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Verification of Estimating Rotational Field Power in an Induction Motor Based on the NAGT Method

Abstract*. In light of the Energy Efficiency Act of 2011, increasing attention has been paid to reducing energy consumption of industrial processes. Maximising efficiency of industrial drives is one of the methods of improving energy efficiency. Information about in-service motor efficiency becomes essential. There is a lot of methods for determining efficiency of squirrel-cage induction motors, including those based on estimating air-gap torque (AGT). This paper attempts to verify non-Intrusive air-gap torque (NAGT) method as presented in international publications. It is demonstrated that the dependencies included in the method can be formulated so as to facilitate application and simplify calculation of the rotational magnetic field power. Certain inaccuracies of the method, relating to omission of selected power losses in the motor, are indicated.*

Streszczenie. *W świetle ustawy o efektywności energetycznej z 2011 roku coraz większa uwaga poświęcana jest na zmniejszenie energochłonności w procesach przemysłowych. Jednym ze sposobów zwiększenia efektywności energetycznej jest maksymalizacja sprawności napędów przemysłowych. Istotna staje się informacja na temat sprawności silnika w trakcie jego pracy. Znanych jest wiele metod wyznaczania współczynnika sprawności silnika indukcyjnego klatkowego. Wśród nich można wyróżnić metody bazujące na wyznaczaniu momentu elektromagnetycznego w szczelinie powietrznej silnika (AGT). W niniejszym artykule dokonano weryfikacji metody NAGT prezentowanej w literaturze zagranicznej. Wykazano, że zależności w prezentowanej metodzie można sformułować w sposób ułatwiający aplikacyjność oraz upraszczający obliczenia mocy pola wirującego. Zwrócono również uwagę na niedokładność metody związaną z pominięciem wybranych strat cząstkowych w silniku. (**Weryfikacja metody wyznaczania mocy pola wirującego w silniku indukcyjnym w oparciu o metodę NAGT**).*

Keywords: NAGT method verification, rotational magnetic field power, power distribution of induction motor, induction motor efficiency,
Słowa kluczowe: Weryfikacja metody NAGT, moc magnetycznego pola wirującego, podział strat w silniku indukcyjnym, sprawność silnika

Introduction

Estimating efficiency of squirrel-cage induction motors has often been discussed in Polish and international literature. Testing has been pursued for years to improve the motor's efficiency by introducing new design solutions. As rotational speed drives have evolved, demand for energy-efficient motor control systems has increased. In light of current energy efficiency legislation, it is important not only to create new energy-saving solutions but also to modernise the existing applications to reduce energy consumption by electric motors. Information on momentary efficiency of a given machine is key to effective energy processing by electrical equipment. There is a variety of methods to estimate in-service motor efficiency. Some of them are easy to use but lack precision of efficiency estimations. Methods characterised by low estimation errors normally require additional, specialist laboratory testing, which involves motor disassembly. Methods of estimating efficiency of squirrel-cage induction motors based on determination of air-gap torque need to be emphasised [1,2,3]. Their accuracy and uncomplicated calculations may prove a good way of determining efficiency of in-service motors.

These methods are effective at estimating rotational magnetic field power. This paper verifies a method of determining rotational magnetic field power and proposes another solution producing similar estimation results.

Rotational magnetic field power in an induction machine

Power P_Ψ of a rotational magnetic field is defined as power supplied from stator to rotor via a rotational magnetic field [4]. According to a motor's power distribution (fig. 1), P_Ψ is determined by:

(1a) $$P_\Psi = P_1 - \Delta P_{Cus} - \Delta P_{Fes} - \Delta P_{dods}$$

(1b) $$P_\Psi = P_2 + \Delta P_{Cur} + \Delta P_{dodr} + \Delta P_m$$

where: P_1 – input motor active power, ΔP_{Cus} – stator cooper losses, ΔP_{Fes} – stator core losses, ΔP_{dods} stator stray load losses- , ΔP_{Cur} rotor cooper losses- , ΔP_{dodr} – rotor stray load losses, ΔP_m – friction and windage looses, ΔP_2 – shaft power.

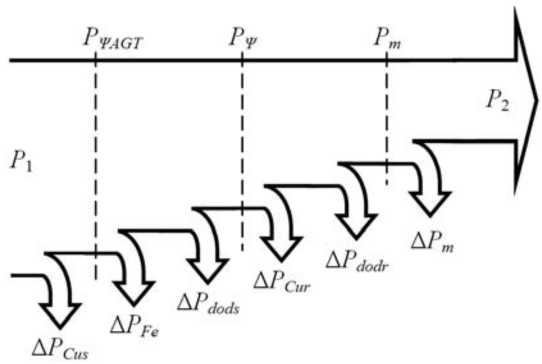

Fig.1. A simplified power distribution of squirrel-cage induction motor

Equation (1a) helps to define P_Ψ on the basis of P_1 consumed by a motor and power losses across a stator. (1b) defines power on the basis of P_2 yielded by a motor and power losses yielded across the rotor of an induction motor. Losses appearing in (1a) and (1b) can be determined by means of test procedures described in the standard [5]. In the circumstances, it is necessary to disassemble a motor and conduct a series of tests at a laboratory station. Such operations may cause production downtime and generate costs associated with testing of the motor. The particular losses across a motor may vary both over time and with changing operating conditions. This applies in particular to motors operating at variable rotational speed (e.g. drives of pumps and ventilators).

Determining rotational magnetic field power according to a mathematical model of induction motor

Non-Intrusive Air Gap Torque (NAGT) method, proposed in [6,7,8], is among the methods of estimating P_Ψ. Its application is conditional on introduction of the following assumptions:

- three-phase stator winding is symmetrical,
- equivalent symmetrical three-phase stator windings is introduced,
- a motor is supplied with a symmetrical three-phase source of sinusoidally alternating voltage in a three-wire system,
- magnetic fluxes produced by the individual stator and rotor phase windings along the air gap are sinusoidal,

– effects of anisotropy, hysteresis and magnetic loop saturation, as well as current displacement from winding wires are ignored.

These assumptions lead to the following vector voltage equation for the stator:

(2) $$\boldsymbol{u}_\mathbf{s} = \mathbf{R_s}\boldsymbol{i}_\mathbf{s} + \frac{d\boldsymbol{\psi}_\mathbf{s}}{dt}$$

where: $\mathbf{R_s}$ – matrix of the stator winding phase resistance defined as:

(3) $$\mathbf{R_s} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix}$$

$\boldsymbol{u}_\mathbf{s}$ – vector of momentary phase voltages supplied to the motor, defined as:

(4) $$\boldsymbol{u}_\mathbf{s} = [u_U \quad u_V \quad u_W]^T$$

$\boldsymbol{i}_s$ – vector of momentary phase currents of the stator, defined as:

(5) $$\boldsymbol{i}_\mathbf{s} = [i_U \quad i_V \quad i_W]^T$$

$\boldsymbol{\psi}_\mathbf{s}$ – vector of momentary phase fluxes of the stator, defined as:

(6) $$\boldsymbol{\psi}_\mathbf{s} = [\psi_U \quad \psi_V \quad \psi_W]^T$$

$\boldsymbol{\psi}_\mathbf{s}$ is defined according to (2):

(7) $$\boldsymbol{\psi}_\mathbf{s} = \int (\boldsymbol{u}_\mathbf{s} - \mathbf{R_s}\boldsymbol{i}_\mathbf{s})dt$$

Phase resistance R_s can be determined by DC current injection method [9] or by winding temperature measurements. In the latter case, resistance R_{so} measured with the reference temperature t_{so} must be converted into R_s, part of the winding temperature t_p at the time of measurement in line with the following dependence:

(8) $$R_s = R_{so}\left(1 + 0{,}0043(t_p - t_{so})\right)$$

Employing $\boldsymbol{\psi}_\mathbf{s}$ (7) and $\boldsymbol{i}_s$ (5), momentary torque t_{ag} can be computed [10]:

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

where: p – number of motor pole pairs.

A dependency has been formulated on the basis of mathematical conversions presented in [6,7,8] which helps to calculate t_{ag}:

(10) $$t_{ag} = \frac{\sqrt{3}p}{3}\left[\begin{matrix}(i_U - i_V)\int\left(u_{WU} + R_s(2i_U + i_V)\right)dt \\ +(2i_U + i_V)\int\left(u_{UV} + R_s(i_U - i_V)\right)dt\end{matrix}\right]$$

Average T_{ag} results from integration of (10) after a time t:

(11) $$T_{ag} = \frac{1}{t_T}\int_0^{t_T} t_{ag}\,dt$$

where: t_T – duration of t_{ag} under analysis, a total multiple of its period.

On the basis of T_{ag}, a dependency is formulated for power $P_{\Psi AGT}$ of a rotational magnetic field:

(12) $$P_{\Psi AGT} = \frac{2\pi\, T_{ag} n_s}{60}$$

where: n_s – synchronous speed of a machine, defined as:

(13) $$n_s = \frac{60f}{p}$$

On consideration of (10) - (13), $P_{\Psi AGT}$ is defined by [6]:

(14) $$P_{\Psi AGT} = \frac{2\sqrt{3}\pi f}{3t_T}\int_0^{t_T}\left[\begin{matrix}(i_U - i_V)\int\left(u_{WU} + R_s(2i_U + i_V)\right)dt \\ +(2i_U + i_V)\int\left(u_{UV} + R_s(i_U - i_V)\right)dt\end{matrix}\right]dt$$

Determination of rotational magnetic field power according to an induction motor's power distribution

Power is computed by means of Kirchhoff equations defining stator voltage. Accuracy of (14) must be verified using the principle of energy conservation, and thus the stray loss distribution shown in figure 1. To this end, the following dependences for phase-to-phase voltages u_{WU}, u_{UV} and linear currents i_U, i_V will be introduced alongside the earlier assumptions underlying (14):

(15) $$\begin{cases} u_{WU} = \sqrt{2}U_s\left(\sin(\omega t - \frac{4\pi}{3}) - \sin(\omega t)\right) \\ u_{UV} = \sqrt{2}U_s\left(\sin(\omega t) - \sin(\omega t - \frac{2\pi}{3})\right) \\ i_U = \sqrt{2}I_s\sin(\omega t + \varphi) \\ i_V = \sqrt{2}I_s\sin(\omega t + \varphi - \frac{4\pi}{3}) \end{cases}$$

where: U_s – rms value of phase voltage supplied to the motor, I_s - rms value of phase current consumed by the motor.

As (14) is transformed in consideration of (15), $P_{\Psi AGT}$ becomes defined by:

(16) $$P_{\Psi AGT} = 3I_sU_s\cos\varphi - 3R_sI_s^2$$

It can be concluded that the first term of (16) defines P_1 consumed by the motor. The second term defines the stator winding losses, ΔP_{Cus}. (16) can therefore be transformed into:

(17) $$P_{\Psi AGT} = P_1 - \Delta P_{Cus}$$

Considering the power distribution across an induction motor (fig. 1), it must be said that $P_{\Psi AGT}$ as determined in [6] and treated as the rotational field power in fact ignores the core losses ΔP_{Fe} and stator stray load losses ΔP_{dods}. The following inequality obtains:

(18) $$P_\Psi \neq P_{\Psi AGT}$$

In the case of low-power motors (0.75 – 2.2kW), omission of ΔP_{Fe} and ΔP_{dods} is a mistake. The core losses for this ower range may account even for 20% of all losses, depending on efficiency class [11].

Equation (17) shows that the NAGT method of determining P_Ψ of a magnetic field proposed in [6,7] is faulty. It cannot be applied to low- and medium-power motors. It can also be postulated that estimating $P_{\Psi AGT}$ by means of (14), which requires complex calculation processes, may be replaced with a simple mathematical formula expressed by (17). It is thus demonstrated that the method of determining $P_{\Psi AGT}$ becomes useless in comparison to a much simpler algorithm formulated in this paper. This will be verified in the following sections of this article.

Practical verification of calculation results

Equations (14) and (17) are used to estimate rotational magnetic field power in testing of squirrel-cage induction motors. The testing has been undertaken in a laboratory stand at the Department of Electric Drives and Industrial Electronics, Kazimierz Pulaski Technical University of Radom. The block diagram of the stand is illustrated in figure 2.

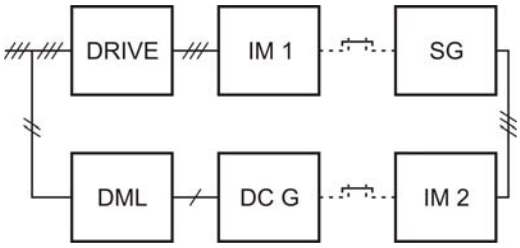

Fig.2. The laboratory stand block diagram

The motors IM2 were supplied with frequency-regulated, sinusoidally alternating voltage from a 4kVA synchronous generator SG. SG was driven by a squirrel-cage induction motor IM1, supplied from a frequency converter (DRIVE) that provided for a smooth regulation of IM1's revolutions. SG was externally excited to regulate voltage across its terminals. Load torque of IM2 was produced by a direct current generator DCG supplied by a thyristor converter DML.

Table 1. Default settings of the tested motors

No.	Manufacturer	P_N [kW]	U_N [V]	I_N [A]	n_N [rpm]	cos [-]	η [-]
1	INDUKTA	2.20	400	4.8	1425	0.80	0.82
2	TAMEL	1.50	380	3.7	1420	0.80	0.77
3	INDUKTA	2.20	400	5.0	2870	0.77	0.82
4	INDUKTA	1.10	400	2.7	1415	0.80	0.74
5	BESEL	1.50	400	4.2	900	0.70	0.71
6	TAMEL	2.20	380	5.1	1410	0.80	0.82
7	TAMEL	1.50	380	3.5	1410	0.80	0.81
8	BESEL	0.75	400	2.7	670	0.61	0.66

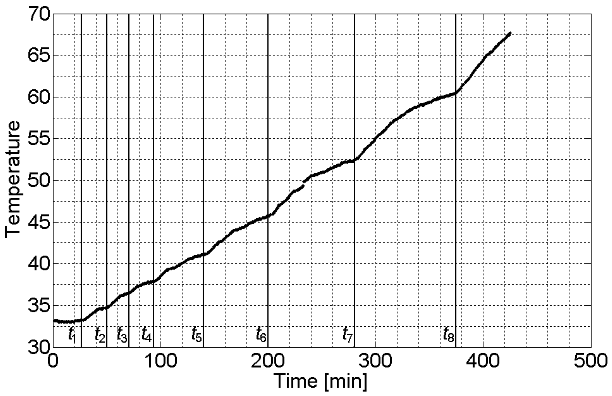

Fig. 3. Temperature chart for the frequency 40Hz

The stand was equipped with a NI-USB 6361 measurement card providing for signal acquisition from measurement probes. In addition, analogue and digital inputs of the card were employed to set operating parameters of the motors, such as: supply voltage frequency, rms value of supply voltage, and motor shaft torque. A fully automated stand for testing induction motors with power ratings below 2.2 kW was produced. The solutions improved precision of the measurements.

Load, short-circuit and no-load tests for supply voltage frequencies f of 15 - 55Hz were conducted on the motors in Table 1. After each variation of a motor's operating parameters, temperature of a motor was stabilised (fig. 3). It was necessary to stabilise operating temperature of a motor due to the method of determining R_s of the induction motor's stator winding. The temperature stabilisation by the measurement system provided for measurements if temperature variations were below 2°C an hour. Times (t_1 - t_8) of the measurements were plotted with a vertical black line (fig. 3). It was proven that the error of R_s determination caused by the assumed inaccuracy of the temperature stabilisation was several times lower than the measurement errors caused by other measurement devices.

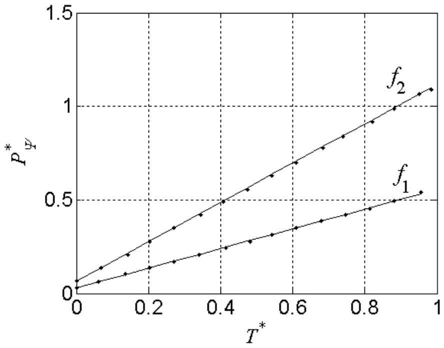

Fig.4. $P_{\Psi AGT}$ as a function of active power P_1 consumed by a motor for f_1=25Hz and f_2=50Hz – motor 1

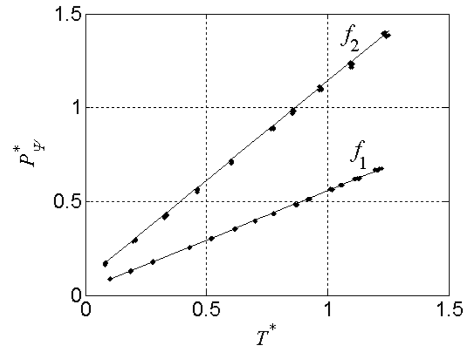

Fig.5. $P_{\Psi AGT}$ as a function of active power P_1 consumed by a motor for f_1=25Hz and f_2=50Hz – motor 2.

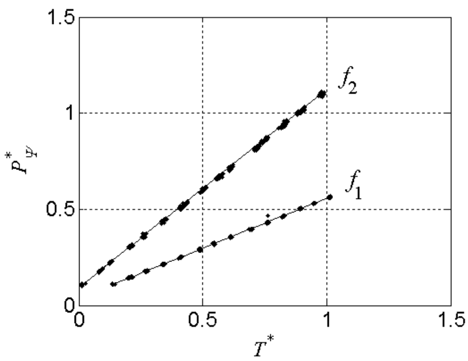

Fig.6. $P_{\Psi AGT}$ as a function of active power P_1 consumed by a motor for f_1=25Hz and f_2=50Hz – motor 3

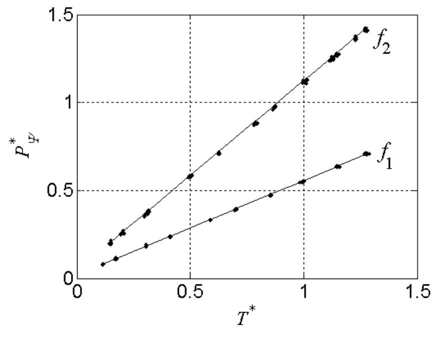

Fig.7. $P_{\Psi AGT}$ as a function of active power P_1 consumed by a motor for f_1=25Hz and f_2=50Hz – motor 4

Graphs of $P_{\Psi AGT}$ as a function of motor shaft torque T (figs. 4 - 11) were plotted based on the testing. $P_{\Psi AGT}$ estimated with the NAGT method (14) was marked with dots. $P_{\Psi AGT}$ based on the power distribution (17) was potted with a straight line.

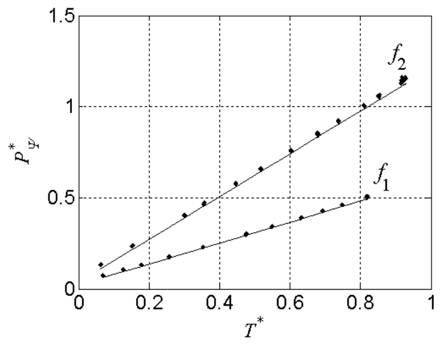

Fig.8. $P_{\Psi AGT}$ as a function of active power P_1 consumed by a motor for f_1=25Hz and f_2=50Hz – motor 5

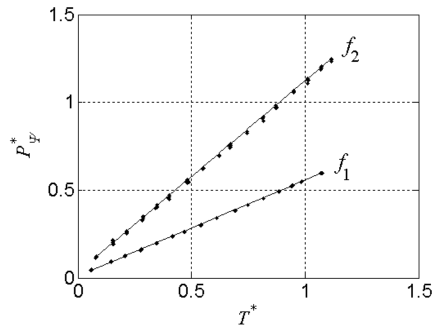

Fig.9. $P_{\Psi AGT}$ as a function of active power P_1 consumed by a motor for f_1=25Hz and f_2=50Hz – motor 6

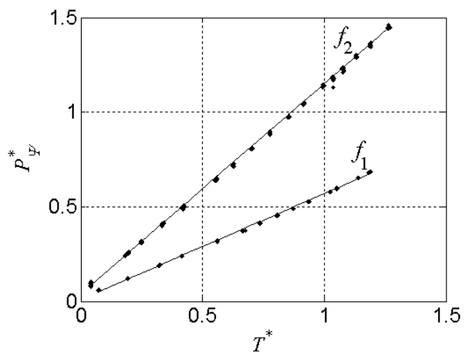

Fig.10. $P_{\Psi AGT}$ as a function of active power P_1 consumed by a motor for f_1=25Hz and f_2=50Hz – motor 7

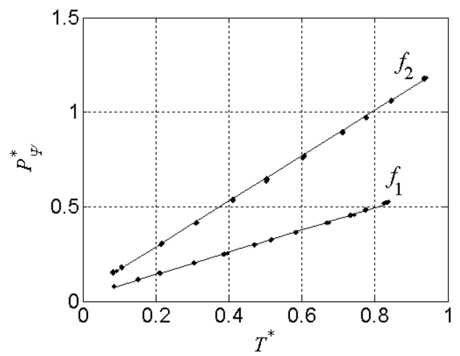

Fig.11. $P_{\Psi AGT}$ as a function of active power P_1 consumed by a motor for f_1=25Hz and f_2=50Hz – motor 8

Differences between the methods of estimating $P_{\Psi AGT}$ are below 2% and arise from measurement errors and approximations applied to the numerical determination of integral values. The diagrams present results for the supply frequencies f_1=50 Hz and f_2=25 Hz. The results in figures 4 – 11 are expressed as relative values referred to default motor ratings according to the following dependences:

$$\begin{cases} P^*_{\Psi AGT} = \dfrac{P_{\Psi AGT}}{P_{\Psi AGTN}} \\ T^* = \dfrac{T}{T_N} \end{cases} \tag{19}$$

where: $P_{\Psi AGTN}$ – power estimated under nominal operating conditions of the motor, P_{1N} – nominal active power consumed by a motor.

Conclusion

This verification of the dependences defining rotational magnetic field power in a squirrel-cage induction motor and presented by international authors demonstrates certain differences between the actual and calculated values of the rotational magnetic field power. The differences arise because core losses and stray load losses are ignored. In the case of motor powers below 3 kW, omission of such losses may lead to a faulty estimation of the rotational field power in a motor. It is therefore necessary to take account of the omitted losses as part of this method. It has been proved, in addition, that the proposed integral calculus can be substituted with a dependence based on simple mathematical calculations. This simplification may facilitate practical applications of the method.

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