squirrel-cage motor efficiency, motor efficiency testing,
AGT method, efficiency estimating,
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THE SQUIRREL-CAGE MOTOR EFFICIENCY DETERMINATION BY MODIFIED AGT METHOD

The modified air gap torque method to determine the efficiency coefficient of squirrel-cage induction motor was presented. The results of a continuation of work on the application of the method to estimate the efficiency coefficient also are shown. The verification of the proposed method on a few selected motors of small power are presented in this article

WYZNACZANIE WSPÓŁCZYNNIKA SPRAWNOŚCI SILNIKA KLATKOWEGO ZMODYFIKOWANĄ METODĄ AGT

W artykule została zaprezentowana zmodyfikowana metoda Air Gap Torque (AGT) do wyznaczania współczynnika sprawności silnika indukcyjnego klatkowego. Zaprezentowane również zostały wyniki badań będące kontynuacją prac nad zastosowanie metody AGT do estymacji współczynnika sprawności. W artykule dokonano weryfikacji proponowanej metody na kilku wybranych silnikach małych mocy

1. INTRODUCTION

Squirrel-cage induction motors are widely used in various industrial applications. These engines usually operate below nominal values because they are oversized in relation to the power-driven machinery and equipment. In many cases, these motors are powered by inverters to change the rotor speed. Under such conditions, the motor efficiency varies as a function of not only the load but olso the supply voltage and frequency. Economic considerations related to the lowering of energy consumption in industrial processes make it expedient to act in the direction of monitoring the engine operating efficiency ratio, and

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ultimately control the operation of the engine in an energy-efficient [1,2,3]. This paper presents matters relating estimation of the coefficient of efficiency selected based methods of estimation method of electromagnetic torque in the motor air gap, allowing factor estimates motor efficiency at on-line mode.

Several methods of determining factor induction motor efficiency η are known. They can be divided as follows [2]:

- slip measuring methods,
- methods based on measurement of stator phase current,
- methods based on equivalent circuit,
- methods of determining the losses involved,
- AGT (Air Gap Torque) methods
- torque measuring methods.

The article was adopted way of determining factor efficiency η by determining the electromagnetic torque in the motor air gap. This solution requires no installation on the actual specialized propulsion system of the measuring instrumentation.

The efficiency η is defined in the following relationship:

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

where: P_1 – average of input motor active power
P_2 – average of the output motor power

The average input motor power P_1 for the special case in which the variables are balanced and sinusoidal supply voltage symmetrical three-phase motor is determined as follows [4,5]:

$$P_1 = u_U i_U + u_V i_V + u_W i_W \tag{1}$$

where: u_U, u_V, u_W – instantaneous value of the phase motor voltages
i_U, i_V, i_W – instantaneous value of the motor wired currents

The output power P_2 was determined using the direct method by measuring the average value of torque T and the average value of rotor speed n in the laboratory. The power P_2 was calculated according to the relation [4,6]:

$$P_2 = \frac{2\pi T n}{60} \tag{3}$$

The above method of determining the output power P_2 is not applicable in practice. The output power P_2 is determined based on parameters measured on the supply side of the motor, such as voltage, current or frequency. These methods are subject to estimation error.

2. THE OUTPUT POWER ESTIMATION METHOD

Distribution of the power losses of induction motor is shown at the figure no. 1. The output power P_2 is determined by the relation [6]:

$$P_2 = P_\Psi - \Delta P_{Cur} - \Delta P_{Fer} - \Delta P_{dodr} - \Delta P_m \tag{4}$$

where: ΔP_{Cur} – rotor cooper losses
ΔP_{Fer} – rotor core losses
ΔP_{dodr} – rotor stray load losses
ΔP_m – friction and windage losses

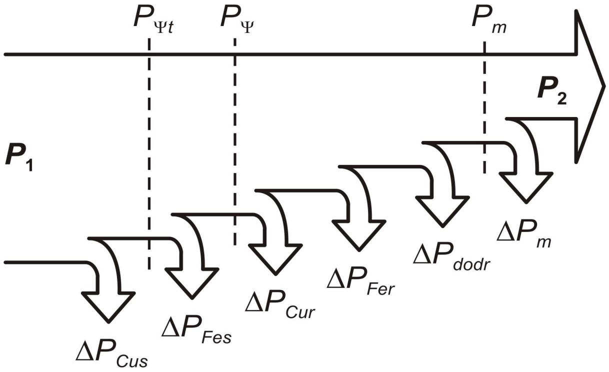


Fig. 1. Distribution of the squirrel-cage induction motor power losses

The power losses ΔP_{Cur} in the winding rotor are defined with the relationship:

$$\Delta P_{Cur} = sP_\Psi \tag{5}$$

The rotating field power P_Ψ is determined based on the average electromagnetic torque T_{ag} found in the air gap and the synchronous speed n_s:

$$P_\Psi = \frac{2\pi\, T_{ag} n_s}{60} \tag{6}$$

where: T_{ag} – the average electromagnetic torque determined from the instantaneous values of electromagnetic torque:

$$T_{ag} = \frac{1}{T}\int_0^T t_{ag}\, dt \tag{7}$$

Taking into account the dependence (5) and (6) the output power P_2 can be determine as follows:

$$P_2 = \frac{2\pi\, T_{ag} n}{60} - \Delta P_{Fer} - \Delta P_{dodr} - \Delta P_m \tag{8}$$

The equation (8) provides a basis for estimating capacity of donated P_2 on the motor shaft during operation by the electric control system. The electromagnetic torque t_{ag} is defined as the product module of the instantaneous values vector of stator flux $\boldsymbol{\psi}_s$ and instantaneous values vector of stator currents [7,8,9]:

$$t_{ag} = p\left|\boldsymbol{\psi}_{\mathbf{s}} \times \boldsymbol{i}_{\mathbf{s}}\right| \tag{9}$$

where: p – pole pairs number
$\boldsymbol{\psi}_s$ –the instantaneous values vector of stator flux
$\boldsymbol{i}_s$ – instantaneous values vector of stator currents.

The flux $\boldsymbol{\psi}_s$ in equation (9) determines its real value in the motor and is the basis for calculating the power P_Ψ rotating field (Fig. 1). Analytical determination of stator flux value is based on generally accepted surrogate motor circuit [4], which are omitted in the core loss of stator ΔP_{Fes}. Introducing the concept of a replacement vector $\boldsymbol{\psi}_{\mathbf{st}}$ instantaneous values of stator flux:

$$\boldsymbol{\psi}_{\mathbf{st}} = \int \left(\boldsymbol{u}_{\mathrm{s}} - \mathbf{R}_{\mathrm{s}}\boldsymbol{i}_{\mathrm{s}}\right)dt \tag{10}$$

where: $\mathbf{R}_{\mathbf{s}}$ – stator winding resistance matrix
$\boldsymbol{u}_{\mathrm{s}}$ – instantaneous values vector of phase stator currents

On the substitute flux vector $\boldsymbol{\psi}_{\mathbf{st}}$ basis the power $P_{\Psi t}$ was calculated according to [7,8,9]. At the same time formula (9) and (10) for three-wire, sinusoidal and symmetrical three-phase power system receives a temporary replacement expression for the electromagnetic torque t_{agt} defined as:

$$t_{agt} = \sqrt{3}p\left[i_V \int \left(u_U - R_s i_U\right)dt - i_U \int \left(u_V - R_s i_V\right)dt\right] \tag{11}$$

Based on the equation (11) it is possible to calculate power $P_{\Psi t}$ (6) replacement of the rotating field (Fig. 1). According to the adopted advance assumption the relationship is correct:

$$P_\Psi = P_{\Psi t} - \Delta P_{Fes} \tag{12}$$

In the known literature to calculate the output power P_2 the stator core losses ΔP_{Fes} and the rotor core losses ΔP_{Fer} were omitted [7,8,9]. Simultaneously assumes that the value of the stray load losses ΔP_{dodr} is in accordance with IEEE 112 [10]. It is assumed that losses are tabulated value, depending on the percentage of motor output power P_2 (Table 1). Also assumed that the friction and windage losses ΔP_m a fixed value of 1,2% P_2.

Table 1. Stray load losses ΔP_{dodr}

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%

The authors of this article made a substitute verification of losses in the engine model adopted in [7,8,9] by comparing the actual value of the coefficient of efficiency of the engine with the value estimated. The results showed high values of estimation error which makes the simplification made in the literature [7,8,9] cannot find practical application in the evaluation of the efficiency factor of the motor during operation.

The resulting negative coefficient estimate motor efficiency [11,12] have made this article the authors formulated a new, unfamiliar with the literature, according to calculations with motor output power P_2. On the basis of calculations and studies the compatibility of the theoretical and laboratory capacity $P_{\Psi t}$ replacement of the rotating field. It is assumed that losses in the copper stator ΔP_{Cus} are subject to constant identification. Other losses, due to its multithreading calculation assumes that a single group estimated losses ΔP_{est}. Losses ΔP_{est} are estimated new concept whose interpretation is the aim of this article.

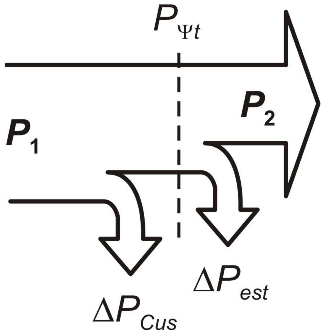


Fig. 2. Simplified distribution of power losses squirrel-cage induction motor

Based on the assumptions the Sankey diagram is simplified to the form shown in figure 2. At the same time dependence (8) specifies the output power P_2 is expressed as follows:

$$P_2 = \frac{2\pi\, T_{agt} n}{60} - \Delta P_{est} \tag{13}$$

where: ΔP_{est} – estimated losses (fig. 2) defined dependence:

$$\Delta P_{est} = \frac{n}{n_s} \Delta P_{Fes} - \Delta P_{Fer} - \Delta P_{dodr} - \Delta P_m \tag{14}$$

In this paper assumes that the estimated losses ΔP_{est} are a function rotor speed n ($\Delta P_{est} = f(n)$) defined as follows:

$$\Delta P_{est}^* = \left(n^*\right)^{\alpha} \tag{15}$$

where: $\Delta P_{est}{}^*$ – the relative value of the estimated losses
n^* – the relative value of the rotor speed
α – exponent, where $\alpha \in$ R

and:

$$\Delta P_{est}^{*} = \frac{\Delta P_{est}}{\Delta P_{estN}} \tag{16}$$

$$n^{*} = \frac{n}{n_N} \tag{17}$$

where: ΔP_{estN} –value of etimated losses at a nominal motor operating conditions
n_N – the nominal rotor speed

On the basis of dependence (15) for rotor speed n equal zero the estimated losses ΔP_{est} are equal zero too. For the nominal rotor speed $n = n_N$ the estimated losses correspond to the nominal value $\Delta P_{est}(n_N)=\Delta P_{estN}$. The nominal losses are determined according to (14):

$$\Delta P_{estN} = \frac{2\pi}{60} T_{agtN} n_N - P_{2N} \tag{18}$$

where: P_{2N} – the nominal motor power
T_{agtN} – the average value of the nominal torque t_{agtN}:

$$t_{agtN} = \sqrt{3} p \begin{bmatrix} i_{VN} \int \left(\frac{u_{UVN} - u_{WUN}}{3} - R_s i_{UN} \right) dt \\ + i_{UN} \int \left(\frac{2u_{UVN} + u_{WUN}}{3} + R_s i_{VN} \right) dt \end{bmatrix} \tag{19}$$

where: i_{UN}, i_{VN} – instantaneous value of stator nominal current $I=I_N$
u_{UVN}, u_{WUN} – instantaneous value of nominal supply voltage $U=U_N$.

The nominal value of estimated losses ΔP_{estN} is the second point on the characteristics of $\Delta P_{est}=f(n)$. There is no rule that determines the value of the exponent α (15). Assumed that the empirical results make its verification. At this stage, the a-priori assumed value of α=1 [12].

3. BADANIA LABORATORYJNE

The laboratory tests were made using the laboratory stand, which illustrates a block diagram of figure 3. The tested motors IM2 (Table 2) were suplayed with the sinusoidal voltage fed to the synchronous generator with a nominal power SG SGN = 4.0 kVA. The tested motors IM2 were loaded with direct current generator DCG. The drive unit DML with a programmable speed indicator allowed to produce the required braking torque on the shaft of tested motors.

The research process was implemented using a scripting system for industrial automation control devices [13] developed at the Institute of Electrical Drives and Industrial Electronics (ZNEiEP) at the Department of Transport and Electrical Engineering Technical University of Radom. It allowed for simultaneous reading of measured values.

Table 2. The technical data of tested motors

L.p.	Company	P_N [kW]	U_N [V]	I_N [A]	n_N [1/min]	cos [-]	η [-]
1	INDUKTA	2,2	400	4,8	1425	0,80	0,82
2	INDUKTA	2,2	400	5,0	2870	0,77	0,82
3	TAMEL	1,5	380	3,7	1420	0,80	0,77
4	TAMEL	1,5	380	3,5	1410	0,80	0,81

There have been attempts to load motors for frequency range of 25 to 50Hz, which is a reasonable range of work the most common application in the form of sets of pump and compressor units. The motor efficiency was determined using the direct method by measuring the torque on the motor shaft and its speed in accordance with PN-EN 60034-2-1 [14]. Obtained from measurements of the efficiencies η for the tested motors were as real values.

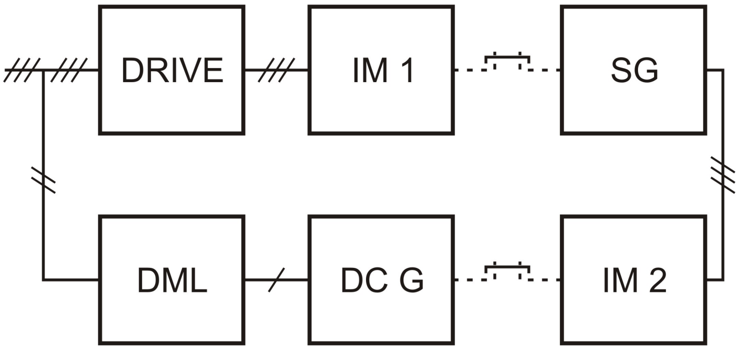
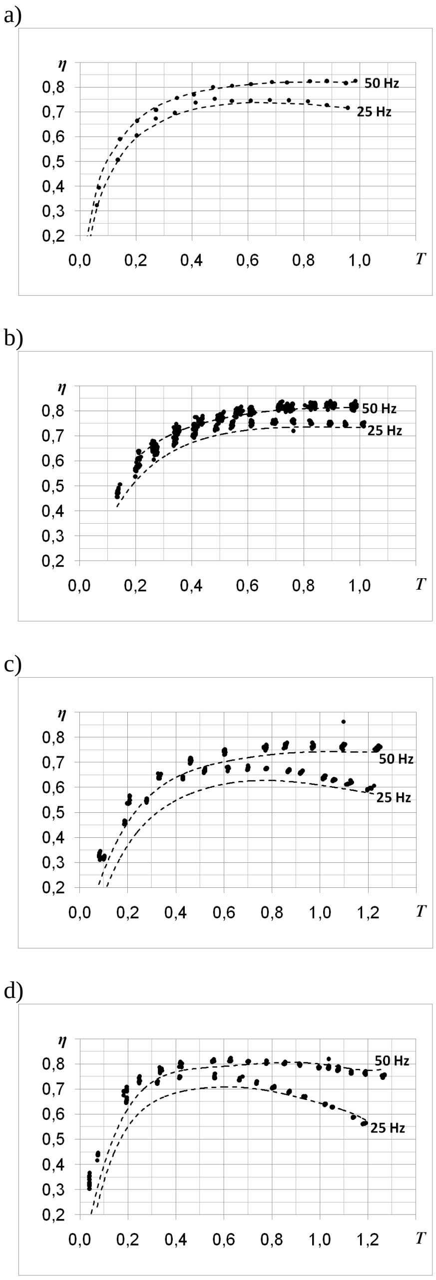


Fig. 3. Block diagram of laboratory stand

The efficiency η_e was calculated for squirrel-cage induction motor on the basis of AGT method, modified for estimated losses determination ΔP_{est} according to the relation (15). The results of calculations efficiency η_e and real efficiency η is shown in figure 4. The efficiency η determined using the direct method of measuring torque on the motor shaft was marked with dots in the figures. The estimated efficiency η_e was marked as a dotted line. The results show a large divergence depending on motor model. Motor no. 1 (fig. 4a) obtained estimation error rate performance is satisfactory and is less than 4%. But divergences are unacceptable for other motors (fig. 4b, c, d). This is the reason for the verification of the definition of estimated losses ΔP_{est} specific relation (15) by introducing a correction factor β:

$$\Delta P_{est}^{*} = \beta\left(n^{*}\right)^{\alpha} \tag{20}$$

factor β, because it takes different values for the tested motors.



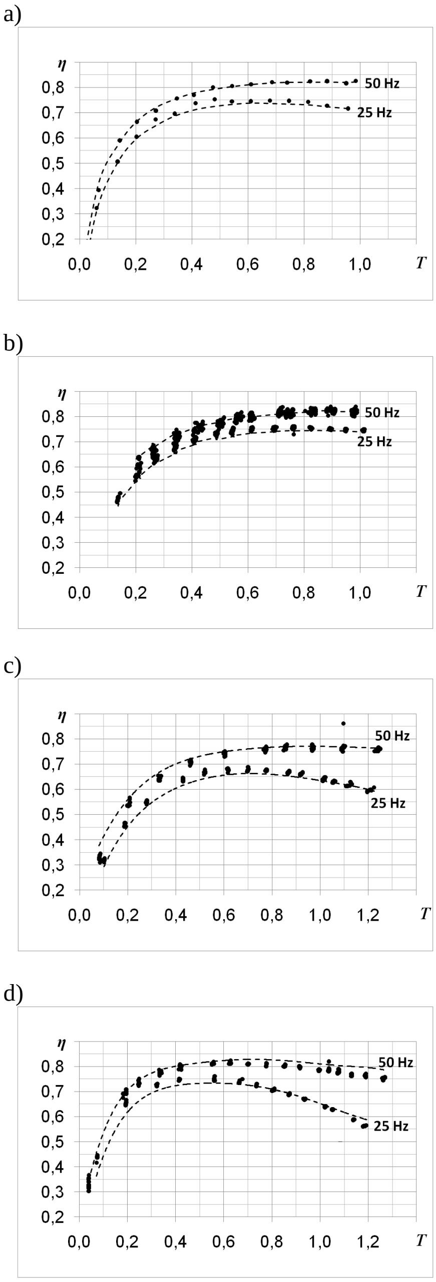


Fig. 4. The motor efficiency in a function shaft torque $\eta=f(T)$: a) motor no. 1, b) motor no. 2, c) motor no. 3, d) motor no. 4

Fig. 5. The motor efficiency in a function shaft torque $\eta=f(T)$ with a correction coefficient β: a) motor no. 1, b) motor no. 2, c) motor no. 3, d) motor no. 4

Coefficient β adopt different values for the tested motors. It takes into account the change in motor power losses during the period of his life. At this stage, the determination of a correction coefficient β is possible on the basis of laboratory tests performed. The use of individually selected values of the correction coefficient β causes the error of estimated efficiency is reduced for the motors tested in the laboratory ZNEiEP (fig. 5).

The results of estimating the coefficient of efficiency for the motor no. 1 does not require any adjustment factor β (fig. 4a and 5a). In this case the correction factor β takes value of 1. The value of estimation error is comparable with the value of systematic error assigned on the basis of accuracy classes of measuring instruments used.

The motor no. 2, 3 and 4 the results of estimation efficiency factor deviate from the measured values and the estimation error increases with decreasing torque on the motor shaft (fig.4b, c and d). The correction coefficient β caused a reduction in estimation error (fig. 5b, c and d) to the level of systematic error. The values of correction coefficient are in the range from 0.6 to 0.9 for the tested motors 2, 3 and 4.

4. CONCLUSIONS

Laboratory tests were made for new and exploited motors. It was shown that the modified method allows to determine the coefficient of AGT efficiency squirrel cage induction motor. Estimation error occurring can be reduced by applying an adjustment factor β. At this stage, the authors look for dependencies, which can be used to determine the correction Made studies confirm the validity of the adoption of the exponent $\alpha = 1$. This means that defined in this article estimated losses, can be determined as linearly dependent on speed, specific for the motor tested.

5. REFERENCES

[1] Banach H.: Sprawność maksymalna indukcyjnego silnika klatkowego. *Zeszyty Problemowe – Maszyny Elektryczne*, (2010) nr 88, 147 - 152

[2] Figura R., Szychta L.: Extreme controlling for pump set of irrigation systems. *Monographs Faculty of Transport*, (2008), nr 122, 547 - 552

[3] Figura R., Szychta E., Szychta L., Kiraga K.: Efficiency estimation of pump-loaded squirrel-cage induction motor. *5TH International Conference Electrical and Control Technologies*, 2010, 223-227

[4] Grunwald Z.: Napęd elektryczny. *WNT*, (1987)

[5] Hsu, J.; Kueck, J. D.; Olszewski, M.; Casada, D. A.; Otaduy, P. J.; Tolbert, L. M.: Comparison of induction motor field efficiency evaluation methods, *IEEE Transactions on industry applications*, 34 1998, nr 1, 117 - 125

[6] Plamitzer A. M.: Maszyny elektryczne. *WNT*, (1982)

[7] Kueck, J. D., Olszewski M., Casada D. A., Hsu J1, Otaduy P. J., Tolbert L. M.: Assessment of methods for estimating motor efficiency and load under field conditions, *Oak Ridge National Laboratory ORNL*, (1996)

[8] Lu B., Habetler T. G., Harley R. G.: A Survey of Efficiency Estimation Methods of In-Service Induction Motors with Considerations of Condition Monitoring Requirement,. *Electric Machines and Drives*, (2005), 1365 - 1372

[9] Lu B., Habetler T. G., Harley R. G.: A Nonintrusive and In-Service Motor Efficiency Estimation Method using Air-Gap Torque with Considerations of Condition Monitoring, *Industry Applications Conference*, (2006), 1535 - 1540

[10] IEEE Standard test procedure for polyphase induction motors and generators. *IEEE 112*, 2004.

[11] Figura R., Szychta L., Szychta E.: Wyznaczanie współczynnika sprawności silnika klatkowego pracującego ze zmienna prędkością obrotową. *Zeszyty Problemowe – Maszyny Elektryczne*, (2011), nr 90, 163 - 168

[12] Figura R., Szychta L.: Estymacja sprawności silnika indukcyjnego klatkowego pracującego w zespole pompowym. *Zeszyty Problemowe – Maszyny Elektryczne*, (2011), nr 92, 175 - 180

[13] Kwiecień R., Szychta L., Figura R.: Skryptowy informatyczny system sterowania urządzeniami automatyki przemysłowej, *Przegląd Elektrotechniczny Electrical Review*, (2010), nr 2, 285 – 288

[14] Polska Norma PN-EN 60034-2-1, Maszyny elektryczne wirujące - Część 2-1: Znormalizowane metody wyznaczania strat i sprawności na podstawie badań (z wyjątkiem maszyn pojazdów trakcyjnych), *PKN*, (2010)

[15] MICHALIK J., BUDAY J.: Electric Machines, EDIS – University of Žilina, Žilina 2006, ISBN 80-8070-568-2.