

## ANALYSIS OF EFFICIENCY CHARACTERISTICS OF SQUIRREL-CAGE INDUCTION MOTOR LOADED WITH WATER SYSTEM PUMP

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**Abstract.** The article presents a method of calculating efficiency of squirrel-cage induction motor. This efficiency depends on frequency of the voltage supplied to the motor and on electrical power. Results of laboratory testing of the motor's efficiency are presented.

**Key words.** Efficiency, induction motor

### 1. INTRODUCTION

Most pump drives employ squirrel-cage induction motors whose rated efficiency  $\eta_{sn}$  at power of above 2kW, are most often greater than 80%. High efficiency is maintained across a wide variation range of the relative torque  $m^*$  (10) loading the motor's shaft, at rated frequency and supply voltage (Fig.1).

Rated frequency voltage motor supply limits the choice of methods of controlling a pump station's productivity. The commonly applied, variable rotational speed pump drives require that squirrel-cage induction motors be supplied with voltage of variable: frequency and rms value. These parameters influence rotational speed and electromagnetic torque gained by the motor [7, 11]. Harmonics of current and voltage are also greater, which induces additional losses in the motor, reducing its efficiency  $\eta_s$  [3, 4, 5, 7, 10, 12, 13, 17, 18]. In [6] is presented a method of calculating losses in the induction motor powered from a frequency converter, applying the induction machine model, where each harmonic of the supply voltage corresponds to an independent equivalent circuit.

Losses in the stator core  $\Delta P_{Fe}$  depend on frequency of the supply voltage and induction  $B$ . When the motor is supplied with non-sinusoidal voltage, the core losses  $\Delta P_{Fe\nu}$  at  $\nu$ -th harmonic are expressed [6]:

$$\Delta P_{Fe\nu} = \Delta P_{Fe(\nu=1)} \left( \frac{U_\nu}{U_{\nu=1}} \right)^2 \cdot \left( \frac{f_\nu}{f_{\nu=1}} \right)^\beta \cdot \left( \frac{f_{\nu=1}}{f_\nu} \right)^2 \quad (1)$$

where:

$\nu$  -  $\nu$ -th harmonic,

$P_{Fe}$  - the core losses,

$U_\nu$  -  $\nu$ -th harmonic of supply voltage,

$f_\nu$  -  $\nu$ -th harmonic of voltage frequency.

Assuming  $\beta = 1.3$  the result is:

$$\Delta P_{Fe\nu} = \Delta P_{Fe(\nu=1)} \cdot \left( \frac{U_\nu}{U_{\nu=1}} \right)^2 \cdot \left( \frac{f_{\nu=1}}{f_\nu} \right)^{0.7} \quad (2)$$

Equation (2) indicates the core losses caused by higher harmonics are low and decrease as the harmonic order increases.

Some authors include iron losses in the equivalent model of squirrel-cage induction machine [6]. To compare losses when the motor is supplied by voltage and current converter, a mathematical model of the induction machine is presented in the form of differential equations in consideration of iron losses during vector control [7]. Loss distribution in the induction motor as a function of supply voltage's frequency during PWM control was analysed in [5, 19]. The results discussed in [19] indicate that, for supply voltage frequencies  $f > 0.6f_n$ , the total losses caused by higher harmonics of the supply voltage reduce efficiency by a maximum of 2%÷5%. The losses in the motor can be limited by employing a sinusoidal filter at the output of the frequency converter [15, 16].

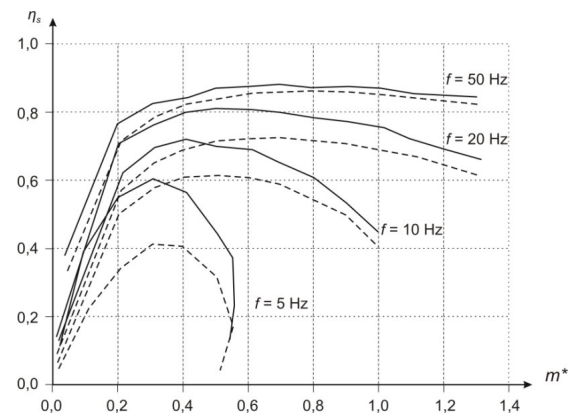


Fig.1. Efficiency of induction motor  $\eta_s$  of 7.5kW INDUKTA as a function of relative load torque  $m^*$  (10) [18]; continuous line - motor is supplied with sinusoidal voltage; broken line - motor is supplied with non-sinusoidal voltage

Figure 1 shows impact of all losses, presenting efficiency variations of the motor  $\eta_s$  supplied with sinusoidal voltage and with non-sinusoidal voltage from a PWM frequency converter. Efficiency  $\eta_s$  of both the supply systems has similar values in the frequency range  $f \in (30 \div 50)$ Hz. Usually the same

range frequency of voltage supply is applied for water pump sets drives. Pump sets should work at the energy-efficient rule. It is possible when the motor efficiency  $\eta_s$  is of high value. The dependency defining efficiency  $\eta_s$ , during motor operation, is unknown. In the article there is presented the way of calculating the estimated efficiency  $\eta_{se}$ , of a motor in a working pump set, by measurements of electrical power  $P_1$ .

## 2. GENERALISED EFFICIENCY MODEL OF SQUIRREL-CAGE INDUCTION MOTOR

It is assumed that the motor is supplied with sinusoidal voltage of variable frequency  $f$  and rms value of voltage  $U$ . The dependency is assumed to obtain:

$$\frac{U}{f} = \text{const} \quad (3)$$

where:

$U$  – rms value of sinusoidal voltage [V],

$f$  – frequency [Hz].

The maximum range of frequency is  $f \in (30, 50)\text{Hz}$ , and the rated frequency is 50Hz.

Power losses  $\Delta P$  in the induction motor equal:

$$\Delta P = P_1 - P_2 \quad (4)$$

where:

$P_1$  – the electrical input power [kW],

$P_2$  – the mechanical output power [kW].

Rated losses  $\Delta P_n$  occur at rated mechanical  $P_n$  and rated electric  $P_{1n}$  power of the motor:

$$\Delta P_n = P_{1n} - P_n = \frac{1 - \eta_{sn}}{\eta_{sn}} P_n \quad (5)$$

where:

$$P_{1n} = \frac{P_n}{\eta_{sn}}$$

$\eta_{sn}$  – the rated motor efficiency,

$P_n$  – the rated motor power [kW].

On the basis of experimental testing, motor losses when supplied with variable frequency sinusoidal voltage are defined [2]. Power losses split into components including no load operation losses, losses dependent on supply voltage frequency, and losses dependent on loading torque:

$$\Delta P = 0,2 \cdot \Delta P_n + 0,15 \cdot \left(\frac{f}{f_n}\right)^2 \cdot \Delta P_n + 0,65 \cdot \left(\frac{M}{M_n}\right)^2 \cdot \Delta P_n \quad (6)$$

where:

$M$  – the motor torque,

$M_n$  – the rated motor torque.

Losses  $\Delta P$  (6) can be rearrange:

$$\Delta P = \alpha_0 + \alpha_1 (m^*)^2 \quad (7)$$

where:

$$\alpha_0 = 0,2 \Delta P_n + 0,15 \left(\frac{f}{f_n}\right)^2 \Delta P_n \quad (8)$$

$$\alpha_1 = 0,65 \Delta P_n \quad (9)$$

$$m^* = \frac{M}{M_n} \quad (10)$$

Employing dependencies defining mechanical power  $P_2$  as a function of load torque  $M$ , the dependence between frequency and rotational speed with respect to induction motor, the relative torque  $m^*$  is obtained:

$$m^* = \beta_m \eta_s \quad (11)$$

where:

$$\beta_m = \frac{P_{1n} (1 - s_n) f_n}{P_n (1 - s) f} \quad (12)$$

where:

$\eta_s$  - efficiency of induction motor,

$s$  – the slip,

$s_n$  – the rated slip.

Slip  $s$  variations as a function of  $m^*$  are complex across the operating range of the induction motor [11]. At low values of  $s$  the dependence applies:

$$s = s_n \cdot m^* \quad (13)$$

On the basis of (11), (12), (13), the torque  $m^*$  loading the motor shaft results:

$$m^* = \frac{\alpha_f (1 - \sqrt{1 - 2\alpha_0 \eta_s})}{2} \quad (14)$$

where:

$$\alpha_f = \frac{1}{s_n} f^* \quad (15)$$

$$\alpha_0 = 2 \cdot \frac{P_{1n}}{P_n} \frac{1}{f^* \alpha_f} (1 - s_n) \quad (16)$$

$$f^* = \frac{f}{f_n}$$

Following on (7), (14), losses  $\Delta P$  are obtained as a function of the motor efficiency  $\eta_s$ :

$$\Delta P = \alpha_0 + \frac{\alpha_1 \alpha_f^2 (1 - \sqrt{1 - 2\alpha_0 \eta_s})^2}{4} \quad (17)$$

Resulting from the general definition of efficiency and from (4):

$$\eta_s = 1 - \frac{\Delta P}{P_1} \quad (18)$$

On the basis of (7), (8), (9), (10), (14), (15), (16), (17), (18), the estimated efficiency  $\eta_{se}$  of the induction motor is defined as a function of electric power  $P_1$  and frequency  $f$  of the supply voltage:

$$\eta_{se} = \frac{\lambda_0 \lambda_1 - \lambda_2^2 a_0 + \lambda_2 \sqrt{\lambda_2^2 a_0^2 - 2 \cdot \lambda_0 \lambda_1 a_0 + \lambda_1^2}}{\lambda_1^2} \quad (19)$$

where:

$$\lambda_0 = \lambda_2 + \alpha_0 - P_1 \quad (20)$$

$$\lambda_1 = \lambda_2 a_0 - P_1 \quad (21)$$

$$\lambda_2 = \frac{\alpha_1 \alpha_f^2}{2} \quad (22)$$

The well-known dependence determining the motor's tested efficiency  $\eta_{sb}$  can be expressed [11]:

$$\eta_{sb} = \frac{M \cdot n}{9550 P_1} \quad (23)$$

$n$  – the rotary speed [r.p.m],

$P_1$  – the electrical input power [kW],

$M$  – the motor torque [Nm].

In conditions of actual pump operation, load torque  $M$  is difficult to measure to calculate efficiency  $\eta_{sb}$  (23). Drive systems that employ the method of direct torque control (DTC), where electromagnetic torque is computed in the control process, are an exception. On the other hand, (19) can be employed to calculate the motor efficiency  $\eta_{se}$  in any operating conditions of the drive system through measurements of electric power  $P_1$ . It is possibly after calculating the rated losses  $\Delta P_n$  (5) bases on rated motor power  $P_n$  and rated motor efficiency  $\eta_{sn}$ .

### 3. TESTING OF EFFICIENCY OF SQUIRREL-CAGE INDUCTION MOTOR

The dependence (23), expressing tested efficiency  $\eta_{sb}$  of the induction motor, is a generally known definition of this efficiency. It is interesting to verify (19) by means of laboratory testing of the motor's efficiency and reciprocal comparison of results [1, 8, 9]. Efficiency of the induction motor was tested at a measurement station whose block diagram is shown in Figure 2.

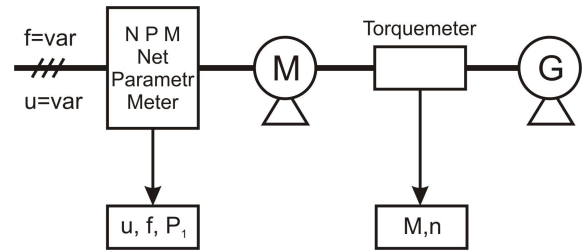


Fig.2. Block diagram of the testing station employed to determine efficiency of the induction motor

The following magnitudes are measured at the testing station:

- electric power  $P_1$  (measure of NPM network parameters),
- frequency  $f$  (measure of NPM network parameters),
- torque  $M$  (torquemeter ALPHA),
- rotational speed  $n$  (torquemeter ALPHA).

For purposes of efficiency analysis, a 2.2kW motor is employed. The mechanical power  $P_2$ , corresponding to power of the working pump, is generated by a direct current generator. Following from the theory of similarity, its value is defined:

$$P_2 = P_{2n1} \left( \frac{n}{n_n} \right)^3 \quad (24)$$

where:

$P_{2n1}$  – motor mechanical output power for pump rated rotary speed,

$n_n$  – rated rotary speed.

The value of  $P_{2n1}$  is variable and dependent on the pump's capacity  $Q$ . An expression of the relation between  $P_{2n1}$  and  $Q$  is unknown. A CR5-12 pump unit was tested, consisting of a pump and 2.2kW motor, which fulfilled the following working conditions:  $Q \in (0, Q_n)$  ( $Q_n$  – rated capacity output),  $h = \text{const}$ , at relative heads:  $h=0.6$ ,  $h=0.8$ ,  $h=1$ . The relative head  $h$  is defined:

$$h = \frac{H}{H_n} \quad (25)$$

where:

$H$  – pump head,

$H_n$  – rated pump head.

At these working conditions of the pump set, electric power  $P_1$  and frequency  $f$  were measured, and the motor's efficiency  $\eta_{se}$  was estimated (19), as illustrated in Figure 3.

In the second testing cycle, a 2.2kW motor was loaded with a direct current generator. Loading torque varied in such a way that the electric power  $P_1$  and frequency  $f$  reached the same values as in the first testing cycle of the pump unit. A torquemeter was attached to the motor shaft at the laboratory station (Fig.2). At known  $P_1$  and  $f$ , loading torque  $M$  and rotary speed  $n$  were measured. The tested motor

efficiency  $\eta_{sb}$  was calculated on the basis of (23), as illustrated in Figure 3.

Loading torque  $M$  of the motor depends on the pump's operating conditions. For each pump, there is an optimum operation point related to the optimum pump's efficiency (maximum efficiency for a known head  $H$  and rotary speed  $n$ ) [14]. Optimum efficiency occurs at the frequencies  $f_{opt1}=50\text{Hz}$ ,  $f_{opt2}=44\text{Hz}$ ,  $f_{opt3}=39\text{Hz}$ , corresponding to heads  $h=1$ ,  $h=0.8$ ,  $h=0.6$  (optimum efficiency can be determine bases on pump iso-efficiency curves). The motor's efficiency  $\eta_s$  varies slightly across the frequency range  $f \in (f_{opt}, f_n)$ . As the frequency reduces by 3÷4 Hz in reference to the optimum frequency, the motor's efficiency greatly deteriorates.

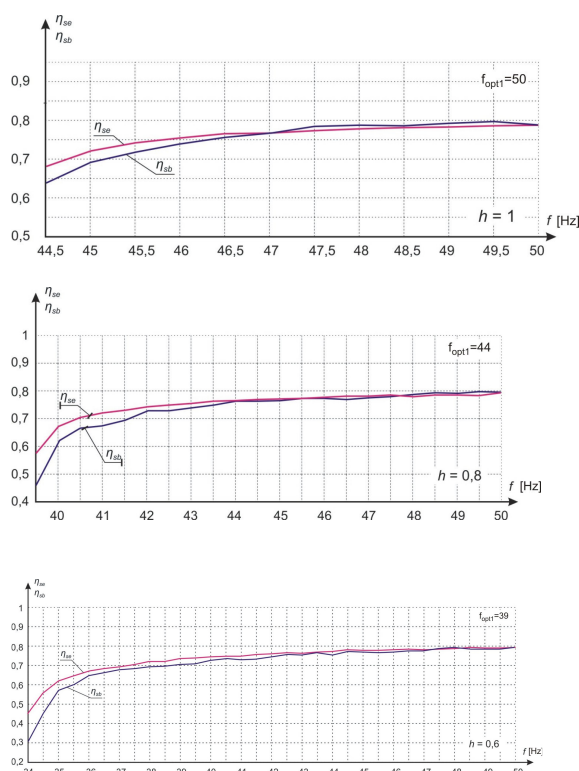


Fig.3. Estimated efficiency  $\eta_{se}$  and tested efficiency  $\eta_{sb}$  of the induction motor at constant head  $h$  of the pump:  
a)  $h=1$ ; b)  $h=0.8$  c)  $h=0.6$

#### 4. CONCLUSION

The test results of the induction motor's efficiency in the two cases indicate that the estimated  $\eta_{se}$  (19) and tested efficiency  $\eta_{sb}$  (23) have similar values. The tested efficiency results from basic dependencies concerning electric machines, defining the relation of mechanical  $P_2$  and electric  $P_1$  power of the motor. The dependence of estimated efficiency  $\eta_{se}$  bases on measurements of electric power  $P_1$  and frequency  $f$  of supply voltage, if rated losses  $\Delta P_n$  are known.



Fig. 4. Prototype pumping station implementing an energy-efficient control system

The original aspect of  $\eta_{se}$  lies in the dependence of its value on the voltage frequency  $f$  and electric power  $P_1$  of the motor. Thus, efficiency of the motor can be computed in the PLC (Programmable Logic Controller) during operation of a pump set. This enables to control operation of the drive in the region of greatest efficiencies. Figure 4 presents a prototype pumping station including three pumps with independent power supply from frequency converters. Water runs in a closed circuit. A working sequence of a pump set is implemented in PLC, employing (19), which reduces its energy consumption to the maximum possible extent.

#### REFERENCES

- [1] CHWALEBA, A., LUFT, M.: *Właściwości i projektowanie wybranych przetworników mechano-elektrycznych (Characteristics and Design of Chosen Mechano-Electrical Transducers)*, Wydawnictwa Politechniki Radomskiej, Radom 1998.
- [2] Efficiency Tool.: Energy savings calculator for AC Motor and Driver Replacements, ABB 2002.
- [3] ELTON, D.: An Application At a Model – Based Measurement Technique to the Inspection of Induction Machines, IMEKO 1988.
- [4] HOWARD, E.: *Energy efficient electric motors and their application*, USA 1983.
- [5] KACZMAREK, R., AMAR, M., PROTAT, F.: *Iron Loss Dunder PWM Voltage Supply on Epstein Frame and In Induction Motor Core*, Transaction on Magnetics 1/1996.
- [6] KOKOTKIEWICZ, J.: *Projektowanie silników indukcyjnych klatkowych o zmniejszonych stratach mocy spowodowancy zasilaniem poprzez przemiennik częstotliwości (Designing Squirrel-Case Induction Motors with Reduced Power Losses When Supplied From Frequency Converters)*, BOBRE Komel Katowice. 1995.

- [7] KRAUSE, P.C.: *Analysis of Electric Machinery*, McGraw-Hill International Editions, Singapore 1987.
- [8] LUFT, M., CIOĆ, R.: *Increase of accuracy of measurement signals reading from analogue measuring transducers*, Zeszyty Naukowe Politechniki Śląskiej – Transport, Katowice 2005.
- [9] LUFT, M., ŁUKASIK, Z.: *Podstawy teorii sterowania (The Principles of Control Theory)*, Technical University of Radom, 2007.
- [10] MOULAHOU, S., TOUHAMI, O., BENHADDADI.: *Iron loss in vector controlled induction machine*, Canada.
- [11] PLAMITZERA, M.: *Maszyny Elektryczne (Electric Machines)*, WNT, Warszawa 1986.
- [12] PRZYGODZKI, J.R.: *Minimisation of Energy Losses In Magnetic Cores of Electric Motors and Transformers*, Energy Saving in Electrical Engineering, Warsaw 2001.
- [13] Pump Save 2.0.: *Energy Saving Calculator for Pump Drivers*, ABB 1999.
- [14] SZYCHTA, L.: *Zasady doboru systemu sterowania pompowni wodociągowych, (Principles of selection of control system for pump station)* Monograph No 93, Politechnika Radomska, 2006.
- [15] SZYCHTA, E.: *Multirezonansowe przekształtniki ZVS napięcia stałego na napięcie stałe, (Multiresonant DC/DC ZVS converters)*, Oficyna Wydawnicza Uniwersytetu Zielonogórskiego, Monograph, Vol.6 2006.
- [16] SZYCHTA, E.: *Control characteristics of multiresonant ZVS boost converter*, Przegląd Elektrotechniczny, No.2/2007.
- [17] ZAKRZEWSKI, K.: *Overloss coefficient for dynamo sweet during axid magnetization with nonsinusoidal flux*, Archives of Electrical Engineering Warsaw, Poland 3/1997.
- [18] ZAKRZEWSKI, K.: *Porównanie charakterystyk eksploatacyjnych silnika indukcyjnego przy zasilaniu napięciem sinusoidalnym I napięciem falownikowym MSI (Comparison of Operation Characteristics of Induction Motor Supplied With Sinusoid Voltage and MSI Converter Voltage)*, Politechnika Łódzka, Łódź. 1993.
- [19] ZAKRZEWSKI, K., SOBCZAK, F., KUBIAK, W., SZULAKOWSKI, J.: *Porównanie charakterystyk eksploatacyjnych silnika indukcyjnego przy zasilaniu napięciem sinusoidalnym i napięciem falownikowym MSI (Comparison of Operation Characteristics of Induction Motor Supplied With Sinusoid Voltage and MSI Converter Voltage)*, Instytut Maszyn Elektrycznych i Transformatorów Politechniki Łódzkiej, Łódź. 1995.