A New Method for Control of the Efficiency of Gear Reducers

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Abstract. This article proposes a new method to control the energy efficiency of gear reducers. The method allows evaluating the friction losses in a drive motor, drive motor bearing assemblies, and toothed both at the stage of control of the finished product and in the course of its operation, maintenance, and repair. The proposed method, unlike currently used methods for control of the efficiency of gear reducers, allows determining the friction losses without the use of strain measurement, which requires calibration of tensometric sensors and expensive equipment. The method is based on the idea of invariability of mechanical characteristics of the induction motor at constant voltage, resistance of windings, and mains frequency, regardless of the driven inertia mass. This paper presents experimental results which verify the theoretical predictions. The proposed method can be implemented in the procedure of acceptance test at the companies that manufacture gear reducers, thereby assess their effectiveness and the level of degradation processes that significantly affect the service life of the research object. The method can be implemented both with universal and with specialized hardware and software complexes. At that, both an increment of the inertia moment and acceleration time of a gear reducer may serve as a performance criterion.

1. Introduction

The problem of improving the quality of products of modern engineering is complex. Its resolution depends on a number of purposes including increasing the efficiency of machines in a wide range of possible modes of their operation. The solution of the problem is associated with the development of methods and instruments for their testing, control, and diagnostics. The present level of development of methods and instruments for control of the efficiency of gear reducers does not allow comprehensively evaluating the technical condition of the equipment in a wide range of possible modes of operation [1–6]. In order to register a change of friction losses rate in gear transmissions, it is most often applied the strain measurement that requires a calibration of strain sensors and the use of expensive equipment [7–10]. At that, the efficiency is registered with a low measurement rate, which is caused by the time required to recover elastodeformed state of a strain element [11].

Thus, on the one hand, there is a need to resolve the problem of increasing the efficiency of gear reducers; on the other hand, there are no adequate methods and instruments to solve the problem.

Analysis of the works carried out on the basis of the Closed Joint-Stock Company “Research Institute of Introscopy of MSIA “Spectrum” (together with the Departments of Power Engineering, Mechanical Engineering, Mechanics and Control Processes) headed by the academician of RAS, Vladimir V. Kluyev [12], proves that inertia methods for control, testing, and diagnostics of gear reducers have not been developed due to the main unresolved problem associated with the inertial
testing - the problem of determining the normalized with respect to the power take-off axis effective moment of inertia of rotating parts.

This article gives the solution of the problem hampering the development of inertial methods for control, testing, and diagnostics of gear reducers.

In order to solve the stated problems, we need to find a new approach to control the efficiency of gear reducers. This approach should not have the disadvantages, which other known methods have (the need for calibration of strain sensors, high cost of equipment, and the complexity of the measurement process). The measurement accuracy obtained using the new method is to meet the requirements of modern engineering and to be comparable to the accuracy of measurements obtained with the help of well-known and approved methods of measurement.

The purpose of this paper is to develop a cost-effective, highly accurate, and less labor consuming method for control of the efficiency of gear reducers based on the use of additional bodies with the known moments of inertia.

In order to achieve this purpose, we assigned the following objectives:

- To develop the theoretical justification of the method for the efficiency control of gear reducers.
- To develop the theoretical justification of the method for evaluating the rate of losses caused by the friction in bearing assemblies and toothing.
- To prove the theoretical predictions experimentally.

2. Methodology

Let us consider the proposed method for control of the efficiency of gear reducers with the use of a gear reducer operating as part of an induction electric drive. Figure 1 shows a scheme of a single-stage bevel gear speed reducer connected to an induction motor.

![Figure 1](image)

Figure 1. Scheme of a gear reducer driven by an induction motor; where 1 is an induction motor, 2 is a safety clutch, 3 is a high-speed (input) gear-shaft, 4 are bearings supporting the high-speed (input) shaft, 5 is a low-speed (output) shaft together with a gear wheel, 6 are bearings supporting a low-speed (output) shaft, 7 is a safety clutch of a reducer, 8 is a frequency converter (inverter).

Let us consider the implementation of the developed method for an induction motor with a safety clutch.

Knowing the calculated or experimentally determined moment of inertia of a safety clutch 2, \( J_{scim} \), it is possible to determine the moment of inertia of the induction motor rotor 1, \( J_{im}(\omega) \), taking into account the friction losses in bearings in accordance with the scheme in Figure 2.
Figure 2. Scheme for determining the moment of inertia of a rotor of an induction motor taking into account the friction losses in its supports.

First, it is necessary to determine the angular accelerations of the rotor with the safety clutch installed on an output shaft of the motor, \( \varepsilon_1(\omega) \), and then - without it, \( \varepsilon_2(\omega) \). Considering that the speeding up has actually been at idle mode, the products of the moments of inertia and the angular accelerations during the first and the second accelerations can be equated to each other:

\[
(J_{scim} + J_{im}(\omega)) \cdot \varepsilon_1(\omega) = J_{im}(\omega) \cdot \varepsilon_2(\omega). \tag{1}
\]

Based on Equation 1, we can calculate the moment of inertia of the rotor taking into account the friction losses in bearings as follows:

\[
J_{im}(\omega) = \frac{J_{scim} \cdot \varepsilon_1(\omega)}{\varepsilon_2(\omega) - \varepsilon_1(\omega)}. \tag{2}
\]

Based on the described method, the methodology for control of the efficiency of a gear reducer is implemented according to the following steps:

1. Determination of the effective capacity depending on the angular velocity of a rotor of an electric motor by the developed method.
2. Determination of the moment of inertia of an input gear shaft together with a gear wheel mounted on it by torsional oscillation.
3. Determination of the frictional power losses in input shaft bearing supports depending on the angular speed of a rotor by the developed method.
4. Determination of the moment of inertia of an output shaft of a gear reducer together with a gear wheel mounted on it by torsional oscillation.
5. Determination of the frictional power losses in output shaft bearing supports depending on the angular velocity of a rotor by the developed method.
6. Determination of the total frictional power loss in bearings of input and output shafts of a gear reducer depending on the angular velocity of a rotor of an electric motor.
7. Determination of the frictional power losses in toothing depending on the angular velocity of a rotor of an electric motor.

In the last step, the reducer is totally assembled and the induction motor 1 is connected to the high-speed gear-shaft 3 through the safety clutch 2.

Then we determine the normalized with respect to the rotor axis moment of inertia of the rotating parts of the entire drive according to the conventional method based on the law of conservation of kinetic energy without taking into account the losses in the gear mechanism:

\[
J_{norm}(\omega) = \frac{\omega^2}{2} = [J_{im}(\omega) + J_{scim} + J_{gs}(\omega)] \frac{\omega^2}{2} + [J_{lss}(\omega) + J_{scred}] \frac{\omega^2}{2}. \tag{3}
\]
\[ J_{\text{norm}}(\omega) = J_{im}(\omega) + J_{scim} + J_{gs}(\omega) + \frac{J_{\text{lss}}(\omega)}{i^2} + \frac{J_{\text{scred}}}{i^2}, \] (4)

where \( i \) is the gear ratio; \( J_{gs}(\omega) \) is an array of values of the moment of inertia of the gear-shaft taking into account the friction losses in supports; \( J_{\text{lss}}(\omega) \) is an array of values of the moment of inertia of the low-speed shaft taking into account losses in bearings supporting the low-speed shaft; \( J_{\text{scred}} \) is the moment of inertia of a safety clutch.

Then the induction motor 1 speeds up and an array of values of the angular accelerations, \( \varepsilon_3(\omega) \), is measured. The torque, developed by the electric motor, is determined as follows:

\[ M(\omega) = (J_{\text{norm}}(\omega) + J_{\text{loss.tooth}}(\omega)) \cdot \varepsilon_3(\omega). \] (5)

The torque developed on an output of the motor safety clutch 2 can be determined as follows:

\[ M(\omega) = (J_{im}(\omega) + J_{scim}) \cdot \varepsilon_1(\omega). \] (6)

Equating Equations 5 and 6, we determine the normalized with respect to the rotor axis moment of inertia of losses in toothings as follows:

\[ J_{\text{loss.tooth}}(\omega) = (J_{im}(\omega) + J_{scim}) \cdot \frac{\varepsilon_1(\omega)}{\varepsilon_3(\omega)} - J_{\text{norm}}(\omega). \] (7)

The total normalized with respect to the rotor axis moment of inertia of rotating parts of the gear reducer together with the induction motor can be determined as follows:

\[ J_{\text{norm}}(\omega) = J_{im}(\omega) + J_{scim} + J_{gs}(\omega) + J_{\text{loss.tooth}}(\omega) + \frac{J_{\text{lss}}(\omega)}{i^2} + \frac{J_{\text{scred}}}{i^2}. \] (8)

Let us write Equation 8 in terms of elementary components:

\[ J_{\text{norm}}(\omega) = J_{\text{rim}} + J_{\text{blim}}(\omega) + J_{scim} + J_{gs} + J_{\text{bllss}}(\omega) + J_{\text{loss.tooth}}(\omega) + \frac{J_{\text{lss}}(\omega)}{i^2} + \frac{J_{\text{bllss}}(\omega)}{i^2} + \frac{J_{\text{scred}}}{i^2}. \] (9)

where, \( J_{\text{rim}} \) is the moment of inertia of the rotor; \( J_{\text{blim}}(\omega) \) is the losses in the bearings 4 supporting the low-speed shaft 5.

The power developed by the separate parts of the electric gear drive is determined as follows:

\[ N(\omega) = J_{\text{rim}} \cdot \varepsilon_3(\omega) \cdot \omega + J_{\text{blim}}(\omega) \cdot \varepsilon_3(\omega) \cdot \omega + J_{scim} \cdot \varepsilon_3(\omega) \cdot \omega + J_{gs} \cdot \varepsilon_3(\omega) \cdot \omega + J_{\text{bllss}}(\omega) \cdot \varepsilon_3(\omega) \cdot \omega + J_{\text{lss}}(\omega) \cdot \frac{\varepsilon_3(\omega)}{l^2} + J_{\text{bllss}}(\omega) \cdot \frac{\varepsilon_3(\omega)}{l^2} + J_{\text{scred}} \cdot \frac{\varepsilon_3(\omega)}{l^2} \cdot \omega. \] (10)

Knowing an array of values of the active electric power supplied to the input of the induction motor, \( N_{im}(\omega) \), knowing \( N(\omega) \), knowing the power of dissipation in windings of the motor, \( N_{\text{diss}}(\omega) \), we can determine the power of loss for the eddy current and hysteresis in the induction motor:
3. Experimental validation of a new method

In order to substantiate the reliability of the values obtained with the developed method, we carried out the following experiment. We compared the values of the torque obtained with the developed method with those obtained with the torque sensor M40-100 during an induction motor speeding-up.

The experiment was carried out according to the scheme shown in Figure 3.

For measuring the angular acceleration, we used an encoder E40HBP, which sends an analog signal corresponding by its dynamic range to the measuring channel of a registration data unit. The personal computer with installed software provides mathematical treatment of a data array and calculation of the angular velocities and the average values of the accelerations of a rotating motor. Based on the values of the angular accelerations obtained during the motor speeding up, both with a reference body and without it, the moment of inertia is computed. To minimize voltage fluctuation, which influences the measurement error, voltage stabilizer Saturn SNE-O-10 (11 kW, 50 A) was used.

![Figure 3](image-url)

**Figure 3.** Scheme for control of the electric gear drive torque with a torque sensor M40-100, where 1 is an induction motor, 2 is a safety clutch, 3 is a high-speed gear-shaft, 4 are bearings supporting a high-speed shaft, 5 is a low-speed shaft together with a gear wheel, 6 are bearings supporting a low-speed shaft, 7 is a safety clutch of a reducer, 8 is a torque sensor M40-100, 9 is a frequency converter (inverter), 10 is an encoder E40HBP.

In the application of both methods 10 measurements were carried out, blunders were eliminated, random errors were determined, and the average torque values were found. Table 1 shows the values obtained.

**Table 1.** The comparison of the average torque values within selected speed range obtained with the novel method (NM) and using the torque sensor (TS).

| Variable | Number of revolutions, [rev/min] |
|----------|----------------------------------|
|          | 250–400  | 400–500  | 500–600  | 600–700  | 700–800  | 800–850  | 850–950  |
| $M_{NM}$, N·m |       |         |         |         |         |         |         |
| $M_{TS}$, N·m |       |         |         |         |         |         |         |
| $\delta$, % |       |         |         |         |         |         |         |
4. Conclusion

The experimental results show that the convergence of the measurements obtained with the developed method and with the torque sensor varies within 1.7%, which proves the validity of the values obtained with the developed method.

Having determined an array of values of $J_{\text{norm}}(\omega)$ at the stage of a technical control department of the manufacturer of gear reducers, having determined the acceptable level of this parameter during operation of a gear reducer, and equipping a gear drive with hardware and software system, the user has the ability to promptly respond to the deterioration of the energy performance of the drive. On the basis of measuring $J_{\text{norm}}(\omega)$, it is possible to carry out maintenance and repair work to the extent necessary to maintain the efficiency at a high level. With the implementation of the novel method for control of the efficiency of gear reducers, it is possible to achieve high efficiency of a reduction gear for the entire life cycle.

The methodology for determining the efficiency of gear reducers with a fixed transmission ratio having a number of steps more than two is similar to the developed one. The developed method for control of the efficiency of gear reducers can be used for research purposes during the engineering development, for testing newly manufactured products in the industrial stages, and for testing gear reducers in the technical operation stage during the entire life cycle.

Acknowledgements

The reported study was funded by Ministry of Education and Science of the Russian Federation according to the research project No. 02.G25.31.0204.

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