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Verification of the modified AGT method applied to determining efficiency of squirrel-cage induction motor

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Abstract. The modified air gap torque method to determine the efficiency of squirrel-cage induction motor was presented. of testing which continues the authors' work on application of AGT method to estimating induction motor's efficiency are discussed. The proposed method is verified in a number of selected low-power motors.

Key words: AGT method, motor efficiency, motor efficiency testing, efficiency estimating

1. Introduction

Squirrel-cage induction motors are commonly used in a variety of industrial applications. They normally operate below their ratings as they are most often overmotored in relation to machinery and equipment they drive. A number of these motors are supplied from frequency converters which provide for variable rotational speed of a motor. In the circumstances, efficiency of a motor varies as a function of not only loading but also frequency of supplied voltage. Economic considerations of reducing energy consumption by industrial processes make reasonable monitoring of in-service motor efficiency and, ultimately, energy-saving control of a motor [1-3]. The article discusses efficiency estimations using a variety of methods based on estimating electromagnetic torque in the motor air gap which enables efficiency estimations of in-service motors.

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

- methods employing indirect slip measurements,
- methods based on measurements of stator's phase current,
- methods based on equivalent diagrams,
- methods of determining partial losses,

- methods of determining air gap torque,
- methods of motor shaft torque measurement.

The method of determining efficiency η on the basis of the electromagnetic torque in the motor air gap is employed here. This solution does not require installation of specialist measurement equipment in industrial drive systems.

The motor efficiency η is defined in the following dependency:

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

where: P_1 – mean active power consumed by a motor, P_2 – mean shaft power of motor.

In the special case of symmetrical and sinusoid variable voltages supplied to a three-phase symmetrical motor, power P_1 can be assumed to equal [4, 5]:

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

where u_U, u_V, u_W – instantaneous values of voltages supplied to the motor; i_U, i_V, i_W – instantaneous values of conduction currents.

The power P_2 in laboratory conditions was determined by direct measurements of mean shaft torque T and mean rotational speed n of the rotor according to the formula [4, 6]:

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

Applying the above method of P_2 measurements is not practicable. In actual applications, it is more convenient to determine P_2 according to measured supply parameters, such as voltage, current or frequency. These methods are liable to an estimation error, however, as they provide misleading information on real efficiency values.

2. Method of shaft motor power estimating

The division of induction motor's power losses (Fig. 1) implies a dependency between P_2 and power P_Ψ of the rotating field [6]:

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

where: ΔP_{Cur} – copper losses of rotor; ΔP_{Fer} – core losses of rotor; ΔP_{dodr} – stray load losses of rotor; ΔP_m – friction and windage losses.

The copper losses ΔP_{Cur} are defined:

$$\Delta P_{Cur} = s P_\Psi . \tag{5}$$

P_Ψ of the rotating field is determined on the basis of mean electromagnetic torque T_{ag} in the air gap and rotational speed n_s of the magnetic field:

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

where: T_{ag} is defined according to a momentary value of electromagnetic torque:

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

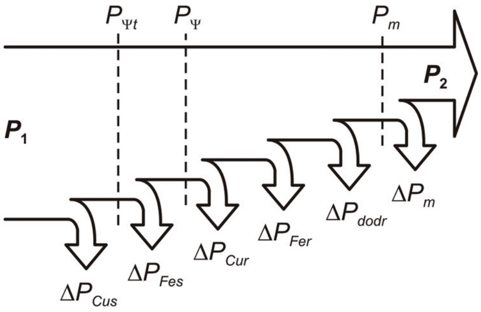

Fig. 1. Power flow of squirrel-cage induction motor

Considering (5) and (6), P_2 can be defined by the dependence:

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

The Equation (8) provides the basis for estimating P_2 across in-service motor shaft by means of the control system of electric drive. T_{ag} is a result of momentary value of t_{ag} defined as a module of the product of momentary values of stator fluxes vector $\boldsymbol{\psi}_\mathbf{s}$ times momentary values of stator currents vector $\boldsymbol{i}_\mathbf{s}$ [7-9]:

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

where: p – number of pole pairs in the motor; $\boldsymbol{\psi}_s$ – vector of values of stator fluxes; $\boldsymbol{i}_s$ – vector of values of stator phase currents.

The flux $\boldsymbol{\psi}_s$ in (9) defines its real value in the motor air gap and provides the basis for calculating P_{Ψ} of the rotating field (Fig. 1). The analytical valuation of the stator's flux is based on the generally accepted equivalent diagram of the motor [4] which ignores losses ΔP_{Fes} in the rotor core. Therefore, the concept of an equivalent vector $\boldsymbol{\psi}_\mathbf{st}$ of momentary values of stator flux $\boldsymbol{\psi}_\mathbf{st}$ is introduced:

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

where: $\mathbf{R}_\mathbf{s}$ – matrix of phase resistances of stator winding; $\boldsymbol{u}_\mathbf{s}$ – vector of momentary values of phase voltages supplied to the motor.

This equivalent fluxes vector $\boldsymbol{\psi}_{\mathbf{st}}$ has produced an equivalent power P_{ψ_t} of the rotating field (Fig. 1), which conforms with the analysis in [7-9]. Dependences (9) and (10) for three-wire, sinusoidal, and symmetrical power supply system of a three-phase motor produce the following expression of momentary electromagnetic torque t_{agt}:

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

With regard to inter-phase voltages, (11) can be formulated as:

$$t_{agt} = \sqrt{3}p\left[\begin{array}{l} i_V\int\left(\frac{u_{UV}-u_{WU}}{3} - R_s i_U\right)dt + \\ + i_U\int\left(\frac{2u_{UV}+u_{WU}}{3} + R_s i_V\right)dt \end{array}\right]. \tag{12}$$

t_{agt} expressed by (12) helps to compute the equivalent power P_{ψ_t} of the rotating field (Fig. 1). In accordance with the earlier assumption, the following dependence obtains:

$$P_{\psi} = P_{\psi_t} - \Delta P_{Fes}. \tag{13}$$

Available literature ignores losses ΔP_{Fes} in the stator's core and ΔP_{Fer} in the rotor's core to compute P_2 [7-9]. Stray load losses ΔP_{dodr} are assumed to comply with IEEE 112 [10]. The assumed ΔP_{dodr} have tabulated values and are percentages of P_2 discharged by a motor (Tab. 1). Friction and windage losses ΔP_m are assumed to equal 1.2% P_2.

Table 1. Additional loading losses

Range of motor power	Percentage share of stray load losses ΔP_{dodr} in the discharged power P_2
1-90 kW	1.8%
91-375 kW	1.5%
376-1850 kW	1.2%
1851 kW and up	0.9%

These authors have verified the equivalent model of motor losses adopted in [7-9] by comparing the actual motor efficiency its estimated value. The results indicate great estimation errors, therefore, the simplifications accepted in [7-9] cannot be applied to practical assessments of in-service motor efficiency.

These negative results of motor efficiency estimation [11, 12] led the authors to formulate new dependencies to compute P_2 discharged by a motor. According to calculations and testing, the theoretical and laboratory values of the equivalent power P_{ψ_t} of the rotating field were demonstrated to match. It was assumed that stator copper losses ΔP_{Cus} are constantly identified. Due to the variety of calculation methods, the remaining losses were assumed to belong to a single group, defined as estimated losses ΔP_{est}. ΔP_{est} are a new concept whose interpretation is the aim of this article.

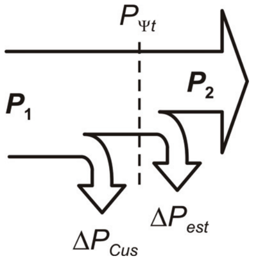

Fig. 2. A simplified division of power losses of squirrel-cage induction motor

On the basis of such assumptions, Sankey diagram is simplified as shown in Figure 2 (8), which defines P_2, is expressed as:

$$P_2 = \frac{2\pi T_{agt} n}{60} - \Delta P_{est}, \tag{14}$$

where: ΔP_{est} – estimated losses (Fig. 2) defined by:

$$\Delta P_{est} = \frac{n}{n_s} \Delta P_{Fes} - \Delta P_{Fer} - \Delta P_{dodr} - \Delta P_m . \tag{15}$$

are assumed here to be a function of rotational speed n ($\Delta P_{est} = f(n)$) and expressed as:

$$\Delta P_{est}^{*} = \left(n^{*} \right)^{\alpha}, \tag{16}$$

where: ΔP_{est}^{*} – relative estimated losses; n^{*} – relative rotational speed of the rotor; α – power's exponent, where $\alpha \in \mathrm{R}$, with:

$$\Delta P_{est}^{*} = \frac{\Delta P_{est}}{\Delta P_{estN}}, \tag{17}$$

$$n^{*} = \frac{n}{n_N}, \tag{18}$$

where: ΔP_{estN} – estimated losses under rated operating conditions of the motor; n_N – rated rotational speed of the motor.

According to (16), ΔP_{est} are zero for n equal zero. Where the rated rotational speed $n = n_N$ of the rotor, on the other hand, estimated losses correspond to the rated value. $\Delta P_{est}(n_N) = \Delta P_{estN}$. Rated losses are defined in line with (14):

$$\Delta P_{estN} = \frac{2\pi}{60} T_{agtN} n_N - P_{2N}, \tag{19}$$

where: P_{2N} – rated motor power; T_{agtN} – mean rated torque t_{agtN} in the motor's air gap, defined by:

$$t_{agtN} = \sqrt{3}p\begin{bmatrix} i_{VN}\int\left(\dfrac{u_{UVN}-u_{WUN}}{3}-R_s i_{UN}\right)dt \\ +i_{UN}\int\left(\dfrac{2u_{UVN}+u_{WUN}}{3}+R_s i_{VN}\right)dt \end{bmatrix}, \tag{20}$$

where: i_{UN}, i_{VN} – instantaneous currents across the stator's winding for rms value of current $I = I_N$; u_{UVN}, u_{WUN} – instantaneous conduction voltages for rms value of voltage $U = U_N$.

The estimated rated losses ΔP_{estN} are the second point of the characteristic $\Delta P_{est} = f(n)$. There is no rule for determining the exponent α (21). It is assumed to be verified by empirical results. At this stage, its value has been assumed as $\alpha = 1$ [12].

3. Laboratory testing

The testing employed a laboratory stand whose flow diagram is illustrated in Figure 3. IM2 motors (Table 2), were supplied with sinusoidal variable voltage from an SG of rated power $S_{GN} = 4.0$ kVA. IM2 motors were loaded with a DCG. The drive assembly DML and a programmed rotational speed meter helped to produce a desired braking torque across the motor shafts.

The testing process employed a script IT control system for automatic industrial equipment [13] developed by the Department of Electric Drive and Industrial Electronics, Faculty of Transport and Electrical Engineering, Technical University of Radom. It provides for simultaneous reading of measured values.

Table 2. Ratings of tested motors

L.p.	Manufacturers	P_N [kW]	U_N [V]	I_N [A]	n_N [rpm]	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

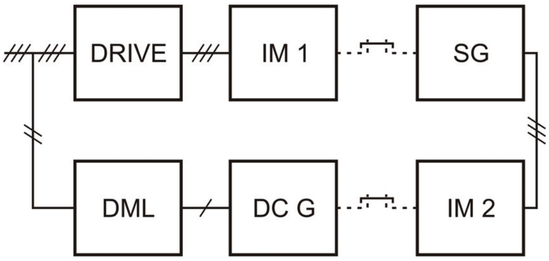

Fig. 3. Flow diagram of the measurement station

The motor load testing covered the frequency range of 25-50 Hz as operation of pumping sets or compressors in wider regulation ranges is not practicable. Motor efficiency was determined by direct measurements of shaft torque and motor rotational speed in line with PN-EN 60034-2-1 [14]. These measured efficiencies η of the test motors were treated as actual values.

According to the AGT method, modified by determining ΔP_{est} in conformity with (16), efficiency η_e of a squirrel-cage induction motor was calculated. Calculation results of η_e and actual efficiency η are shown in Figure 4. η determined by direct measurements of shaft torque of a tested motor is plotted with black dots. Estimated efficiency η_e is shown with a broken line. The results vary substantially across motor models. In respect of motor 1 (Fig. 4a), the estimation error of efficiency is satisfactory and below 4% while the divergences are unacceptable for the remaining motors (Fig. 4b, c, d). Accordingly, the definition of estimated losses ΔP_{est} in (16) must be verified by means of a correction factor β:

$$\Delta P^{*}_{est} = \beta\left(n^{*}\right)^{\alpha}, \tag{21}$$

β varies for the test motors. It includes variations of power losses over the lifecycle of a motor. Determination of β on the basis of laboratory testing is feasible at this stage. Application of an individually selected β for each motor reduced the error of estimated efficiency concerning the motors tested at the laboratory (Fig. 5).

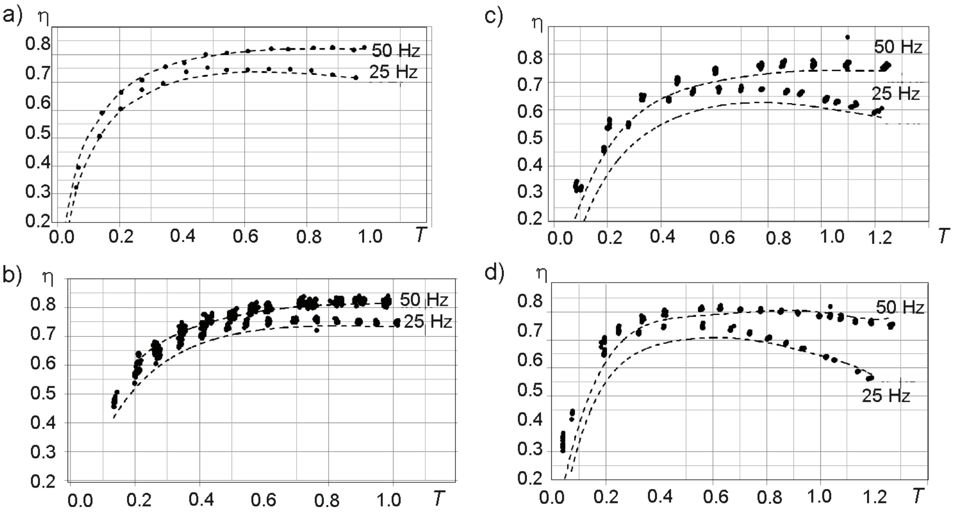

Fig. 4. Motor efficiency as a function of electromagnetic torque $\eta = f(T)$: a) motor 1, b) motor 2, c) motor 3, d) motor 4

Application of individually selected values of β reduces the error of estimated efficiency concerning the motors tested at the laboratory (Fig. 5).

Efficiency estimation results for motor 1 do not require application of a correction factor β (Fig. 4a and 4a). In the circumstances, β becomes 1. The estimation error is comparable to the systematic error determined according to accuracy classes of the measurement instruments.

Efficiency estimation results for motors 2, 3, and 4 differ from measured values and the estimation error rises as the motor shaft torque reduces (Fig. 4 b, c, and d). Introduction of β reduced the estimation error (Fig. 5 b, c, and d) to the level of the systematic error. The correction factor is in the range 0.6-0.9 with regard to motors 2, 3, and 4

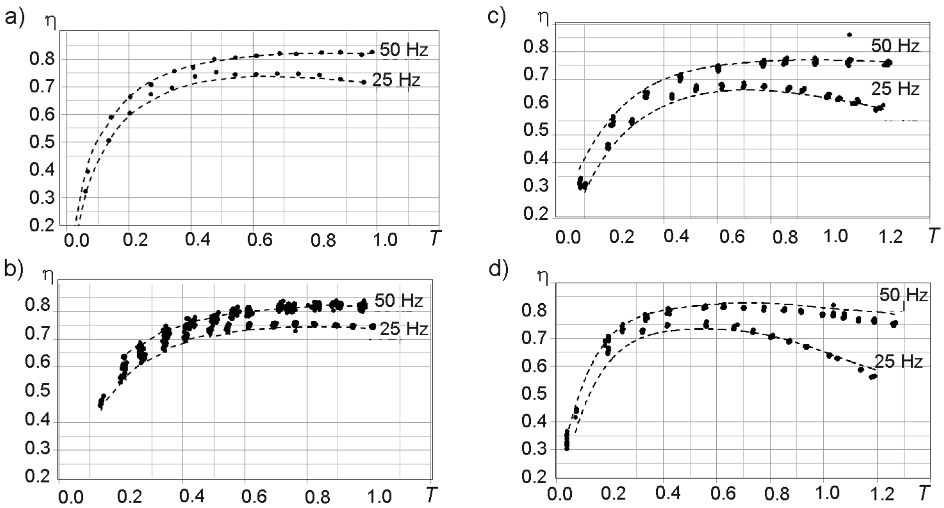

Fig. 5. Motor efficiency as a function of electromagnetic torque $\eta = f(T)$ on introduction of factor β: a) motor 1, b) motor 2, c) motor 3, d) motor 4

4. Conclusion

The laboratory testing involved new and in-service motors. It was demonstrated that the modified AGT method can be applied to determining efficiency of a squirrel-cage induction motor. The estimation error can be reduced by application of the correction factor β. The authors are searching for a dependence that can be employed to determine β as the latter varies across tested motors. The testing confirms it is correct to assume α = 1. This means that estimated losses defined in this article can be determined as linearly dependent on rotational speed.

References

[1] Banach H., *Sprawność maksymalna indukcyjnego silnika klatkowego* (*Maximum Efficiency of Squirrel-Cage Induction Motor*). Zeszyty Problemowe – Maszyny Elektryczne 88: 147-152 (2010).

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

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

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

[5] Hsu J., Kueck J.D., Olszewski M. et al., *Comparison of induction motor field efficiency evaluation methods*. IEEE Transactions on industry applications 34(1): 117-125 (1998).
[6] Plamitzer A.M., *Maszyny elektryczne (Electric Machines)*. WNT (1982).
[7] Kueck J.D., Olszewski M., Casada D.A. et al., *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, pp. 1365-1372 (2005).
[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, pp. 1535-1540 (2006).
[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* (*Determining Efficiency of a Squirrel-Cage Motor Operating At Variable Rotational Speed)*. Zeszyty Problemowe – Maszyny Elektryczne No 90: 163-168 (2011).
[12] Figura R., Szychta L., *Estymacja sprawności silnika indukcyjnego klatkowego pracującego w zespole pompowym* (*Estimating Efficiency of a Squirrel-Cage Induction Motor Operating As Part of a Pumping Set*). Zeszyty Problemowe – Maszyny Elektryczne 92: 175-180 (2011).
[13] Kwiecień R., Szychta L., Figura R., *Skryptowy informatyczny system sterowania urządzeniami automatyki przemysłowej* (*Script IT System for Control of Industrial Automatic Equipment*), Przegląd Elektrotechniczny Electrical Review 2: 285-288 (2010).
[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) (Polish Standard PN-EN 60034-2-1, Rotational electrical machines. Part 2-1: Standardised methods of determining losses and efficiencies by testing (excluding traction vehicle machinery*). PKN (2010).