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EXPERIMENTAL IDENTIFICATION OF THE ELECTRIC MOTOR MOMENT OF INERTIA AND ITS EFFICIENCY USING THE ADDITIONAL INERTIA

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ABSTRACT

The purpose of this paper is to develop a method for determining the moment of inertia of rotating masses of an electric motor and evaluation of its mechanical losses, as well as its theoretical and experimental study. The idea of the method is based on the known method of the retardation test of an electric motor with different values of the moment of inertia of its rotating masses. However, unlike existing methods, the proposed one gives more accurate results due to the use of additional bodies of different moments of inertia but of the same weight. This creates approximately the same conditions of friction in bearings during the entire measurement process. Experimental results were obtained on the basis of an induction motor and showed a higher accuracy compared with existing methods. The developed method can be used in companies producing electric motors to improve the accuracy of determining the moment of inertia of their rotating masses and to evaluate their mechanical efficiency with fewer financial expenses than using existing experimental methods.

Keywords: induction motor efficiency, induction motor losses, moment of inertia measurements, reference flywheel, retardation method

INTRODUCTION

The moment of inertia of rotating masses and the mechanical losses in electric motors are one of the most important their indicators since they define their dynamics and efficiency. Friction conditions have a significant impact on the rate of degradation processes, such as wear and back-to-back endurance of friction units, which are the criteria for their efficiency, and therefore have a significant impact on electric motors life cycle and operation reliability (Bhattacharya, [1]; Egorov *et al*., [5]; Egorov *et al*., [6]). Moreover, the identification of the above parameters, with good accuracy, is highly desirable, because these parameters are crucial for the design of high-performance speed and position controllers (Reljic and Jerkan, [14]; Yang and Deng, [18]).

At present, to determine the moment of inertia of electric motors, it is used computational and experimental methods (Cheol *et al*., [2]; Doppelbauer, [4]; Kotelnets *et al*., [9]; Podzharenko and Kucheruk, [12]; Rahul and Tarnekar, [13]; Saekok and Lumyong, [16]; Seduki et al., [17]). Computational methods (Ilina, [8]; Pyrhonen *et al*., [11]; Rusnok *et al*., [15]; Seduki *et al*., [17]; unlike experimental ones (Despalatovic et al., [3]; Pillai, [10]) are more labor intensive because of the inhomogeneity of the materials used and the complexity of the geometric shapes of a rotor and bearing assemblies in electric motors.

The most commonly experimental methods used for these purposes are the following: torsion oscillation method, pendulum method and retardation method (IEEE Std. 112-2004, [7]).

The use of torsion oscillation and pendulum methods leads to large errors since a rotor has to be well balanced and there is a difficulty connected with determining the center of gravity or the suspension center of a rotor; moreover, it is impossible to use these methods when an electric motor is assembled, i.e. it is necessary to demount a rotor.

The retardation method is based on the determining the power of mechanical losses. A disadvantage of this method is that the mechanical losses have to be the same throughout the whole speed range during the retardation. Since mechanical friction losses depend on the rotation speed of an electric motor, it leads to measurement errors. In addition, the power of mechanical losses is determined by measuring the voltage and the current in the windings of an electric motor at its idling, which leads to additional errors in the measurement process.

In (Podzharenko and Kucheruk, [12]) authors described an experimental method for determining the moment of inertia of rotating masses and the torque of mechanical losses of an electric motor, which is based on the retardation. However, according to this method in the determination of the unknown quantities authors neglected mechanical losses, which take place in bearing units of an additional system of rotating masses and are difficult to calculate, as well as the moment of inertia of bearing units rotating masses. Thus there are errors that do not allow evaluating the level of mechanical losses in an electric motor and determining the moment of inertia of its rotating masses with high accuracy.

The purpose of this paper is to develop a method for determining the moment of inertia of an electric motor and evaluating its efficiency, which will enhance the measurement accuracy compared to existing methods. To solve the assigned task, it is necessary to get not only theoretical but also experimental validation and on the basis of the results to make decision on the appropriateness of the proposed method.

ARPN Journal of Engineering and Applied Sciences

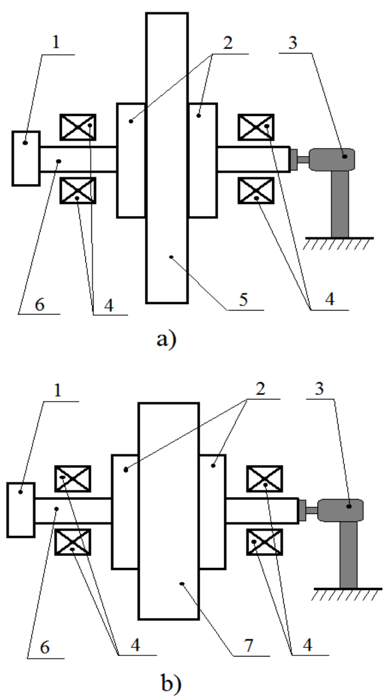
MATERIALS AND METHODS

In order to improve the accuracy of determining the moment of inertia and the torque of mechanical losses of an electric motor by means of the method presented in (Podzharenko and Kucheruk, [12]), it is necessary to accurately determine the value of the additional moment of inertia, i.e. the total moment of inertia of rotating parts of an additional system of rotating masses (see. Figure-1), as well as the mechanical losses in its bearing units.

Let us consider a method proposed in this paper to solve the assigned problem in more detail.

Determination of the moment of inertia and the torque of mechanical losses of an additional system of rotating masses

Figure-1 is a scheme of an additional system of rotating masses with different rotary bodies, 5 and 7, of the same weight but different values of the moment inertia.



1 is a half-clutch for connecting an electric motor; 2 is a half-clutch for fixing rotary bodies, 5 and 7; 3 is an encoder; 4 is a bearing unit; 5 is a reference rotary body of the weight *m* and the moment of inertia J_1; 6 is a shaft; 7 is a reference rotary body of the weight *m* and the moment of inertia J_2.

Figure-1. Scheme of an additional system of rotating masses with different rotary bodies of the same weight and different values of the moment of inertia: a) with a rotary body of the weight *m* and the moment of inertia J_1; b) with a rotary body of the weight *m* and the moment of inertia J_2.

In order to determine the moment of inertia of the additional system of rotating masses and the mechanical losses in its bearing units (braking torque due to mechanical losses in the bearing units), neglecting other losses (e.g., air friction), it is necessary to perform the following steps.

We mount the reference rotary body 5 to the half-clutch 2 with fasteners (Figure-1). The system of rotating masses with the rotary body 5 is driven by an electric motor, and then, when the rated speed is reached, we disconnect the drive motor and, using the encoder 3, we register values of the angular deceleration ε_1 at running-out of the additional system of rotating masses from rated to zero speed. An equation for the braking torque of mechanical losses in bearing units can be written as:

$$M_{BASRM} = (J_1 + J_{ASRM}) \cdot \varepsilon_1 = (J_{ref} + J_2 + J_{ASRM}) \cdot \varepsilon_1 \quad (1)$$

Where, J_{ASRM} is the moment of inertia of the additional system of rotating masses without a reference rotary body, kg·m^2; J_{ref} is the difference between the values of the moments of inertia, J_1 and J_2, kg·m^2.

Then we demount the reference rotary body 5 and, using fasteners, we mount the reference rotary body 7 (Figure-1b). In so doing the moment of inertia of the rotating masses is reduced and therefore the resulting angular deceleration of the additional system of rotating masses at running-out from rated to zero speed increases (since the amount of energy, which a rotary body with a smaller moment of inertia is able to accumulate, reduces). A drive electric motor sets in motion, the angular velocity of the rotating masses is brought to the rated value, then the drive motor is detached, so that the system of rotating masses starts self-braking and the resulting angular deceleration ε_2 of the additional system of rotating masses with the reference rotary body 7 is registered.

An equation for the braking torque of mechanical losses in the additional system of rotating masses can be written as:

$$M_{BASRM} = (J_2 + J_{ASRM}) \cdot \varepsilon_2 \quad (2)$$

In both of running-out of the additional system of rotating masses (with the reference rotary body 5 and with the reference rotary body 7) the amount of mechanical losses remains unchanged, therefore the right-hand sides of Eq. (1) and Eq. (2) can be equated and we can find an equation for J_{ASRM}+J_2:

$$J_{ASRM} + J_2 = J_{ref} \cdot \frac{\varepsilon_1}{\varepsilon_2 - \varepsilon_1} \quad (3)$$

With known J_{ASRM}, J_1 and J_2, one can determine the braking torque caused by mechanical losses in the bearing units according to Eq. (1) or Eq. (2).

Evaluation of mechanical and added losses in an electric motor

In order to determine mechanical and added losses in an electric motor (the braking torque caused by

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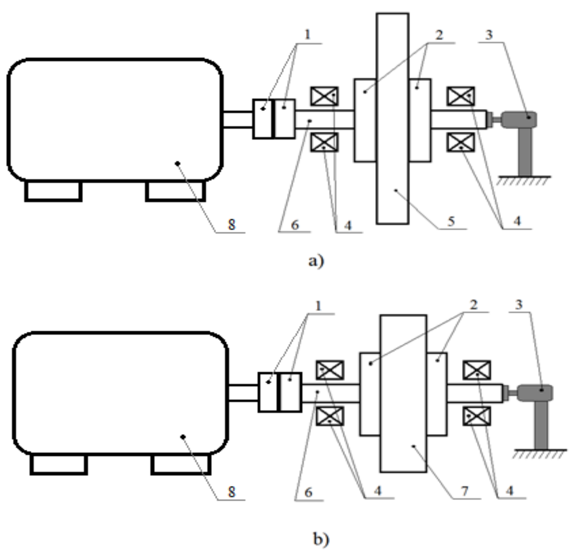
mechanical and added losses in an electric motor), it is necessary to perform the following steps.

We connect an induction motor 8 through a half-clutch 1 to the additional system of rotating masses (see Figure-2).



1 is a half-clutch for connecting an electric motor; 2 is a half-clutch for fixing rotary bodies 5 and 7; 3 is an encoder; 4 is a bearing unit; 5 is a reference rotary body of the weight m and the moment of inertia J_1; 6 is a shaft; 7 is a reference rotary body of the weight m and the moment of inertia J_2.

Figure-2. Scheme of connecting an electric motor to the additional system of rotating masses with different rotary bodies of the same weight and different values of the moment of inertia: a) with a rotary body of the weight m and the moment of inertia J_1; b) with a rotary body of the weight m and the moment of inertia J_2.

First, we mount the reference rotary body 5 to the half-clutch 2 with fasteners (Figure-2a). The system of rotating masses with the rotary body 5 speeds up, and then, when the rated speed is reached, the power is switched off, thus the system starts self-braking due to the action of the friction forces in bearing units and a propeller, as well as added losses in an electric motor. Using the encoder 3, we register values of the deceleration ε_3 at running-out of the system of rotating masses from rated to zero speed. An equation for the braking torque of mechanical and added losses can be written as:

$$M_B = (J_1 + J_{ASRM+IM}) \cdot \varepsilon_3 = (J_{ref} + J_2 + J_{ASRM+IM}) \cdot \varepsilon_3 \quad (4)$$

Where, $J_{ASRM+IM}$ is the total moment of inertia of rotating masses of an electric motor and an additional system of rotating masses without a reference rotary body, kg·m^2; J_{ref} is the difference between the values of the moments of inertia J_1 and J_2, kg·m^2.

Then we demount the reference rotary body 5 and mount the reference rotary body 7 with fasteners. The induction motor starts up; the angular velocity of the rotating masses is brought to the rated value. Then the power is switched off, so that the retardation begins and the resulting angular deceleration ε_4 of the system of rotating masses with the reference rotary body 7 is registered. An equation for the braking torque of mechanical and added losses can be written as:

$$M_B = (J_2 + J_{ASRM+IM}) \cdot \varepsilon_4 \quad (5)$$

In both of running-out of the considered system of rotating masses (with the reference rotary body 5 and with the reference rotary body 7) the amount of mechanical and added losses remains unchanged, therefore the right-hand sides of Equation (4) and Equation (5) can be equated, and we can find an equation for $J_{ASRM+IM}$:

$$J_{ASRM+IM} + J_2 = J_{ref} \cdot \frac{\varepsilon_3}{\varepsilon_4 - \varepsilon_3} \quad (6)$$

From Equation (3) and Equation (6) one can determine the moment of inertia of rotating masses of an electric motor:

$$J_{IM} = J_{ASRM+IM} + J_2 - J_{ASRM} - J_2 \quad (7)$$

With the known $J_{ASRM+IM}$, J_1 and J_2, one can determine the braking torque caused by mechanical and added losses in the considered system of rotating masses according to Equation (4) or Equation (5).

Knowing M_B and M_{BASRM}, one can determine the braking torque caused by mechanical and added losses in an electric motor according to the following equation:

$$M_{BIM} = M_B - M_{BASRM} \quad (8)$$

Instruments for measuring the moment of inertia and evaluating the mechanical efficiency of an Electric Motor

In order to measure the moment of inertia and evaluate mechanical losses in an electric motor, a hardware-software complex (HSC) was proposed. It consists of an encoder, a transmitter (registrating unit) and a personal computer (PC) with installed software for registrating and analysis of the digital signal (Figure-3).

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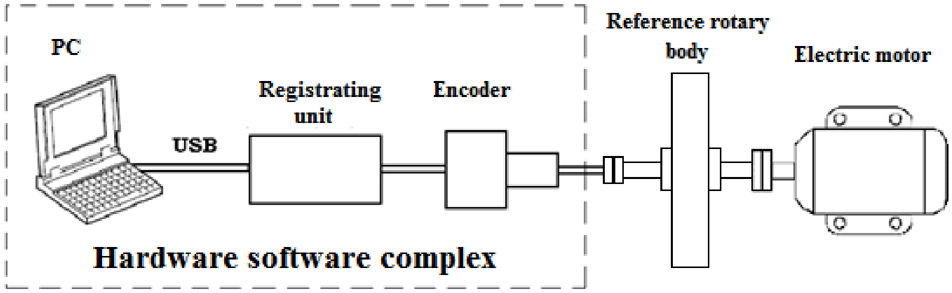


Figure-3. Scheme for control of the mechanical parameters of an electric motor.

For the experimental validation of the proposed method to enhance the accuracy of parameters measurement, a stand was designed and assembled on the basis of an induction motor (Figure-4).

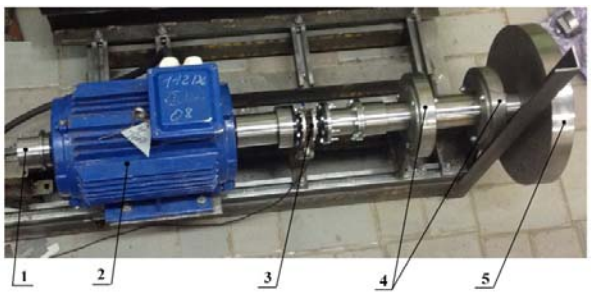
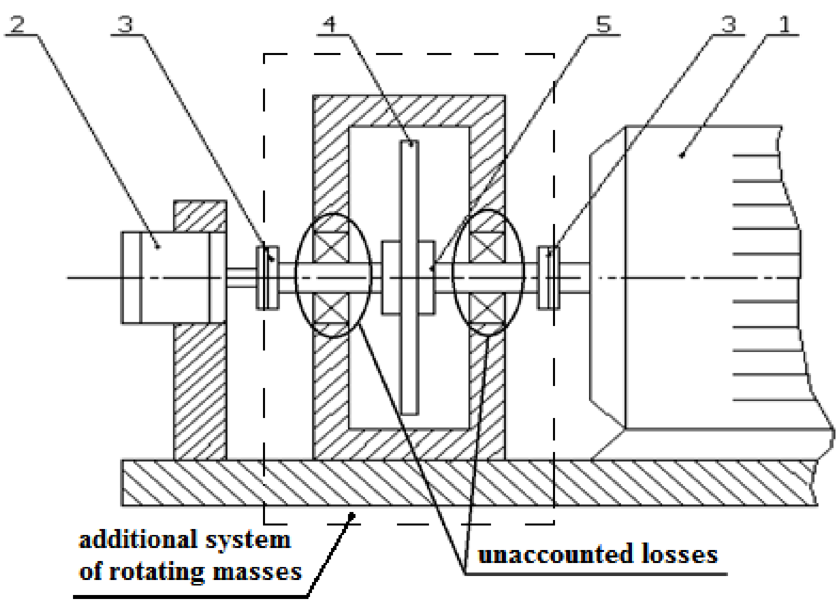


Figure-4. Stand for determining the moment of inertia and the torque of mechanical and added losses in an induction motor: 1 is a seat for fixing a rotary body with the reference moment of inertia; 2 is an induction motor AIR 112MV6 (220/380 V), 4 kW, n = 940 rev/min; 3 is an encoder; 4 are bearing units of an additional system of rotating masses; 5 is a reference rotary body.

This stand allows registering the time and the angular deceleration of a system of rotating masses connected to HSC during the retardation.

RESULTS AND DISCUSSIONS

It is currently known the method (Podzharenko and Kucheruk, [12]), wherein an additional reference rotary body is used for determining the moment of inertia and the torque of mechanical losses of an electric motor (see Figure-5).



1 is an electric motor; 2 is an encoder; 3 is a clutch; 4 is an additional rotary body with the reference moment of inertia J_{ref}; 5 is a half-clutch for mounting an additional rotary body with the reference inertia.

Figure-5. Scheme of an assembly for determining the moment of inertia of rotating masses of an electric motor according to (Podzharenko and Kucheruk, [12]).

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Measurements were made in the following sequence. At first, the electric motor started without a reference body; when the rated speed was reached, it turned off, and the rate of angular velocity change from the rated to zero speed ε_0 was measured. Then the electric motor was attached to the additional system of rotating masses with a rotary body 4; and the rate of change of the angular velocity from the rated to the zero value ε_{ref} was measured. According to authors' idea, based on these measurements, one could calculate the moment of inertia of rotating masses of the electric motor J and the torque of mechanical and added losses M_0:

$$J = \frac{\varepsilon_{ref}}{\varepsilon_{ref} - \varepsilon_0} \cdot J_{ref}, \tag{9}$$

$$M_0 = \frac{\varepsilon_{ref} \cdot \varepsilon_0}{\varepsilon_{ref} - \varepsilon_0} \cdot J_{ref}, \tag{10}$$

Where, J_{ref} is the moment of inertia of the additional rotary body 4, kg·m^2.

However, the moment of inertia of rotating parts of bearing units of supports for fixing the reference body 4 (see unaccounted losses in Figure-5) and mechanical losses were not taken into account.

The method proposed in this paper solves this problem thereby increasing measurement accuracy.

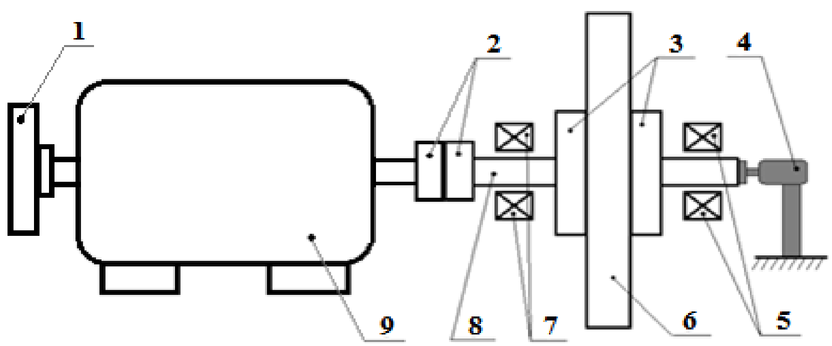
In order to justify the accuracy enhancement when using the proposed method, it was used a rotary body with the pre-determined moment of inertia. Schematically, the essence of the experiment is illustrated in Figure-6.

In this experiment an induction motor AIR112MV6 (220/380 V), 4 kW, n = 940 rev/min was tested. Two rotary bodies of the same weight and the moments of inertia of 0.1123 kg×m^2 and 0.1823 kg×m^2 were used.

We measured the moment of inertia of the rotary body 1 (see Figure-6) by means of two methods (existing (Podzharenko and Kucheruk, [12]) and developed).

In the application of both methods 10 measurements were carried out, blunders were eliminated, the average moments of inertia values were found, and random errors were determined.

First, we measured the moment of inertia of the rotating masses of the system without the rotary body 1 using the method described in (Podzharenko and Kucheruk, [12]). Then we fastened the rotary body 1 to the back of the induction motor 9 and determined the moment of inertia of the rotating masses with the rotary body 1 in the same manner. An absolute value of the difference of two measurements was compared with the determined value of the moment of inertia of the rotary body 1.



1 is a rotary body, the moment of inertia of which is determined in the experiment; 2 is a clutch for connecting an electric motor 9 with an additional system of rotating masses; 3 is a clutch for mounting a reference rotary body 6; 4 is an encoder; 5, 7 are bearing units; 6 is a reference rotary body; 8 is an additional system of rotating masses; 9 is an induction motor.

Figure-6. Scheme of the experimental determination of the moment of inertia of a rotary body of the pre-determined moment of inertia by means of existing and developed method in order to compare the accuracy of determining the moment of inertia of an induction motor.

The results obtained are shown in Table-1.

Table-1. Error of determining the moment of inertia of a rotary body 1 using the existing method.

n, rev/min	200-300	300-400	400-500	500-600	600-700	700-800
J_{calc}, kg·m^2	0.0319	0.0319	0.0319	0.0319	0.0319	0.0319
J_{im}, kg·m^2	0.0313	0.0315	0.0312	0.0310	0.0307	0.0307
J_{im+add}, kg·m^2	0.0618	0.0619	0.0619	0.0618	0.0617	0.0618
J_{add}, kg·m^2	0.0305	0.0304	0.0306	0.0308	0.0308	0.0310
Δ, kg·m^2	-0.0014	-0.0015	-0.0013	-0.0011	-0.0011	-0.0009
δ, %	-4.5	-4,9	-4,1	-3,5	-3,5	-3.1

Where, J_{calc} is the pre-determined moment of inertia of the rotary body 1; J_{im} is the experimentally determined moment of inertia of rotating masses of the induction motor without the rotary body 1; J_{im+add} is the experimentally determined moment of inertia of rotating masses of the induction motor with the rotary body 1; J_{add} is the experimentally determined moment of inertia of the rotary body 1 found as the difference between J_{im+add} and J_{im}; Δ is the absolute random error in the measurement of the moment of inertia of the rotary body 1; δ is the relative random error in the measurement of the moment of inertia of the rotary body 1.

Likewise, we determined the moment of inertia of the rotary body 1 with the proposed method and compare it with the calculated value of the moment of inertia. Table-2 shows the results obtained.

On the basis of Table-1 and Table-2 it can be concluded that the accuracy of measurement of the moment of inertia when using the method proposed in this paper has increased almost 3 times in comparison with the method described in (Podzharenko and Kucheruk, [12]). A random error in the application of the proposed method is likely related to the change of friction conditions in the induction motor bearings when attaching the rotary body 1 to the back of the induction motor 9.

Table-2. Error of determining the moment of inertia of a rotary body 1 using the developed method.

n, rev/min	200-300	300-400	400-500	500-600	600-700	700-800
J_{calc}, kg·m^2	0.0319	0.0319	0.0319	0.0319	0.0319	0.0319
J_{im}, kg·m^2	0.0320	0.0321	0.0317	0.0315	0.0312	0.0311
J_{im+add}, kg·m^2	0.0634	0.0635	0.0632	0.0630	0.0628	0.0627
J_{add}, kg·m^2	0.0314	0.0314	0.0315	0.0315	0.0316	0.0315
Δ, kg·m^2	0.0005	0.0005	0.0004	0.0004	0.0003	0.0004
δ, %	-1.6	-1.6	-1.3	-1.3	-1.0	-1.3

CONCLUSIONS

The obtained error values indicate that the developed method significantly improve the accuracy of determining the moment of inertia of an electric motor. Moreover, determination of the moment of inertia is performed without dismantling of a rotor, which greatly simplifies the process of control of operated electric motors.

The developed method can be used to evaluate the mechanical efficiency of different electric motors, eliminating the need for strain measurement instruments, which require precise calibration of strain gauges and have relatively low frequency rate, which have great impact on the measurement accuracy when transient conditions take place. Equipping presented stand with a hardware-software complex and setting the acceptable level of the torque of mechanical losses in an electric motor, it is possible to control its efficiency in the process of production and operation.

It is expected that further research will be focused on the application of this method to determine the mechanical efficiency of different electric motors and comparing the values of the mechanical efficiency in the application of the developed and various existing methods.

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