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In-Service Efficiency Estimation with the use Modified Air-Gap Torque Method for Squirrel-Cage Induction Motor

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Introduction

Squirrel-cage induction motors are used in many industrial applications. Their advantages such as low price and low failure rate has caused the expansion of these machines in many industries compared to other types of electrical machines. These motors are often below face value because they are oversized in relation to the load with which they work most of the time. Squirrel-cage induction motors are supplied from frequency converters. Then motors can work with variable speed. In these case the motor efficiency changes as a function not only load but also frequency. Economic considerations associated are going to move to low energy consumption. Thas why it is necessary to monitoring the efficiency factor of the motor, and ultimately control of his work in energy-efficient [1–3].

Induction-cage motor efficiency

There are many methods used to field efficiency evaluation in the literature [2–9], and new methods are appearing every year. The coefficient of efficiency is the ratio of mechanical output power P_2 obtained at the motor shaft to the active power absorbed by the induction motor P_1, and it defines as follows

$$\eta = \frac{P_2}{P_1}. \tag{1}$$

The efficiency estimation is made for the following assumptions:

- Three-phase power source is symmetrical;
- The phase voltages are sinusoidal;
- The stator windings are symmetrical;
- The rotor windings is replaced by a symmetrical three-phase windings;
- The motor is a linear receiver.

The value of instantaneous power collected by the motor p_1 is equal to the average active power P_1 for these assumptions. The active power P_1 can be determined from the instantaneous value of phase currents and instantaneous value of phase voltages measured on the supply side of the motor. The instantaneous value of motor power P_1 can be calculated according to the relationship

$$P_1 = u_U i_U + u_V i_V + u_W i_W \,. \tag{2}$$

For a three-phase connected motor without the neutral points, the phase voltages and phase currents are assumed to add to zero as in:

$$\begin{cases} i_U + i_V + i_W = 0, \\ u_U + u_V + u_W = 0. \end{cases} \tag{3}$$

According to the equation (3) measurement of voltages and currents can be reduced to measuring these value in two phases only. In this way the number of measuring instruments needed to be installed on the supply side of the motor could be limited. To reduce the ripples caused by the energy stored in the windings, the average value of instantaneous power is used to calculate efficiency.

Determination of mechanical power P_2 devoted to the motor shaft is is more complicated. The laboratories method of motor shaft power P_2 measure is the indirectly methods. The motor shaft torque T and the rotor speed n [10, 11] are measured. The motor power P_2 is calculated as follows

$$P_2 = \frac{2\pi T n}{60}. \tag{4}$$

This method is characterized high accuracy depending on the class of precision measuring instruments used [8]. But this solution is not used in industrial environments. The main reason is the need of mechanical interference with the propulsion machinery. This is due to the high cost of structural alterations and the cost of buying measuring equipment.

One of non-intrusive method of motor shaft power P_2 determine is method which is based on the distribution of power losses occurring in the induction motor [2, 3, 8, 9].

Power flow of induction motor

The motor shaft torque P_2 could be calculated as the difference of input active motor power P_1 and the total motor power loss $\Sigma\Delta P$. I could be determined as follows

$$P_2 = P_1 - \Sigma\Delta P\,. \tag{5}$$

The total motor power loss $\Sigma\Delta P$ is defined as the sum of the stator copper loss (ΔP_{Cus}), the stator stray load loss (ΔP_{dods}), the core loss (ΔP_{Fe}), the friction and windage loss (ΔP_m), the rotor copper loss (ΔP_{Cur}) and the rotor stray load loss (ΔP_{dodr}). The total motor power loss $\Sigma\Delta P$ is calculated according to

$$\Sigma\Delta P = \Delta P_{Cus} + \Delta P_{Fe} + \Delta P_{dods} + \Delta P_{Cur} + \Delta P_{dodr} + \Delta P_m\,. \tag{6}$$

The total power loss from the distribution of power loss in the stator and the rotor is illustrated in figure 1. The power losses of stator are denoted as the subscript "*s*" and the power losses of rotor are denoted as the subscript "*r*".

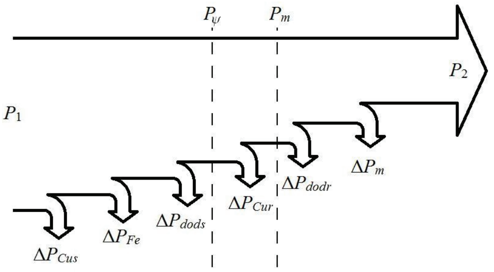


Fig. 1. The power loss distribution of squirrel-cage induction motor

Using the equation (4) the flux power in the air gap can be defined as the dependence of electromagnetic torque T_{ag} in the air-gap and rotational speed n_s of the magnetic field generated in the stator. The flux power can be calculated as

$$P_\Psi = \frac{2\pi\, T_{ag} n_s}{60}\,. \tag{7}$$

The mechanical power P_m (Fig. 1) is defined as difference between the flux power P_Ψ and the rotor copper loss ΔP_{Cur}

$$P_m = P_\Psi - \Delta P_{Cur}\,. \tag{8}$$

The rotor copper loss P_{Cur} is proportional to flux power P_Ψ and slip s in the squirrel-cage induction motor. The copper loss P_{Cur} is defined as

$$\Delta P_{Cur} = sP_\Psi\,. \tag{9}$$

According to equations (8) and (9), the mechanical power P_m can be calculated as

$$P_m = (1-s)P_\Psi\,. \tag{10}$$

Based on figure 1 and according to equations (6) and (9), the motor shaft power P_2 is finally defined as

$$P_2 = \frac{2\pi}{60} T_{ag} n - \left(\Delta P_m + \Delta P_{dod}\right), \tag{11}$$

where

$$n = (1-s)n_s\,. \tag{12}$$

Determination of efficiency of squirrel-cage induction motor

According to equation (1) and (11) to designate the squirrel-cage induction motor efficiency coefficient η it is needed to determine the values of electromagnetic torque T_{ag}, rotational speed n of the motor shaft, the value of friction and windage power losses ΔP_m and value of rotor stray load loss ΔP_{dodr}.

Rotor speed n depends on the frequency f of supply voltage and the motor shaft torque T. The rotor speed estimation was repeatedly discussed in scientific publications [12,13,14,15,16]. In this study, was used direct measurement of motor speed, assuming the possibility of using the methods listed in the literature.

Air-gap torque determination

Air-gap torque T_{ag} of squirrel-cage induction motor is defined as the product of the vector $\boldsymbol{\Psi}$ of instantanious phase flux value and the vector $\boldsymbol{i}_\mathrm{s}$ of instantanious stator phase current value of the motor

$$T_{ag} = p\left|\boldsymbol{\Psi} \times \boldsymbol{i}_\mathrm{s}\right|, \tag{13}$$

where p – number of poles pairs; $\boldsymbol{\Psi}$ – vector of instantanious phase flux value defined as follows

$$\boldsymbol{\Psi} = \begin{bmatrix}\Psi_U & \Psi_V & \Psi_W\end{bmatrix}^{-1}, \tag{14}$$

where $\boldsymbol{i}$ – vector of instantanious phase currents value defined as follows

$$\boldsymbol{i}_\mathrm{s} = \begin{bmatrix}i_U & i_V & i_W\end{bmatrix}^{-1}. \tag{15}$$

The flux vector $\boldsymbol{\Psi}$ can be determined on the basis of the stator voltage equation in vector form. The flux vector $\boldsymbol{\Psi}$ is

$$\boldsymbol{\Psi} = \int\left(\boldsymbol{u}_\mathrm{s} - R_\mathrm{s}\boldsymbol{i}_\mathrm{s}\right)dt\,, \tag{16}$$

where R_s – stator phase resistance; $\boldsymbol{u}_\mathrm{s}$ – vector of instantanous value of phase voltages

$$\boldsymbol{u}_\mathrm{s} = \begin{bmatrix}u_U & u_V & u_W\end{bmatrix}^{-1}. \tag{17}$$

According to equation (3) the voltage and the current of third phase can be determined as

$$u_W = -u_U - u_V \tag{18}$$

and the current

$$i_W = -i_U - i_V\,. \tag{19}$$

On the basis equations from the (13) to (19) the electromagnetic torque T_{ag} in the motor air-gap is defined

$$T_{ag} = \sqrt{3}\,p_\mathrm{b}\left[i_V \int\left(u_U - R_\mathrm{s} i_U\right)dt - i_U \int\left(u_V - R_\mathrm{s} i_V\right)dt\right]. \tag{20}$$

For many induction motors, the neutral points are not accessible from the motor terminals. Therefore, only the line-to-line voltages are available. The equation (20) for line-to-line voltage is

$$T_{ag} = \sqrt{3}p\begin{bmatrix} i_V \int\left(\dfrac{u_{UV} - u_{WU}}{3} - R_s i_U\right)dt \\ + i_U \int\left(\dfrac{2u_{UV} + u_{WU}}{3} + R_s i_V\right)dt \end{bmatrix}. \tag{21}$$

According to equation (21) the air-gap electromagnetic torque T_{ag} can be calculated knowing the number of induction motor pole pairs p and the instantaneous values of the two phase currents (i_U, i_V) and the instantaneous values of the two line-to-line voltage (u_{UV}, u_{WU}). Occurring phase resistance R_s can be measured with technical metod or estimate [17–21].

Measurement of stator windings resistance R_s with technical method is quite difficult because the supply cable of motor must be disconnected and changes of stator winding teperature must be take into account when the air-gap torque T_{ag} is determining. In this case, the motor should be equipped with thermistors to measure the temperature of the windings.

One of estimating method of the value of the stator winding resistance is the injection of DC current in one phase of the stator windings. This method provides accurate estimation of stator resistance R_s at start up, load changes and abnormal cooling conditions. When the motor is supply from the inverter, the injection of DC current can be achieved by interfering with the drive software.

Friction and windage loss and rotor stray-load loss determination

The friction and windage losses ΔP_m of the squirrel cage induction motor are interfered with power loss of the friction in the birings and the power loss of the cooling system. The friction and windage loss ΔP_m is grow into proportional to square of rotor speed n. The approximate value of the friction and windage loss ΔP_m can be determined as follows [5]

$$\Delta P_m \approx (a_1 \mu F + a_2)n^2 . \tag{22}$$

Rotor stray load losses ΔP_{dodr} are the fundamental and highfrequency losses in the structure of the motor, circulating current losses in the stator winding, and harmonic losses in the rotor conductors under load. These losses are proportional to the square of the rotor current [5]

$$\Delta P_{dod} \propto I_r^2 . \tag{23}$$

The value of the friction and windage losses ΔP_m and rotor stray load losses ΔP_{dodr} are defined as a percentage of motor output power P_2 [4] according to IEEE 112 standard. I this paper the value of the friction and windage losses ΔP_m are estimated as a function of rotor speed n. The rotor stray load losses ΔP_{dodr} were adopted as proposed in the IEEE 112 standard (Table 1) [4].

On the basis equations (11) and (21) the value of the sum of the nominal friction and windage losses ΔP_{mN} and the nominal rotor stray load losses ΔP_{dodrN} can be calculated.

Table 1. The rotor stray load losses

Power ranges	Stray load loss percent of rated output power
1 – 90 kW	1,8%
91 – 375 kW	1,5%
376 – 1850 kW	1,2%
1851 kW and up	0,9%

It is posible when the nameplate data are used. The sum the nominal friction and windage losses and the nominal rotor stray load losses (ΔP_{mN}+ΔP_{dodN}) is expression as follows

$$\Delta P_{mN} + \Delta P_{dodN} = P_{mN} - P_{2N} . \tag{24}$$

When the nominal stray load losses ΔP_{dodrN} are defined as the percentage of nominal motor output power P_{2N}, according to table 1, the nominal value of friction and windage losses ΔP_{mN} can be expressed as

$$\Delta P_{mN} = P_{mN} - 1{,}018 P_{2N} . \tag{25}$$

The experimental results of the friction and windage losses ΔP_m of squirrel-cage induction motor shows that the losses ΔP_m can be estimated one of the function: square function or linear function. In this paper the friction and windage losses are estimated with the use the linear function

$$\Delta P_m^e = c_1 n . \tag{26}$$

The c_1 is linear function coefficient. The c_1 value is calculated according to expression

$$c_1 = \frac{\Delta P_{mN}}{n_N} . \tag{27}$$

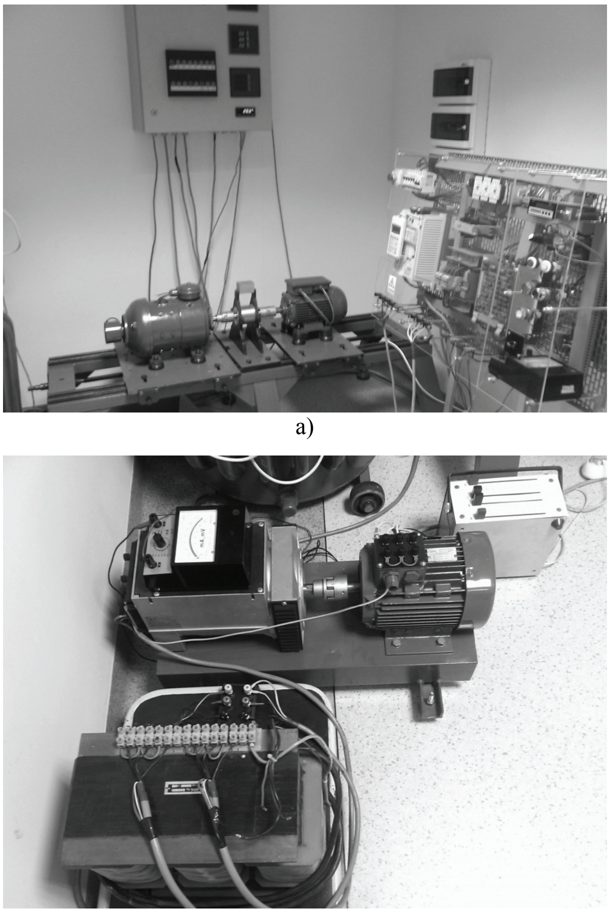
Experimental setup

Measurements of motor efficiency were made using the laboratory stand to test squirrel-cage induction motors (Fig. 2). The tested motor IM2 (Table 2) is supplied by sinusoidal voltage with synchronous generator SG (Fig. 3). Synchronous generator SG allows to change the frequency f and the RMS value of supply voltage U.

The power supply circuit of motor IM2 uses a measuring instrument MPS. As the load of the tested motor IM2 was used DC generator DCG. DCG is powered by thyristor power unit DML which can return of energy to the grid. This has provided the ability to change the motor IM2 shaft torque test range from 0 to 1.2 T_N [22].

Table 2. Technical data of tested motor

Motor type: TAMEL Sg100L		
U_N	400	[V]
I_N	4,8	[A]
P_N	2200	[W]
f_N	50	[Hz]
n_N	1420	[rpm]
T_N	14,8	[Nm]
$\cos\varphi_N$	0,80	[-]
η_N	0,82	[-]



a)

b)

Fig. 2. a – the laboratory stand view: testing motor IM 2, DC generator DCG; b – The laboratory stand view: induction motor IM1 and synchronius generator SG

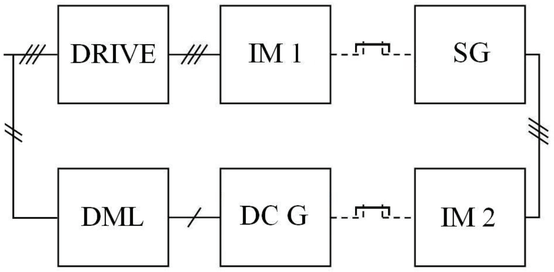


Fig. 3. Block diagram of the station for testing induction-cage motors

Each of the measuring instrument is provided with a standard RS485 serial interface, therefore it is connected to a common network topology Modbus. PLC control circuits, switching power contactors, and reads digital signals indicating the operating status of specific devices. Control and measuring devices are managed by PCs computer. The study was performed for a frequency f range from 15 to 55 Hz. For selected values of the frequency f the motor load tests were performed. The value of phase currents (i_U, i_V, i_W) and voltage (i_{UV}, i_{VW}, i_{WU}), of the motor and value of rotor speed n and the value of shaft torque T were saved.

The accuraces of measuring equipment were shown at table 3. The total measuring error was calculated with the use the total differential method [23, 24].

Table 3. Accuracy of measurement equipment

The measurand	Accuracy of measuring equipment
Line-to-line voltage: u_{UV}, u_{WU}	0,2
Phase current: i_U, i_V	0,5
Rotational speed: n	0,1
Motor shaft torque: T	0,2
Frequecy: f	0,1

Experimental validation

On the basis of measurements the value of the estimating efficiency coefficient was compared using three methods. In the first case, the motor output power P_2 are based on the indication of the shaft torque T and rotational speed n from according to the relation (4). The results obtained by this method is marked as dots in figures 4,5,6 and 7 (marked as „1“). The second estimation method of efficieny coefficient is marked as solid line – number 2. This estimation method based on the estimation friction and windage losses as a linear function acording to equation (26). At last - a third method of estimation efficiency coefficient (dashed line – number 3) used the percetage value of friction and windage losses. The percentage value is determined in accordance with IEEE 112 standard.

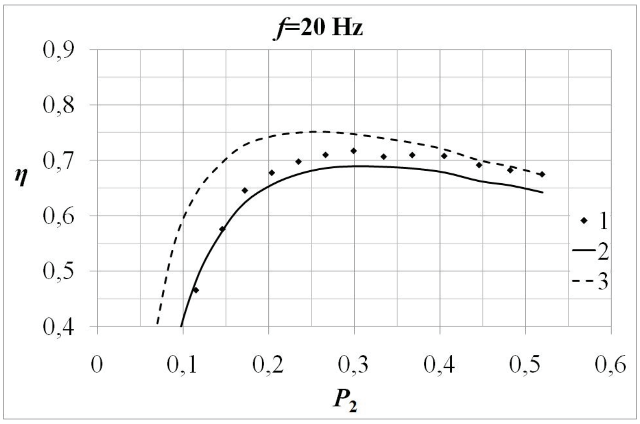


Fig. 4. The squirrel-cage induction motor efficiency coefficient η as the function of motor output power P_2 for the frequency f=20Hz

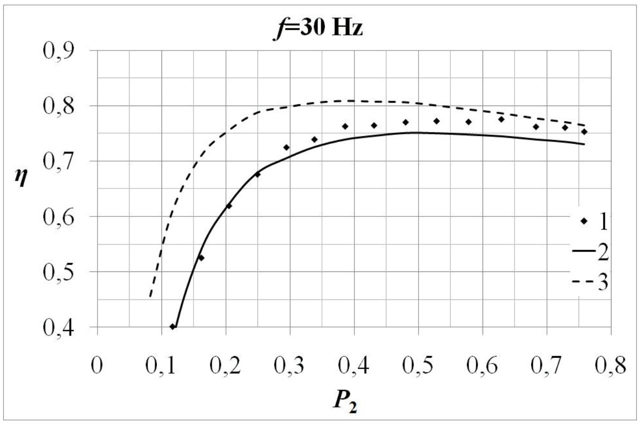


Fig. 5. The squirrel-cage induction motor efficiency coefficient η as the function of motor output power P_2 for the frequency f=30Hz

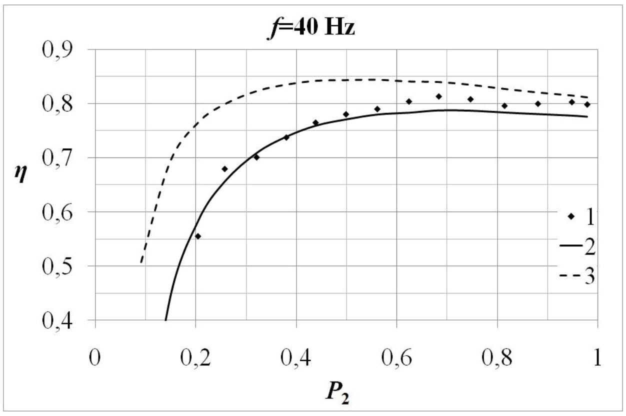


Fig. 6. The squirrel-cage induction motor efficiency coefficient η as the function of motor output power P_2 for the frequency f=40Hz

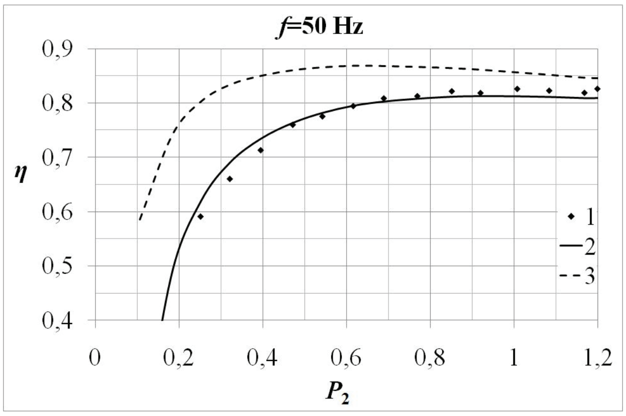


Fig. 7. The squirrel-cage induction motor efficiency coefficient η as the function of motor output power P_2 for the frequency f=50Hz

The experimental results show that the accuracy of the estimation method of friction and windage losses in the tested motor increases with a reduction of the frequency f of supply voltage increases.

Conclusions

In this paper the estimation method of squirrel-cage induction motor efficiency coefficient was presented. The advantage of this method is possibility to on-line estimating efficiency. No-load test, short-circuit test and load test are not required. The data used to determine the coefficient of efficiency derived from the nameplate or measured on the stator side of the motor. The presented method is derived from the method of distribution of power losses in the motor.

The friction and windage losses in squirrel-cage induction motors are estimated at several percent of the motor output power. Results of laboratory tests showed that the change in the estimation of friction and windage losses has important implications for estimating of the motor efficiency. Accuracy of estimation motor efficiency coefficient is of great importance for energy-efficient control systems. Control systems can be chosen point of its work to minimize the energy consumption of the process when the instantaneous value of motor efficiency is known. The presented research has been done for a single engine. The results suggest repeating the tests for a few motors in order to refine the method. It is possibility to applying this method of estimating the efficiency of sqirrel-cage induction motor at the pumping water control systems.

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Energy-efficient industrial drives and control systems are designed to minimize power consumption. Energy consumption is associated with the efficiency of energy conversion in electric motors. In the paper the nonintrusive efficiency estimation method for induction cage motor was shown. The implementation of the method was based on the air-gap torque method. The results were compared with those obtained with the classical air-gap torque method. The authors present a significant impact of estimation of mechanical power losses in the engine on the accuracy of estimating the coefficient of efficiency cage induction motor. Ill. 7, bibl. 24, tabl. 3 (in English; abstracts in English and Lithuanian).

R. Figura, E. Szychta, L. Szychta. Modifikuoto metodo taikymas oro terpės momentu indukcinio variklio efektyvumo koeficientui nustatyti „on-line“ būdu // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2011. – Nr. 8(114). – P. 51–56.

Energiją taupančios sistemos, valdančios pramoninius variklius yra skirtos elektros energijos suvartojimui minimizuoti. Energijos sąnaudos yra susijusios su elektros variklių efektyvumu. Straipsnyje pristatomas neinvazinis indukcinio variklio efektyvumo nustatymo metodas. Šis metodas buvo įgyvendintas remiantis AGT (air-gap torque) metodu. Gauti rezultatai buvo palyginti su klasikiniu metodu gautais AGT rezultatais. Autoriai daug reikšmės teikia mechaninės galios nuostolių variklyje įvertinimui tiksliai nustatant indukcinio variklio naudingumo koeficientą. Il. 7, bibl. 24, lent. 3 (anglų kalba; santraukos anglų ir lietuvių k.).