechnic State University
Odessa, Ukraine
vavodichev@ gmail.com

***Abstract* – The aim of the work is to carry out a comparative analysis of the energy indicators of induction single-motor and multi-motor traction electric drive based on the assessment of energy losses in traction induction electric motors of different power when using frequency control, which ensures the speed regulation of traction induction electric motors with constant magnetic flux. As a result of the analysis, a formula was obtained that allows to determine the number of low-power motors that are part of a multi-motor electric drive, in which the energy effect will be provided from the use of a multi-motor electric drive instead of a single motor electric drive.**

***Keywords* – induction motor, vehicle, power, energy losses, single-motor and multi-motor drive, voltage frequency, voltage amplitude.**

I. INTRODUCTION

In vehicles with an autonomous energy source, it is important to minimize energy losses in the motors of the traction electric drive, since this allows you to increase the vehicle's mileage without additional recharging of the autonomous energy source. Comparison of the overall energy efficiency for internal combustion engine vehicles and electric vehicles was carried out in [1]. If renewable energy is used, the overall efficiency for electric cars will be around 40–70 % depending on the source and the location of the renewable energy systems. When the load of the multi-motor electric drive of the vehicle changes, in order to minimize the loss of electrical energy, it may be necessary to use a different number of traction motors that drive the driving wheels of the vehicle.

In modern vehicles, as a rule, synchronous motors with permanent magnet excitation or induction motors (IM) are used. IM are simpler in design, more reliable and cheaper [2]. Therefore, the article discusses an induction traction electric drive of urban public transport.

A significant number of publications have been devoted to methods for determining and reducing the power losses in IM. In [3], a mathematical model is proposed for the analysis of energy losses in the IM, which is connected to a frequency converter (FC). In [4, 5], methods of IM control were developed, which ensure the minimization of losses in the IM windings with vector control of the stator current and with direct torque control [6]. In [7], an analysis of the energy efficiency of IM was carried out when powered by sinusoidal and non-sinusoidal voltages.

In [8], the analysis of the influence of the fundamental and higher harmonics of voltage and current on losses in steel for motors of different power is carried out. The analysis of energy losses in the IM during voltage dips [93], and also the analysis of energy losses in various elements of the FC-IM system [10 - 14]. In [15] a simplified equivalent scheme is proposed, which takes into account additional energy losses from spatial harmonics. In work [16] the method of equivalent load was proposed to determine the losses in the IM. In [17], a new subway drive control scheme is proposed based on a linear IM with minimization of energy losses. A method has been developed for determining the optimal speed of movement of elevators with minimization of losses in the IM [18].

A mathematical description of the operating modes in which it is possible to reduce losses in the IM when powered from a thyristor voltage converter is carried out in [19].

In the literature, there is no study of electrical energy losses in single- motor and multi- motor induction electric drives in steady-state and transient operating modes. This makes it difficult to choose a single-motor or multi-motor electric drive intended for a vehicle, in terms of energy indicators.

II. RESEARCH OBJECTIVES

The aim of the work is to carry out a comparative analysis of the energy indicators of a single-motor and multi-motor induction traction electric drive based on the assessment of energy losses in induction electric motors of different power when using frequency control, which provides control of the speed of traction induction electric motors with a constant magnetic flux value.

This article provides a comparative analysis of the energy performance of a single-motor and multi-motor induction traction electric drive designed to modify the «Bogdan» A-092 bus, which is equipped with an 89 kW diesel internal combustion engine (ICE). Therefore, when designing an electric bus based on the city bus «Bogdan» A-092, an induction motor with a power of 90 kW with a synchronous shaft speed of 1500 rpm was chosen as the base motor.

In accordance with the traffic rules in the city, the speed of the city bus should not exceed 50 km / h. In addition, a fully loaded bus must overcome an uphill slope of up to 20%. Taking these requirements into account, the resistance force was calculated for the movement of an empty and full auto-bus "Bogdan" A-092 on a horizontal road, as well as when a full bus moves up the road with a slope of 20%. When calculating the force of resistance to the movement of the bus, the rolling friction force of the wheels of the bus on the asphalt road, the rolling force, as well as the force of air resistance were taken into account. Taking into account the results obtained and the nominal parameters of the traction IM, the main parameters of a 3-stage gearbox were determined. The first stage of the gearbox is designed for a full bus to overcome an uphill of the road with a slope of up to 20% at a speed of up to 15 km / h, and the second stage of the gearbox is designed for a full bus to overcome an uphill road with a slope of up to 20% at a speed of up to 30 km / h, the third - for movement of a full bus on a horizontal road at a speed of up to 60 km / h. The reduced radius of the translational movement of the bus to the rotational movement of the IM shaft in the first gear of the gearbox is ρ_1 = 0.0278 m, for the second - ρ_2 = 0.0595 m, for the thirds - ρ_3 = 0.1 m.

Calculation of load diagrams showed that when a traction motor with a power of 45 kW, a fully loaded bus on a horizontal road can move for a long time in 3rd gear at a speed of 60 km / h. When using a traction motor with a power of 90 kW, a full bus can move for a long time in 1st gear up the road with a slope of 20% at a speed of 15 km / h, which corresponds to the technical parameters of the movement of the «Bogdan» bus with an internal combustion engine, and when a full bus moves by 2nd gear up on the road with a slope of 20% at a speed of 30 km / h, the traction motor with a power of 90 kW will be overloaded in power and torque by about 2 times. Table I shows the results of calculating the force of resistance to the movement of the bus «Bogdan» A-092.

When conducting a comparative analysis of the energy indicators of a single-motor and multi-motor induction traction electric drive for the electric modification of the «Bogdan» A-092 bus, two technical solutions were considered:

- a single-motor electric drive, which uses one 90 kW motor (which corresponds to the power of the internal combustion engine) and allows a full auto-bus on a road with a slope of 20% to move for a long time in 1st gear at a speed of 15 km / h;
- a multi-motor electric drive, in which several 45 kW motors are used (one 45 kW motor is enough for a full bus in 3rd gear to move for a long time on a horizontal road at a speed of 60 km / h);

The main technical parameters of induction motors are given in Table II.

A comparative analysis of the energy indicators of a single-motor and multi-motor traction electric drive at the nominal values of the amplitude and frequency of the voltage on the stator windings of the IM was carried out on the basis of the analysis of energy losses in IM of the 4A250M4 and 4A200L4 types with a power of 90 kW and 45 kW respectively.

Let us determine the power of energy losses in induction motors with a power of 90 kW and 45 kW on the basis of the technical parameters of IM 4A250M4 and 4A200L4 and on the basis of their equivalent circuit's parameters at a nominal voltage on their stator windings (380V, 50Hz).

TABLE I

RESULTS OF THE CALCULATION OF THE RESISTANCE FORCE TO THE MOVEMENT OF THE «BOGDAN» A-092 BUS

Bus traffic conditions	The total load torque on the shaft of the traction motor
The movement of an empty bus on a horizontal road at a speed of 60 km / h at ρ_3= 0.1 m	179.16 Nm
The movement of a full bus on a horizontal road at a speed of 60 km / h at ρ_3= 0.1 m	240.63 Nm
The movement of a full bus up the road with a slope of 20% at a speed of 15 km / h, with ρ_1= 0.0278m	540.60 Nm
The movement of a full bus up the road with a slope of 20% at a speed of 30 km / h, with ρ_2= 0.0595 m	1165.2 Nm

TABLE II

MAIN PARAMETERS OF INDUCTION MOTORS OF TYPE 4A250M4 AND 4A200L4

IM parameters	4A250M4	4A200L4
Rated mechanical power P_{2HOM}, kW	90	45
Efficiency at power P_2= P_{2HOM}, %	93	92
cos φ_H, at power P_2= P_{2HOM}	0,91	0,90
Rated angular speed of the shaft ω_H, rad / s	155.0	154.5
Rated mechanical torque $M_{AD.H}$, Nm	580.5	291.3
Critical torque on natural mechanical characteristic $M_{K.E}$, Nm	1335.8	728.2
Rated effective value of the phase current of the stator winding $I_{1F.H}$, A	161.1	82.3

The total power of energy losses in the IM for the nominal operating mode

$$\Delta P_H = P_{2H}\left(\frac{1}{\eta_H}-1\right), \qquad (1)$$

where P_{2H} – rated mechanical shaft power of the IM; η_H – rated IM efficiency.

For the nominal operating mode, the total power of energy losses in the rotor consists of losses in the active resistance of the rotor winding, losses in the rotor steel and mechanical losses in IM

$$\Delta P_{\Sigma.2.H} = M_{AD.H}\omega_{0H}s_H = M_{AD.H}\Delta\omega_H\ , \qquad (2)$$

where $M_{AD.H}$ – rated mechanical torque of the; ω_{0H} – synchronous angular speed of the IM shaft, which corresponds to the nominal value of the voltage frequency on the stator winding; s_H – nominal slip of the rotor relative to the rotating magnetic field; $\Delta\omega_H = \omega_{0H} s_H$ – absolute slip of the IM shaft relative to the rotating magnetic field, which corresponds to the nominal value of the mechanical torque of the motor.

If we neglect the energy losses in the rotor steel and the mechanical energy losses in the IM then we can take power losses in the active resistance of the rotor winding

$$\Delta P_{M.2.H} \cong \Delta P_{\Sigma.2.H} \ . \qquad (3)$$

On the basis of the L-shaped equivalent circuit of the IM at nominal slip, it can be assumed that the branch of the rotor winding has predominantly active resistance, and the magnetizing branch has predominantly inductive resistance. In this case, it can be assumed that the vector of the current flowing in the rotor winding coincides in phase with the vector of the voltage applied to the phase of the stator winding, and the magnetizing current vector lags by π / 2 el. radians from the voltage vector applied to the phase of the stator winding. Whence it follows that the magnetizing current vector lags behind the current vector flowing in the rotor winding by π / 2 el. radians. Therefore, the value of the magnetizing current for the nominal mode of IM can be determined by the formula

$$I_{0.H} = I_{1F.H} \sin\varphi_H = I_{1F.H}\sqrt{1-\cos^2\varphi_H} \ , \qquad (4)$$

where $I_{1F.H}$ – rated effective value of the phase current of the stator winding.

Power of energy losses in the active resistance of the stator winding from the magnetizing current for the nominal mode of operation of the IM

$$\Delta P_{M.1.0.H} = 3R_1 I_{0.H}^2 = 3R_1 I_{1F.H}^2 (1-\cos^2\varphi_H) \ . \qquad (5)$$

Power of energy losses in the stator winding from the current that flows in the rotor winding for the nominal operating mode of the IM

$$\Delta P_{M.1.H} = \Delta P_{M.2.H} \frac{R_1}{R_2'} \ , \qquad (6)$$

where R_1, R_2' – active resistances of the phases of the stator and rotor windings, reduced to the parameters of the stator winding, respectively.

The total power of energy losses in the active resistance of the stator winding and the rotor winding from the current that flows in the rotor winding for the nominal mode of operation of the IM

$$\Delta P_{M.1.H} + \Delta P_{M.2.H} = \Delta P_{M.2.H}\left(1+\frac{R_1}{R_2'}\right). \qquad (7)$$

We assume that the power of additional energy losses in the IM does not depend on the value of the load torque on the IM shaft and on the angular speed of the shaft

$$\Delta P_{DOB} = 0.005\frac{P_{2H}}{\eta_H} \ . \qquad (8)$$

Power of energy losses in IM steel for the nominal operating mode

$$\Delta P_{C.H} = \Delta P_H - (\Delta P_{M.1.H} + \Delta P_{\Sigma.2.H} + \Delta P_{M.1.0.H} + \Delta P_{DOB}) \ . \qquad (9)$$

III. MATERIALS AND RESEARCH RESULTS

The results of calculating the power of energy losses in an IM 4A250M4 and 4A200L4 for the nominal operating mode, carried out in accordance with the presented method, are shown in Table III.

Table III shows that when each of the 4A250M4 and 4A200L4 IMs operates in the nominal mode, the total power of energy losses in a 90 kW motor is 1.73 times higher than the total power of energy losses in a 45 kW motor. The power of energy losses in steel of a 90 kW motor is 2.34 times higher than the power of energy losses in steel of a 45 kW motor. The power of energy losses in the active resistance of the motor rotor winding of a 90 kW motor is 1.62 times higher than in the motor of a 45 kW. The total power of energy losses in the stator winding of a 90 kW motor is 1.36 times higher than the total power of energy losses in the stator winding of a 45 kW motor.

TABLE III

POWER CALCULATION RESULTS OF ENERGY LOSSES IN IM WITH A POWER OF 90 KW AND 45 KW FOR NOMINAL OPERATING MODE

IM type	4A250M4	4A200L4
Rated power, kW	90.0	45.0
Total rated power of energy losses, ΔP_H, W	6774.2	3913.0
Composition of energy losses in the IM		
Power of additional energy losses ΔP_{DOB}, W	483.9	244.6
Power of energy losses in IM steel for the nominal operating mode $\Delta P_{C.H}$, W	2631.1	1122.4
Rated power of energy losses in the active resistance of the rotor winding $\Delta P_{M.2.H}$, W	1185.4	731.7
Power components of energy losses in the stator winding		
Rated power of energy losses in the stator winding from the rotor current $\Delta P_{M.1.H}$, W	2034.6	1463.4
Rated power of energy losses in the stator winding from the magnetizing current $\Delta P_{M.1.0.H}$, W	439.2	350.9

Let us carry out a comparative analysis of the energy indicators of a single- motor and multi-motor traction electric drive at a nominal frequency and voltage amplitude on the stator winding when the load torque on the IM shaft changes.

With the loading torque of on the IM shaft, which satisfies the condition $0 \le M \le 0{,}7 M_{K.E}$, it is possible to represent the working section of the mechanical characteristics of the IM as a straight line. Then at the nominal value of the amplitude and frequency of the voltage on the stator winding, the power of energy losses in the active resistance of the rotor winding for whatever value of the IM torque

$$\Delta P_{M.2} = M_{AD}\omega_{0H} s = M_{AD}\Delta\omega \ , \qquad (10)$$

where M_{AD} – the current value of the torque developed by the motor; s – slip of the rotor relative to the rotating magnetic field, which corresponds to the current value of the torque developed by the IM; $\Delta\omega = \omega_{0H}\, s$ – absolute slip of the IM shaft relative to the rotating magnetic field, which corresponds to the current value of the motor torque.

If we assume that the rigidity of the working section of the mechanical characteristic does not change at a constant value of the frequency and amplitude of the voltage on the stator winding, then we can write

$$s = \frac{M_{AD}}{M_{AD.H}} s_H . \qquad (11)$$

After substituting the right-hand side of formula (11) into formula (10), we obtain

$$\Delta P_{M.2} = \frac{M_{AD}^2}{M_{AD.H}^2} M_{AD.H} \Delta\omega_H . \qquad (12)$$

Taking into account formulas (2) and (3), formula (12) takes the form

$$\Delta P_{M.2} = \frac{M_{AD}^2}{M_{AD.H}^2} \Delta P_{M.2.H} . \qquad (13)$$

With a constant nominal value of the frequency and amplitude of the voltage on the stator winding, according to the formulas (6) and (13), it is possible to determine the power of electrical energy losses in the active resistance of stator winding from the rotor current at the any IM torque

$$\Delta P_{M.1} = \frac{M_{AD}^2}{M_{AD.H}^2} \Delta P_{M.2.H} \frac{R_1}{R_2'} . \qquad (14)$$

When using the law of frequency control, which ensures the constancy of the value of the magnetizing current corresponding to formula (4), the power of energy losses in the active resistance of the stator winding from the magnetizing current at the current value of the torque developed by the IM will be constant and equal to

$$\Delta P_{M.1.0.H} = 3R_1 I_{0.H}^2 . \qquad (15)$$

The power of additional energy losses in the IM ΔP_{DOB} is considered constant in accordance with the formula (8).

With a constant nominal value of the frequency and amplitude of the voltage on the stator winding the power of energy losses in steel will be constant

$$\Delta P_C = \Delta P_{C.H} . \qquad (16)$$

With a constant value of the frequency and amplitude of the voltage on the stator winding of the IM constant energy losses, the power of which does not depend on the moment of load on the motor shaft, include energy losses in the stator steel, energy losses on the active resistance of the stator winding from the magnetizing current and additional energy losses. At constant values of the amplitude and frequency of the voltage on the stator winding, the power of constant energy losses does not change with a change in the load torque on the motor shaft

$$\Delta P_{CONST} = \Delta P_{C.H} + \Delta P_{M.1.0.H} + \Delta P_{DOB} . \qquad (17)$$

Variable losses include energy losses on the active resistance of the stator winding and on the active resistance of the rotor winding from the current flowing in the rotor winding. For a constant voltage value on the stator winding of the IM, the power of variable losses

$$\Delta P_{VARIA.} = \Delta P_{M.1} + \Delta P_{M.2} . \qquad (18)$$

Table IV shows the power of constant and variable energy losses for the nominal operation mode of the motors based on the data given in Table III.

In the nominal operating mode, the power of constant energy losses in a 90 kW motor is 2.07 times higher than the power of constant energy losses in a 45 kW motor. The power of variable energy losses in a 90 kW motor is 1.47 times higher than the power of variable energy losses in a 45 kW motor.

TABLE IV

POWER OF CONSTANT AND VARYABLE ENERGY LOOSES FOR NOMINAL OPERATING MODE OF THE IM

IM type	4A250M4	4A200L4
Power of constant energy losses $\Delta P_{H.CONST}$, W	3554,2	1717,9
Power of variable energy losses $\Delta P_{H.VARIA}$, W	3220,0	2195,1

From formula (18), taking into account formulas (13) and (14), it follows that the power of variable energy losses in the IM at the nominal value of the frequency and voltage amplitude on the stator winding and at an arbitrary value of the load torque on the IM shaft can be determined by the formula

$$\Delta P_{VARIA} = \Delta P_{H.VARIA} \left(\frac{M_{AD}}{M_{AD.H}} \right)^2 . \qquad (19)$$

where $P_{H.VARIA}$ – the total power of variable energy losses at the active resistances of the stator winding and the rotor winding from the current that flows in the rotor winding, for the nominal mode of operation of the IM.

$$\Delta P_{H.VARIA} = \Delta P_{M.2.H} \left(1 + \frac{R_1}{R_2'} \right) . \qquad (20)$$

To save energy when replacing one high-power (90 kW) motor with several lower-power (45 kW) motors, which operate at the same frequency and voltage amplitude on the stator winding, the condition must be met

$$\left(\Delta P_{VARIA.45} + \Delta P_{CONST.45} \right) N_{45} \le \left(\Delta P_{VARIA.90} + \Delta P_{CONST.90} \right) , \qquad (21)$$

where $\Delta P_{VARIA.45}$; $\Delta P_{CONST.45}$ – power of variable and constant energy losses in IM with a power of 45 kW; $\Delta P_{VARIA.90}$; $\Delta P_{CONST.90}$ – power of variable and constant energy losses in IM with a power of 90 kW ; N_{45} – number of IMs with a power of 45 kW, which are used instead of one IM with a power of 90 kW.

In particular, with a constant nominal value of the frequency and voltage amplitude on the stator winding in formula (21), instead of $\Delta P_{VARIA.45}$ and $\Delta P_{VARIA.90}$, we substitute the right side of formula (19), taking into account the number of used motors with a power of 45 kW and a power of 90 kW. As a result, we get

$$\left(\Delta P_{H.VARIA.45} \left(\frac{M_{AD.\Sigma}}{N_{45} M_{AD.H.45}} \right)^2 + \Delta P_{CONST.45} \right) N_{45} \le$$

$$\le \left(\Delta P_{H.VARIA.90} \left(\frac{M_{AD.\Sigma}}{M_{AD.H.90}} \right)^2 + \Delta P_{CONST.90} \right) , \qquad (22)$$

where $M_{AD.H.45}$, $M_{AD.H.90}$ – respectively, the nominal value of the moment of one IM with a power of 45 kW and the nominal value of the moment of one IM with a power of 90 kW; $M_{AD.\Sigma}$ – the total torque developed by all motors that are part of the traction electric drive.

After transformations of formula (22), we obtain

$$N_{45}^2 \Delta P_{CONST.45} - N_{45} \left(\Delta P_{H.VARIA.90} \left(\frac{M_{AD.\Sigma}}{M_{AD.H.90}} \right)^2 + \Delta P_{CONST.90} \right) +$$

$$+ \Delta P_{H.VARIA.45} \left(\frac{M_{AD.\Sigma}}{M_{AD.H.45}} \right)^2 \le 0 . \qquad (23)$$

Inequality (23) can be reduced to the form

$$aN_{45}^2 - bN_{45} + c \le 0\,, \qquad (24)$$

where *a*, *b*, *c* – positive coefficients of the 2nd order polynomial.

$$a = \Delta P_{CONST.45}; \qquad (25)$$

$$b = \left(\Delta P_{H.VARIA.90} \left(\frac{M_{AD.\Sigma}}{M_{AD.H.90}} \right)^2 + \Delta P_{CONST.90} \right); \qquad (26)$$

$$c = \Delta P_{H.VARIA.45} \left(\frac{M_{AD.\Sigma}}{M_{AD.H.45}} \right)^2. \qquad (27)$$

Solving inequality (24), we obtain

$$N_{45.\min} \le N_{45} \le N_{45.\max}\,. \qquad (28)$$

where

$$N_{45.\min} = \frac{b - \sqrt{b^2 - 4ac}}{2a}; \qquad (29)$$

$$N_{45.\max} = \frac{b + \sqrt{b^2 - 4ac}}{2a}. \qquad (30)$$

In the domain of real numbers, inequality (24) has a solution under the condition

$$b^2 - 4ac \ge 0\,. \qquad (31)$$

If condition (31) is not met, then the use of several motors of lower power instead of one high-power IM at a given load torque ($M_{AD.\Sigma}$) will not lead to a positive energy effect.

The left side of inequality (21) determines the total power of energy losses in several 45 kW motors, which are part of a multi-motor electric drive, and the right side of inequality (21) determines the total power loss of energy in a 90 kW motor, which is included in composition of a single- motor electric drive. Therefore, in the general case, you can write an expression that determines the energy effect from the use of a multi-motor electric drive as difference between the total power of energy losses in several 45 kW motors and the total power of energy losses in one motor with a power of 90 kW at a given load torque ($M_{AD.\Sigma}$). In the case under consideration, this formula has the form

$$\Delta P_\Sigma = \left(\Delta P_{VARIA.45} + \Delta P_{CONST.45} \right) N_{45} - \\ - \left(\Delta P_{VARIA.90} + \Delta P_{CONST.90} \right), \qquad (32)$$

Expression (32) can be rewritten taking into account formula (22) in the form

$$\Delta P_\Sigma = \left(\Delta P_{H.VARIA.45} \left(\frac{M_{AD.\Sigma}}{N_{45} M_{AD.H.45}} \right)^2 + \Delta P_{CONST.45} \right) N_{45} - . \\ - \left(\Delta P_{H.VARIA.90} \left(\frac{M_{AD.\Sigma}}{M_{AD.H.90}} \right)^2 + \Delta P_{CONST.90} \right). \qquad (33)$$

Expression (33) makes it possible to estimate the dependence of the energy effect on the total load torque on the motor shaft when using a multi-motor electric drive when using a different number of electric motors. In accordance with expression (33), a negative value ΔP_Σ corresponds to a decrease in the power of energy losses in a multi-motor electric drive in comparison with the power of energy losses in a single-motor electric drive.

Fig. 1 shows the graphs of the dependence of the energy effect $\Delta P_\Sigma = f(M_{AD.\Sigma})$ on the total load torque of the traction electric drive of the bus when using a multi-motor electric drive with a different number of 45 kW motors. The graph number corresponds to the number of 45 kW motors used in a multi-motor electric drive.

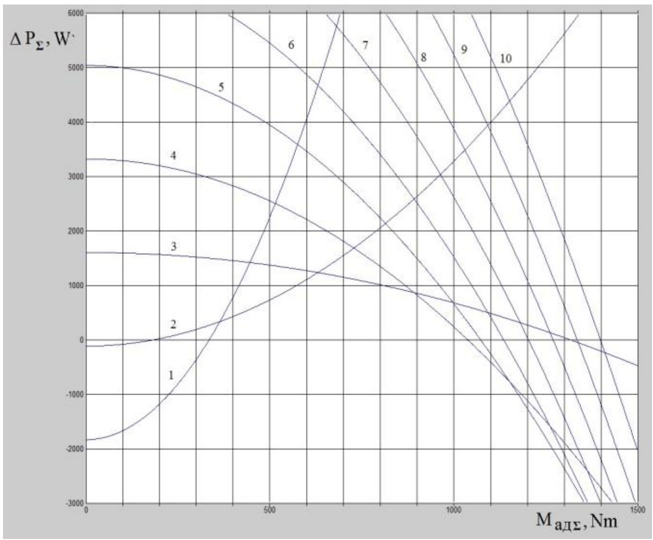

Fig.1. Graphs of the dependence of the energy effect on the total load torque on the motor shaft when using a multi-motor electric drive with 45 kW motors instead of one 90 kW motor

In fig. 1 it can be seen that when using a multi-motor electric drive with 45 kW motors instead of one 90 kW motor, the energy effect takes place at a small value of the total load torque ($M_{AD.\Sigma}$) and at its large value. With a small value of the total load torque, the energy effect takes place with a small number of 45 kW motors used. This is due to the fact that with a small $M_{AD.\Sigma}$ the power of variable energy losses in motors with a power of 45 kW and 90 kW is much less than the power of constant energy losses. Therefore, the energy effect is obtained due to the fact that the power of constant energy losses in a 90 kW motor is more than 2 times higher than the power of constant energy losses in a 45 kW motor (Table IV). Therefore, the use of one or two 45 kW motors instead of one 90 kW motor at a low load torque gives an energy effect that is approximately equal to the difference between the power of constant energy losses in a 90 kW motor and in one or two 45 kW motors.

With a large value of the total load torque the energy effect takes place with a large number of low-power motors used. As follows from Fig. 1, for motors with a power of 45 kW, in order to obtain an energy effect with a large value of the total load torque, the number of motors should be at least 3. This is due to the fact that with a large value of the total load torque, this torque is distributed equally between several motors of lower power, which leads to reducing of the load torque on the shaft of each motor. As a result, the total power of variable energy losses in motors with a power of 45 kW becomes less than the power of variable energy losses in a motor with a power of 90 kW. The total power of constant and variable energy losses in several 45 kW motors becomes less than the total power of constant and variable energy losses in one 90 kW motor.

The total load torque on the IM shaft when an empty bus moves on a horizontal road in third gear at a speed of 60 km / h is 179.16 Nm (Table I). Since the nominal torque of the 45 kW motor is 291.3 Nm (Table II), the movement of an empty bus on a horizontal road at a speed of 60 km / h can be ensured with a single 45 kW motor. In this case, the power of energy losses relative to a 90 kW motor will decrease by about 1200 W (graph 1 in Fig. 1).

The total load torque on the IM shaft when a full bus moves on a horizontal road in third gear at a speed of 60 km / h is 240.63 Nm (Table I). Since the nominal torque of the 45 kW motor is 291.3 Nm (Table II), the movement of a full bus on a horizontal road at a speed of 60 km / h can be ensured with a single 45 kW motor. In this case, the power of energy losses relative to a 90 kW motor will decrease by about 800 W (graph 1 in Fig. 1).

The total load torque on the IM shaft when a full bus moves up the road with a slope of 20% when using the first mechanical gear with a maximum speed of 15 km / h is 540.596 Nm (Table 1). Since the nominal torque of the 45 kW motor is 291.3 Nm (Table 2), the movement of a full bus up the road with a slope of 20% at a speed of 15 km / h in first gear can also be provided with the help of two 45 kW. In this case, the power of energy losses relative to a 90 kW motor will increase by about 800 W (graph 2 in Fig. 1).

The total load torque on the IM shaft when a full bus moves up the road with a slope of 20% when using the second mechanical gear with a maximum speed of 30 km / h is 1165.2 Nm (Table 1). Since the total rated torque of four 45 kW motors is 1165.2 Nm (Table 2), the movement of a full bus up the road with a slope of 20% at a speed of 30 km / h in second gear can also be ensured with the help of four 45 kW. In this case, the total power of energy losses relative to a 90 kW motor will decrease by about 830 W (graph 4 in Fig. 1).

IV. CONCLUSION

1. As a result of the analysis of the energy indicators of a single-motor and multi-motor induction traction electric drive, the formula (23) was obtained, which makes it possible to determine the number of low-power motors, which will provide the energy effect from the use of a multi-motor electric drive instead of single-motor electric drive.

2. Condition (31) was formulated in violation of which the use of several motors of lower power instead of one IM of high power at a given load torque will not lead to a positive energy effect.

3. Based on formula (33), it is possible to build graphs of the dependence of the energy effect on the total load torque of the traction electric drive when using a multi-motor electric drive with a different number of low-power motors.

4. The resulting formula (33) can be used to assess the energy effect from the use of a multi-motor electric drive instead of a single-motor electric drive at other constant values of the frequency and amplitude of the voltage on the stator winding of the IM, which correspond to other values of the angular speed of the traction induction motors.

REFERENCES

[1] Aiman Albatayneh, Mohammad N. Assaf, Dariusz Alterman, Mustafa Jaradat Comparison of the Overall Energy Efficiency for Internal Combustion Engine Vehicles and Electric Vehicles/ Environmental and Climate Technologies, 2020, vol. 24, no. 1, pp. 669–680. https://doi.org/10.2478/rtuect-2020-0041.

[2] Voytenko V.A. Trebovania k parametram asinkhronnogo tyagovogo dvigatelya elektromobilya [Requirements for the parameters of asynchronous traction motor of electric vehicle]. Elektrotekhnicheskie i komp’uternie sistemy, 2014, no. 15(91). – pp. 129 – 131. (In Russian).

[3] Lassi Aarniovuori, Lasse I. E. Laurila, Markku Niemela, Juha J. Pyrhonen Measurements and Simulations of DTC Voltage Source Converter and Induction Motor Losses. IEEE Transactions on Industrial Electronics, 2012, vol. 59, no. 5, pp. 2277 – 2287. doi: 10.1109/TIE.2011.2161061

[4] Antonio T. Alexandridis, George C. Konstantopoulos, Qing-Chang Zhong Advanced Integrated Modeling and Analysis for Adjustable Speed Drives of Induction Motors Operating With Minimum Losses. IEEE Transactions on Energy Conversion, 2015, vol. 30, no 3, pp. 1237 – 1246. doi: 10.1109/TEC.2015.2392256

[5] S. Lim, K. Nam Loss-minimising control scheme for induction motors. IEE Proceedings - Electric Power Applications, 2004, vol. 151, no. 4, pp. 385 – 397. doi: 10.1049/ip-epa:20040384

[6] Ali M. Bazzi, Veysel T. Buyukdegirmenci, Philip T. Krein System-Level Power Loss Sensitivity to Various Control Variables in Vector-Controlled Induction Motor Drives. IEEE Transactions on Industry Applications, 2013, vol. 49, no. 3, pp. 1367 – 1373. doi: 10.1109/TIA.2013.2252320

[7] Lassi Aarniovuori, Paavo Rasilo, Markku Niemelä, Juha J. Pyrhönen Analysis of 37-kW Converter-Fed Induction Motor Losses. IEEE Transactions on Industrial Electronics, 2016, vol. 63, no. 9, pp. 5357 – 5365. doi:10.1109/TIE.2016.2555278

[8] Katsumi Yamazaki, Akihiro Suzuki, Motomichi Ohto, Teruyuki Takakura Harmonic Loss and Torque Analysis of High-Speed Induction Motors. IEEE Transactions on Industry Applications, 2012, vol. 48, no. 3, pp. 933 – 941. doi:10.1109/TIA.2012.2191252

[9] Vijaya Huchche; Nita Patne; Anjali Junghare Computation of Energy Loss in an Induction Motor During Unsymmetrical Voltage Sags—A Graphical Method. IEEE Transactions on Industrial Informatics, 2018, volume 14, no. 5, pp.2023 – 2030 doi: 10.1109/TII.2017.2763606

[10] M. Nasir Uddin ; Sang Woo Nam New Online Loss-Minimization-Based Control of an Induction Motor Drive. IEEE Transactions on Power Electronics, 2008, vol. 23, no. 2, pp. 926 – 933. doi: 10.1109/TPEL.2007.915029

[11] Patrick W. Wheeler, Jon C. Clare, Maurice Apap, Keith J. Bradley Harmonic Loss Due to Operation of Induction Machines From Matrix Converters. IEEE Transactions on Industrial Electronics, 2008, vol. 55,no. 2, pp. 809 – 816,doi: 10.1109/TIE.2007.910527

[12] J.R. Espinoza; G. Joos A current-sourceinverter-fed induction motor drive system with reduced losses, IEEE Transactions on Industry Applications, 1998, vol. 34, no 4, pp. 796 – 805.doi: 10.1109/28.703977

[13] Osama S. Ebrahim; Mohamed A. Badr; Ali S. Elgendy; Praveen K. Jain ANN-Based Optimal Energy Control of Induction Motor Drive in Pumping Applications. IEEE Transactions on Energy Conversion, 2010, vol. 25, no. 3, pp. 652 – 660. doi: 10.1109/TEC.2010.2041352

[14] Yunxiang Wu; Mohsin A. Shafi; Andrew M. PROBLEMELE ENERGETICII REGIONALE N (NN) AAAA12Knight; Richard A. McMahon Comparison of the Effects of Continuous and Discontinuous PWM Schemes on Power Losses of VoltageSourced Inverters for Induction Motor Drives. IEEE Transactions on Power Electronics, 2011, vol. 26, no. 1, pp. 182 – 191. doi: 10.1109/TPEL.2010.2054837

[15] Aldo Boglietti, Andrea Cavagnino, Luca Ferraris, Mario Lazzari Induction Motor Equivalent Circuit Including the Stray Load Losses in the Machine Power Balance. IEEE Transactions on Energy Conversion, 2008, vol. 23, no. 3, pp. 796 –803. doi: 10.1109/TEC.2008.921467

[16] A. Mihalcea, B. Szabados, J. Hoolboom Determining total losses and temperature rise in induction motors using equivalent loading methods. IEEE Transactions on Energy Conversion, 2001, vol. 16, no. 3, pp. 214 – 219. doi: 10.1109/60.937199

[17] Dong Hu, Wei Xu, Renjun Dian, Yi Liu, Jianguo Zhu Loss Minimization Control of Linear Induction Motor Drive for Linear Metros. IEEE Transactions on Industrial Electronics, 2018, vol. 65, no. 9, pp. 6870 – 6880. doi:10.1109/TIE.2017.2784343

[18] Shreelakshmi M P; Vivek Agarwal Trajectory Optimization for Loss Minimization in Induction Motor Fed Elevator Systems. IEEE Transactions on Power Electronics, 2018, vol. 33, no. 6, pp.5160 – 5170. doi: 10.1109/TPEL.2017.2735905

[19] Boyko A., Volyanskaya Ya. Synthesis of the system for minimizing losses in asynchronous motor with a function for current symmetrization. Eastern-European Journal of Enterprise Technologies, 2017, no. №4/5 (88), pp. 50 – 59. doi: 10.15587/1729-4061.2017.1-8545