Review of Methods for Determining the Moment of Inertia and Friction Torque of Electric Motors

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Abstract: Our research group, at the Faculty of Engineering of the University of Debrecen, has extensively studied the dynamic modelling and simulation of electric motor's over the past ten years. Many simulation programs have been developed for various motor types. The technical parameters and characteristics of the motors are used as input data for the above-mentioned programs. Among these data, important dynamic characteristics are the moment of inertia and friction torque of the rotor. The friction torque includes windage, ventilation, bearing and brush friction losses. In many cases, however, the manufacturer does not provide these data in the datasheet, so they must be determined experimentally. Several methods exist in the scientific literature for the above purpose. Our research group has also developed and applied such methods in recent years. This publication reviews these methods by presenting the applied experimental setups and procedures. In addition, considering the available literature data and our previous experience, we give the accuracies that can be achieved by the methods and any difficulties that may arise during the experiments and the related computational procedures.

Keywords: electric motor; dynamic characteristics; moment of inertia; friction torque

1 Introduction

At the Faculty of Engineering of the University of Debrecen, our research group has dedicated its efforts to studying electric vehicle drives in the last ten years. The main topic of the research is the modelling, simulation, and optimization of different electric vehicle drives with the original aim to help the more conscious design of the prototype race cars made by student teams at our faculty. To achieve this goal, a vehicle dynamics simulation program has been developed in MATLAB/Simulink environment [1] [2], which can compute the dynamics functions of a vehicle from its technical characteristics and data. With the help of the above program and an optimizing procedure, the most advantageous technical data and characteristics of a vehicle can be determined for a given competition task.

This program includes the simulation of the drive system, including the electric motor [3] [4]. The inputs of the motor simulation module are the electromagnetic and dynamic characteristics of the motor. The dynamic characteristics are the moment of inertia and friction torque of the rotor. These dynamic characteristics serve as inputs also for other simulation programs developed in NI LabVIEW Control Design and Simulation Module [3] [5] and other widely used programs such as Ansys-Maxwell RMxprt [6, 7, 8]. Additionally, they are also important for the accurate dynamic modelling and testing of various high-performance motor control strategies [9].

This paper reviews and classifies the available experimental-based methods in scientific literature to identify the above-mentioned dynamic characteristics as precisely as possible.

2 Review and Classification of Methods for Identifying the Dynamic Characteristics

The methods for identifying the above-mentioned dynamic characteristics can be classified into three groups. These groups are:

1) The direct measurement of the friction torque, and after that, the identification of the moment of inertia.
2) The direct measurement of the moment of inertia and, after that, the identification of the friction torque.
3) The simultaneous identification of the moment of inertia and friction torque.

Methods belonging to the three groups mentioned above are described in Sections 2.1, 2.2 and 2.3, respectively.

2.1 Methods based on the Direct Measurement of the Friction Torque

In these methods, the friction torque of the rotor is directly measured as a function of the angular speed. Figure 1 shows a typical experimental setup for this purpose.

During the experiment, the analyzed motor is driven by an induction motor supplied by a 3-phase AC voltage through a frequency converter. Varying the supply voltage frequency, the angular speed of the induction motor, therefore that of the analyzed motor is varied. Measuring the torque on the shaft of the analyzed motor by a rotary torque meter at different angular speeds, its friction torque-angular speed characteristic ($M_{brake}(\omega)$) is determined. The accurate value of the angular speed is measured by an optical LED sensor.

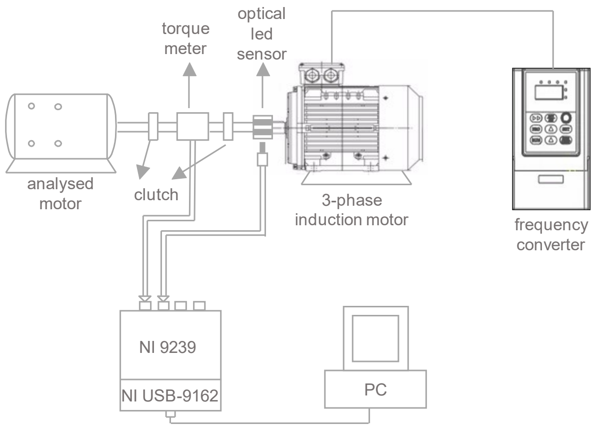

Figure 1
Typical experimental setup for the direct measurement of friction torque, as the function of angular speed

After the measurement of friction torque, the rotor's moment of inertia is identified. For the identification, different methods can be applied (see Section 2.2), but the simplest way is to perform a retardation test on the motor. During the retardation test, the analyzed motor is freely run out until it stops, while its angular speed is measured vs time. From the angular speed vs time curve – obtained from the retardation test – the angular acceleration vs angular speed curve of the rotor can be given. From the angular acceleration vs angular speed ($\varepsilon(\omega)$) and friction torque vs angular speed ($M_{brake}(\omega)$) curves, the moment of inertia of the rotor can be calculated at different angular speeds as:

$$J_r = \frac{M_{brake}(\omega)}{\varepsilon(\omega)} \tag{1}$$

In reference [10], this method is applied for a series-wound DC (SWDC) motor, and the friction torque vs angular speed characteristic of its rotor, together with the result of a retardation test on it, are presented (Figure 2).

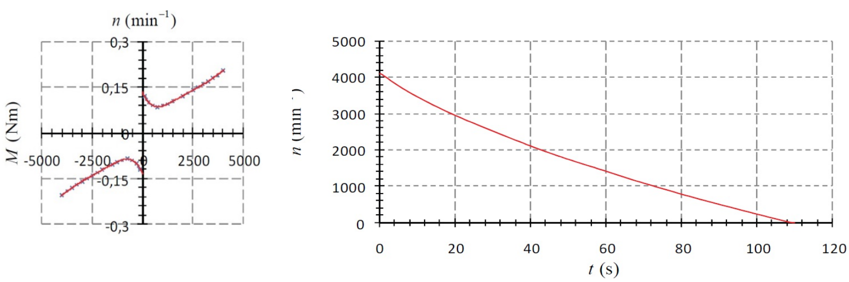

Figure 2
The friction torque vs angular speed characteristic of the analyzed SWDC motor, together with the result of a retardation test performed on it [10]

However, in [10], the obtained value for the moment of inertia and the uncertainties of the measured friction torques are not presented; furthermore, the method's accuracy is not reported. It is crucial to note that the accurate measurement of the friction torque can only be achieved by utilizing a torque meter with low nominal torque and high accuracy class. (Typical values for a commercially available device that can be applied for this purpose are: 0.5 Nm and 0.5%, respectively). Since the friction torque of electric motors, in some instances, can be less than 0.1 Nm, the relative error of torque measurement can be 2.5% or a higher value just because of the inaccuracy of the torque meter. Considering other experimental factors, the above error can be a significantly higher value. Since the relative error of the moment of inertia obtained for the rotor is further increased by the uncertainties of the angular accelerations coming from the retardation test, the approximated relative error of the moment of inertia determination is 4% or a higher value applying this method.

2.2 Methods based on the Direct Measurement of the Moment of Inertia

In this method, the moment of inertia of the rotor is directly measured; after that, the friction torque is identified as a function of angular speed. Knowing the moment of inertia, different methods can be applied to identify the friction torque, but the simplest way is to perform a retardation test on the motor. From the angular speed vs time curve – obtained from the retardation test – the angular acceleration vs angular speed curve of the rotor can be given. Multiplying this curve with the previously measured moment of inertia, the friction torque vs angular speed curve of the rotor can be obtained.

In [11], different experimental technics for directly measuring the moment of inertia of a rigid body are described and critically analyzed. The torsional and multifilar torsional pendulum methods are usually considered the most accurate among the oscillatory methods. In [11] [12], a relative error of less than 1% is reported for a trifilar torsional pendulum. It has to be emphasized, that the main source of error during the measurements with a multifilar pendulum comes from the inaccurate positioning of the center of gravity of the rotor. In [13], the relative error of the physical pendulum method for the determination of the moment of inertia of rigid bodies is presented as the function of the suspension distance. The reported values vary between 2.5 and 5%. According to the conclusion of the article, the optimal distance corresponding to the minimum value of 2.5% is somewhat smaller than the distance at which the total mass of the pendulum, concentrated in one point, must be placed, that the resulting mathematical pendulum's moment of inertia be the same, as the one of the original pendulum [13]. That is, the relative error of the physical pendulum method cannot be less than 2.5%.

Oscillatory methods similar to the physical pendulum method can also be used to determine the moment of inertia of electric motor rotors. The simplest way to do this is to eccentrically attach a point-like body of weight G_1 to the rotor at a given distance (a) from the axis of rotation (Figure 3), and then swing the resulting physical pendulum.

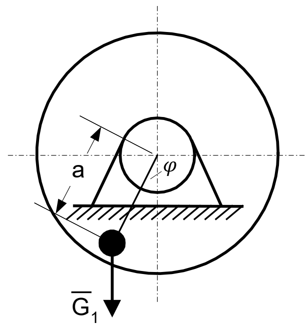

Figure 3
Experimental determination of the moment of inertia using the physical pendulum method

After that, the moment of inertia of the rotor can be calculated with the following formula [14]:

$$J_r = G_1 \cdot a \cdot \left(\frac{T^2}{4 \cdot \pi^2} - \frac{a}{g}\right) \tag{2}$$

In Equation (2), T is the period of the oscillation and g is the magnitude of the gravitational acceleration. It should be noted, that the error caused using the linearized equation of motion when deriving Equations (2) is negligible if, and only if the oscillation amplitude (φ) is less than ~ 0.1 rad, and it causes less than 1% relative error if the oscillation amplitude is below 0.4 rad.

In addition, the larger the friction torque acting on the rotor, the more imprecisely the oscillation time can be measured. Besides, applying the method can lead to considerable inaccuracies if the rotor is not well-balanced, and it is usually challenging to find its center of gravity or suspension center. Consequently, the value of the relative error of the method is significantly higher than the reported minimum value in [13].

Figure 4 shows the measurement arrangement of a modified, more accurate version of the previously presented oscillatory method. In this method, the rotor is placed on two ideal, horizontal, and parallel edges.

By displacing the system from its equilibrium position, it will be swinging. The moment of inertia of the rotor can be calculated as follows [14]:

$$J_r = G_1 \cdot a \cdot \left(\frac{T^2}{4 \cdot \pi^2} - \left(\frac{a}{g} + \frac{r^2}{a \cdot g}\right)\right) \tag{3}$$

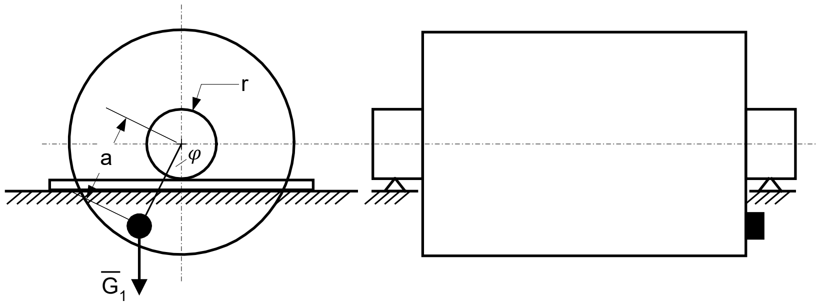

Figure 4
Experimental setup for the modified oscillatory method to measure the moment of inertia of the rotor

In Equation (3), a is the distance between the point-like body and the center line of the rotor, r is the radius of its shaft, T is the period of the oscillation, and g is the magnitude of gravitational acceleration. It has to be emphasized, that the error caused using the linearized equation of motion when deriving Equations (3) is negligible if, and only if, the oscillation amplitude (φ) is less than ~0.1 rad, and it causes less than 1% relative error if, the oscillation amplitude is below 0.4 rad. It has to be also mentioned, that we can get accurate results only, if the rotor is well-balanced, and the edges and the shaft are ideally rigid and smooth surfaced.

Furthermore, the values of parameters a and G_1 have to be chosen optimally to a given rotor with the moment of inertia J_r and rolling radius r. And, of course, all the quantities in the formula must be measured precisely.

In another method [15], the rotor of mass m with rolling radius r rolls down on an incline with an angle α (Figure 5).

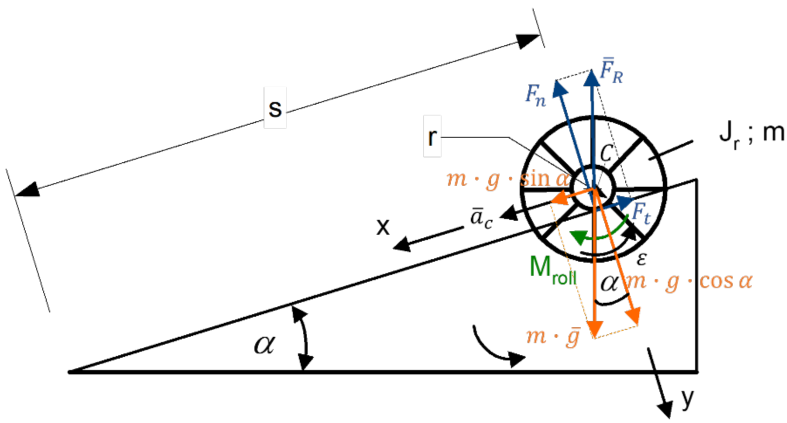

Figure 5
Experimental setup for the measurement of the moment of inertia of the rotor

From a video record – captured by a high-resolution camera – the position-time function of the rotor's center of mass $s(t)$ can be given. From the $s(t)$ function, the velocity-time function, and finally, the acceleration of the rotor's centre of mass (a_c) can be calculated [15]. Because the rolling friction between the rotor and the incline is not negligible, two individual roll-down experiments must be performed using different incline angles (α_1 and α_2). The value of both α_1 and α_2 are typically below 2°, thus rolling without slipping can be assumed. For the two roll-down experiments the following six dynamics equations can be written:

$$m \cdot g \cdot \sin\alpha_1 - F_{t1} = m \cdot a_{c1} \tag{4}$$

$$m \cdot g \cdot \cos\alpha_1 - F_{n1} = 0 \tag{5}$$

$$F_{t1} \cdot r - M_{roll1} = J_r \cdot \varepsilon_1 \tag{6}$$

$$m \cdot g \cdot \sin\alpha_2 - F_{t2} = m \cdot a_{c2} \tag{7}$$

$$m \cdot g \cdot \cos\alpha_2 - F_{n2} = 0 \tag{8}$$

$$F_{t2} \cdot r - M_{roll2} = J_r \cdot \varepsilon_2 \tag{9}$$

In the above equations F_t is the friction force, a_c and ε are the acceleration of the center of mass and angular acceleration of the rotor, M_{roll} is the rolling friction torque, which is calculated as:

$$M_{roll1} = f \cdot F_{n1},\ M_{roll2} = f \cdot F_{n2} \tag{10}$$

In the above equation f is the arm of the rolling friction, which can be also expressed with the rolling friction coefficient (c) as $f = c \cdot r$.

Since the rotor is rolling without slipping:

$$\varepsilon_1 = \frac{a_{c1}}{r},\ \varepsilon_2 = \frac{a_{c2}}{r} \tag{11}$$

From Equations (4-11) the moment of inertia of the rotor can be calculated as [15]:

$$\mathrm{J_r} = \mathrm{mr^2}\left(\mathrm{g}\frac{\tan\alpha_2 - \tan\alpha_1}{\frac{a_{c_2}}{\cos\alpha_2} - \frac{a_{c_1}}{\cos\alpha_1}} - 1\right) \tag{12}$$

It has to be mentioned, that during a usual experiment, the velocity of the center of mass of the rotor is always below 1 km/h [15]. Thus, in case of a rotor with a rolling radius of 1.5 cm [15], the angular velocity of the rotor is always below 19 rad $\mathrm{s^{-1}}$. The normal load on the shaft of the same rotor is about 120 N. Under the above conditions, based on the related scientific literature [16-19], the arm of rolling resistance is constant with a good approximation.

It must be also emphasized, that Formula 12 gives accurate result if, and only if, all the quantities are measured very precisely. If it is fulfilled, calculation with Gauss' Law of Error Propagation and validation measurements prove, the relative error of the method is about 2.5% [15].

In general, it can be concluded that directly measuring the moment of inertia of the rotor with sufficient accuracy is only possible if the rotor is demounted from the motor. Demounting the rotor can be destructive to the motor and laborious; therefore, it is not recommended.

2.3 Simultaneous Identification of the Moment of Inertia and Friction Torque

This section presents methods for simultaneously identifying the moment of inertia and friction torque without demounting the rotor from the motor. Several methods exist for simultaneous identification [9, 16, 20-22]. Section 2.3.1 gives examples for the identification by direct measurement, while Section 2.3.2 by offline methods.

2.3.1 Identification by Direct Measurement

In [20], a procedure for simultaneously and directly measuring the friction torque and moment of inertia of electric motors is given. The procedure is based on retardation tests on the motor applying additional loads – steel discs (1, 2) – on its rotor with different moments of inertia and equal masses (Figure 6). The discs are attached to the steel shafts (8) by applying four clamping rings (9) of the same type.

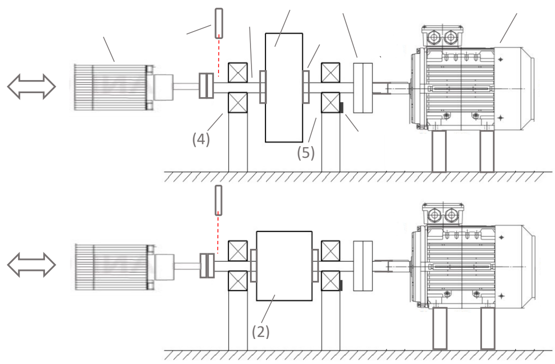

Figure 6

Experimental setup for the simultaneous direct measurement of the moment of inertia and friction torque of the rotor [20]

The equal masses produce equal friction torques in the supporting bearings (4, 5). During the experiments, a drive motor (11) is attached to the system's shaft through a clutch. When voltage is applied to the drive motor, the system starts to rotate from a standstill until it reaches its top speed. Then, the drive motor (11) and the shaft are disconnected, causing the rotating masses to slow gradually until they come to a halt. While the system slows down, its angular speed is monitored by an optical LED sensor (12). Simultaneously, the surface temperature of the outer ring of the bearing (5) is observed using a Resistance Temperature Detector (14). The entire experiment involves four measurements: First with only disc (1), second with disc (1) and the analyzed motor, third with disc (2) and the analyzed motor, and lastly with only disc (2) connected to the drive motor (11). Figure 7 shows the system's angular speed vs time function gained from the second measurement. The connection is released at the moment 1.8 s.

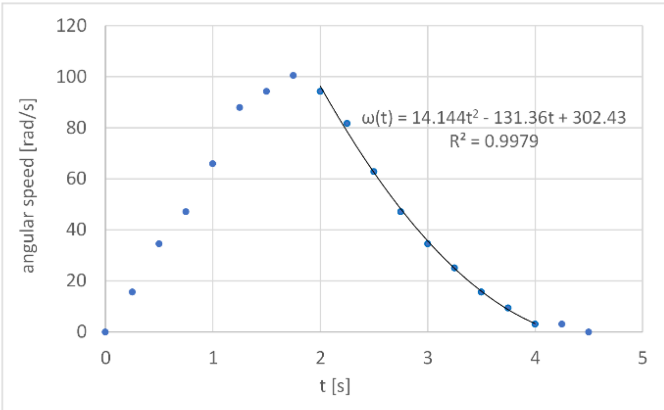

Figure 7

Angular speed vs time function of the system when disc (1) and the analyzed motor are connected to the drive motor. The connection is released at the moment 1.8 *s*

The rotating systems' angular acceleration vs time functions are calculated by derivation from the fitted angular speed vs time functions. After that, the angular acceleration is given as a function of angular speed. Thus, the results of the four experiments are four angular acceleration vs angular speed functions. For the four experiments, we can write the following four equations:

$$M_{brake}^{*} = (J_1 + J_{add1}) \cdot \varepsilon_1 \quad (13)$$

$$M_{brake}^{*} + M_{brake} = (J_1 + J_\mathrm{r} + J_{add2}) \cdot \varepsilon_{1\mathrm{m}} \quad (14)$$

$$M_{brake}^{*} = (J_2 + J_{add1}) \cdot \varepsilon_2 \quad (15)$$

$$M_{brake}^{*} + M_{brake} = (J_2 + J_\mathrm{r} + J_{add2}) \cdot \varepsilon_{2\mathrm{m}} \quad (16)$$

In Equations (13), (14), (15) and (16):

$$J_{add1} = J_{shaft} + 2 \cdot J_{clpr} + 2 \cdot J_{ring} \quad (17)$$

$$J_{add2} = J_{shaft} + 2 \cdot J_{clpr} + 2 \cdot J_{ring} + J_{clutch} \quad (18)$$

In the equations above M_{brake} and J_r are the friction torque and moment of inertia of the rotor of the analyzed motor, M_{brake}^{*} is the summed friction torque of supporting bearings 4 and 5, J_1, J_2, J_{shaft}, J_{clpr}, J_{clutch}, J_{ring} are the moments of inertia of disc (1), disc (2), one shaft, one clamping ring, the clutch and the inner ring of a supporting bearing, which were calculated from their measured geometric data and masses, and ε_1, ε_{1m}, ε_{2m}, ε_2, are the angular accelerations of the four rotating systems during the retardation tests. From Equations (13-16) the following equations can be derived for the moment of inertia and friction torque of the analyzed motor:

$$J_r = \frac{J_2 \cdot \varepsilon_{2m} - J_1 \cdot \varepsilon_{1m}}{(\varepsilon_{1m} - \varepsilon_{2m})} - J_{add2} \tag{19}$$

$$M_{brake} = (J_2 - J_1) \cdot \frac{\varepsilon_{1m} \cdot \varepsilon_{2m}}{(\varepsilon_{1m} - \varepsilon_{2m})} - (J_1 + J_{add1}) \cdot \varepsilon_1 \tag{20}$$

Instead of Equation (20) the friction torque can be also expressed as the function of the moment of inertia of the rotor (J_r) and other parameters. Using the previously determined constant value of the moment of inertia in the whole angular speed range in this formula, the errors of the experimentally determined friction torques can be further reduced, mainly below $30\ \text{rad}\ \text{s}^{-1}$. It has to be noted, that the main advantage of the direct measurement of the friction torque (see in Section 2.1) against this method, that it is more accurate in the low angular speed range.

The accuracy of the presented method strongly depends on the measurement conditions and procedure. In the case of the optimal selection and implementation of the measurement conditions and procedure, the errors of the determined moment of inertia and friction torque can be minimized. To minimize the error, the following should be done:

1) Moments of inertia J_1 and J_2 have to be chosen optimally.
2) The measurement times, thus the heating of the bearings, have to be minimized.

The determination of the optimal values of J_1 and J_2 , at which the error of the experimentally determined moment of inertia is minimum, together with the effect of the heating of the bearings on the accuracy of the method are discussed in detail in Section 4 in Reference [20]. Under optimal measurement conditions, the certified relative error of the method for the measurement of the moment of inertia is 4.3-5.3%, while for the measurement of the friction torque is 3-6% in the $[30; 120]\ \text{rad}\ \text{s}^{-1}$ angular speed range. Under $30\ \text{rad}\ \text{s}^{-1}$ angular speed, the experimental errors are significantly higher, because of the higher standard deviations of the angular accelerations determined from the measured angular speeds. Thus, only the $[30; 120]\ \text{rad}\ \text{s}^{-1}$ angular speed range in Figure 8, where the moment of inertia is approximately constant, can be used for evaluation. The average value of the moment of inertia in the above range, is considered as its experimentally determined value. Figures 8 and 9 show the experimentally determined moment of inertia and breaking torque of a squirrel cage induction motor.

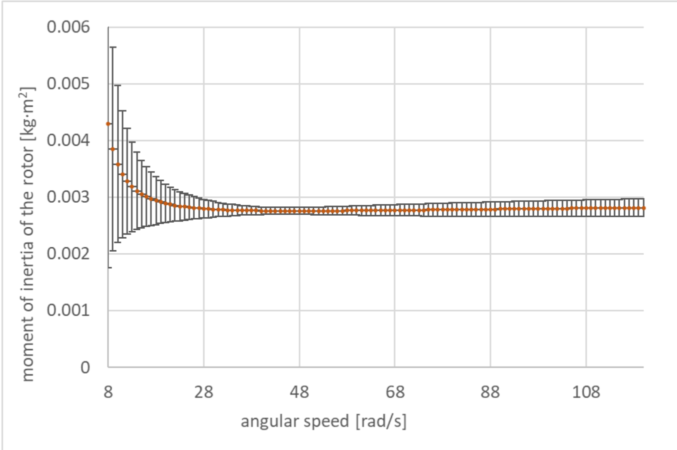

Figure 8
The experimentally determined values of the moment of inertia of the rotor of a squirrel cage induction motor [20]

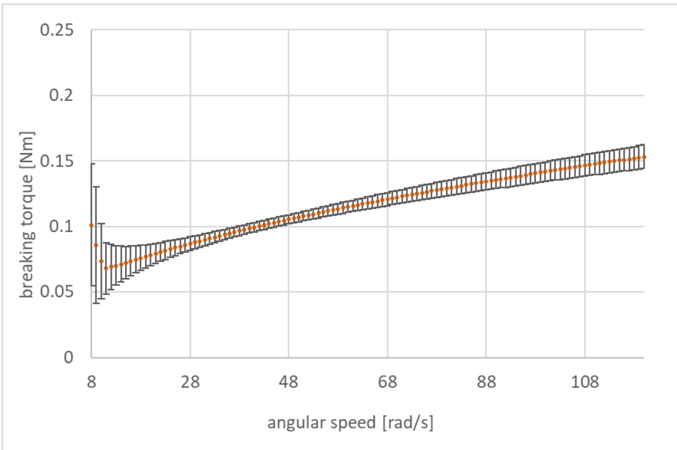

Figure 9
The experimentally determined friction torque of the rotor of a squirrel cage induction motor [20]

2.3.2 Identification by Offline Methods

The goal of offline parameter identification is to accurately estimate various motor parameters, which can include electrical, mechanical, and thermal characteristics. These parameters are essential for motor control, performance analysis, and design optimization. To carry out offline parameter identification, specific tests and measurements are performed on the motor, and the acquired data is then analyzed and processed to estimate the desired parameters. Here are a few commonly used offline parameter identification methods for electric motors:

1) Locked Rotor Test: In this test, the rotor of the motor is mechanically prevented from rotating while an electrical voltage is applied to the stator windings. By measuring the resulting current and voltage, parameters such as winding resistance, leakage inductance, and core losses can be estimated. [23]
2) No-Load Test: This test involves running the motor without any mechanical load applied to the output shaft. By measuring the no-load current, no-load voltage, and rotational speed, parameters like core losses, friction, and windage losses can be determined. [24]
3) Load Test: Load tests are conducted by subjecting the motor to various mechanical loads while measuring the input voltage, input current, and rotational speed. By analyzing these measurements, parameters such as torque constant, motor efficiency, and mechanical losses can be identified. [25]
4) Thermal Analysis: Thermal analysis involves monitoring the temperature rise of the motor during operation under different load conditions. By measuring and analyzing the temperature data, parameters related to thermal resistance, heat transfer coefficients, and thermal time constants can be estimated. [26]

Sometimes, Direct Parameter Measurements are also classified here, in which certain motor parameters are measured directly using specialized equipment. [4]

The acquired data from these tests are typically processed using mathematical modelling, curve fitting techniques, or advanced data analysis methods and algorithms – e.g., genetic algorithm [9] [21] – to estimate the motor parameters accurately. The accuracy and reliability of the estimation depend on the test setup, data quality, and the mathematical models and algorithms used for analysis. Offline parameter identification methods are valuable for obtaining crucial motor information without the need for real-time operation or control. They provide insights into motor characteristics and enable better motor control, system design, and performance optimization.

In [9, 21, 22], experimental offline methods for the parameter identification of an induction motor drive are presented. In [21], the method uses speed-time curves obtained during the retardation test on the drive, with an appropriate model for the mechanical losses and the mean squared error performance function based on a genetic algorithm approach, to obtain the unknown mechanical parameters of the tested drive. Theoretically estimated and experimentally determined speed-time curves, obtained from retardation tests, are compared, but the accuracies of the identified parameters are not given. In [22], a new step-by-step approach to identifying the parameters of an induction machine combining free acceleration and deceleration transient data is presented. When the machine is in standstill without mechanical load, the three-phase ac power is applied to the stator terminals. During the free acceleration transient, the measurement of the stator line voltage and current is required only. The free acceleration torque characteristic is used to identify the moment of inertia of the rotor, and a new algorithm is proposed to perform it with higher accuracy. The identification results are compared with motor parameters determined from locked-rotor and no-load tests, and the obtained relative difference is about 3%. The parameters of the different mechanical losses were not identified. In [9], a method is described for the offline identification of the electromagnetic and mechanical parameters of a mathematical model of an induction motor using genetic algorithms. Identification is performed using data acquired during a test consisting of a transient from standing still to a certain speed and successive free motion to standing still.

Conclusions

Methods for identifying the moment of inertia and friction torque of rotors in electric motors, have been reviewed here, in detail. The following conclusions can be drawn:

- The direct measurement of the moment of inertia, with sufficient accuracy, is usually only possible if the rotor is removed from the motor. In this case, several methods exist, the error of which strongly depends on the selection of the value of the measurement parameters and their measurement uncertainties. The least error can be achieved by using a trifilar torsion pendulum, which is approximately 1%.
- Removing the rotor is laborious and can lead to damage to the motor, so it is usually not recommended.
- If the rotor is not removed from the motor, one of the following procedures is recommended:
    - Direct measurement of the friction torque using a rotary torque meter, then determining the moment of inertia from a retardation test. Applying a commercially available torque meter with a nominal torque of 0.5 Nm and accuracy class 0.5%, the estimated attainable relative error of friction torque and moment of inertia determination is 3% and 5%, respectively.
    - Direct simultaneous measurement of the friction torque and moment of inertia. The attainable relative error with the method presented in this publication is 3-6% and 4-5%, respectively.
    - Applying an offline parameter identification method. The main advantage of these methods is that a lot of, or all the unknown parameters of an electric motor can be identified simultaneously. Their drawbacks are their complexity and the inaccuracy of the applied models and algorithm can result in significant errors in the identified parameters. In addition, a unique model has to be developed for each motor type.

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