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Efficiency determination of inverter-fed induction motor for low power applications

Abstract. *The paper presents the measurement results of the efficiency of an induction motor, the new high efficiency class IE2 based on the direct efficiency measurement. For comparison purposes, the motor under test was fed by both a programmable three-phase AC power source and a frequency converter under the same conditions. The influence of the non-sinusoidal feeding and the harmonic power on the motor efficiency decreasing was investigated. T-model of the induction motor was used for computer simulations.*

Streszczenie. *Artykuł prezentuje wyniki badań sprawnościowych silnika indukcyjnego klasy IE2 o wysokiej sprawności znamionowej, opartych na bezpośrednich pomiarach współczynnika sprawności. Dla celów porównawczych badany silnik zasilany był z trójfazowego, programowalnego źródła prądu przemiennego oraz przemiennika częstotliwości, w tych samych warunkach laboratoryjnych. Przeanalizowano wpływ zasilania niesinusoidalnego oraz wyższych harmonicznych na spadek sprawności badanego silnika. Podczas przeprowadzania symulacji komputerowych wykorzystano model T silnika indukcyjnego. (**Badania sprawności silnika indukcyjnego zasilanego przekształtnikowo w układach małej mocy**).*

Keywords: efficiency, induction motor, efficiency class, non-sinusoidal feeding.
Słowa kluczowe: współczynnik sprawności, silnik indukcyjny, klasa sprawności, zasilanie niesinusoidalne.

Introduction

More and more public attention is now being focused on reducing energy consumption. New energy efficiency legislation has been drawn up in the EU in recent years to protect our environment [1] with an impact on the design of new induction motors as well. The EU has established mandatory minimum efficiency levels of induction motors for low power applications [2-4], which are going to come into force this year. The legislative changes have also caused modification of IEC standard methods for determining electrical machine efficiency [5] to be consistent with the majority of the worldwide standards [6].

According to IEC 60034-2-1 [5], the main change is the stray load losses are no longer assumed to be a lump sum value of 0.5 % of input power. Instead, they are determined by making measurements. It means that the nominal efficiencies decrease from EFF1 to IE2 or EFF2 to IE1 respectively, although nothing changes at the motor – neither technically nor physically [4].

It is well-known that variable-frequency drives equipped with an inverter-fed induction motor with control energy-saving features have improved motor and drive efficiency to make energy savings in comparison with uncontrolled speed drives. However, the efficiency testing methods for these types of drives are not standardized.

The paper presents the measurement results of the efficiency of a squirrel cage induction motor with the rated motor power of 4kW in the new high efficiency class IE2 based on the direct efficiency measurement.

Motor efficiency

Time voltage and current waveforms of an non-sinusoidal or inverter-fed induction motor in steady state are generally alternating, periodic, non-sinusoidal time functions which can be separated according to [7] into the fundamental component (denoted by subscript (1)) and the harmonic component (denoted by subscript h). Thus, for the electrical phase active power holds:

$$P = \frac{1}{T}\left[\int_0^T v_{(1)} i_{(1)}\,\mathrm{d}t + \int_0^T v_{(1)} i_{\mathrm{h}}\,\mathrm{d}t + \int_0^T i_{(1)} v_{\mathrm{h}}\,\mathrm{d}t + \int_0^T v_{\mathrm{h}} i_{\mathrm{h}}\,\mathrm{d}t\right] = P_{(1)} + 0 + 0 + P_{\mathrm{H}}\,, \tag{1}$$

where: T – time period of the fundamental component, v – instantaneous voltage value, i – instantaneous current value, $P_{(1)}$ – fundamental phase active power, P_{H} – harmonic phase active power and for the electrical input power of the three-phase induction motor

$$P_{\mathrm{in}} = P_{(1)\mathrm{in}} + P_{\mathrm{Hin}} = P_{(1)\mathrm{a}} + P_{(1)\mathrm{b}} + P_{(1)\mathrm{c}} + P_{\mathrm{Ha}} + P_{\mathrm{Hb}} + P_{\mathrm{Hc}}\,, \tag{2}$$

where: a,b,c – phase subscripts.

Then, the motor efficiency can be expressed as:

$$\eta_{\mathrm{m}} = \frac{P_{\mathrm{out}}}{P_{\mathrm{in}}} = \frac{T_{\mathrm{m}}\omega_{\mathrm{m}}}{P_{\mathrm{in}}} \tag{3}$$

or for the fundamental component

$$\eta_{(1)\mathrm{m}} = \frac{P_{\mathrm{out}}}{P_{(1)\mathrm{in}}}\,, \tag{4}$$

where: P_{out} – mechanical output power, T_{m} – motor torque, ω_{m} – angular motor shaft velocity. The mechanical output power P_{out} can be determined by the direct measurement or by calculation from a motor model.

As can be seen from (2) the harmonic active powers decrease the motor efficiency value, if their sign is positive. Thus, the time harmonics cause additional (stray) losses but also parasitic torques or forces (vibrations) [8].

Direct efficiency measurement system

The experimental system for the direct efficiency measurement located in the EMC laboratory of our department is shown in Fig.1. The three-phase squirrel cage induction motor in the high efficiency class IE2 under the test has the following rated parameters: P_{n} = 4 kW, I_{n} = 8.1 A, V_{n} = 400 V, f_{n} = 50 Hz, n_{n} = 1440 rpm, η_{n} = 86.6 %.

The motor was fed by the AC programmable power source Pacific AMX 3120 (ACPS) or by the commercial frequency converter whose inverter switching frequency was adjusted to factory setting of 16 kHz. The mechanical load on the test motor was provided by a separately-excited DC motor drive which was controlled by a thyristor rectifier.

Digitized voltage, current, torque and velocity signals were acquired by a 12-bit multi-channel measurement system based on two DAQ boards with a sampling rate of

200 kSa/s per channel. The input power, active powers (2), the output power and the motor efficiency (3) were calculated offline on a computer from recorded, digitized signals by averaging over 50 time periods of the motor voltage. Two line-line voltages were measured by high precision isolation modules. Two Hall-effect transducers were used for accurate current measurement. Motor torque and velocity were obtained by a precision transducer. Bandwidths of all measured signals were limited by signal conditioning modules to 30 kHz. All measurements have been performed in steady-state.

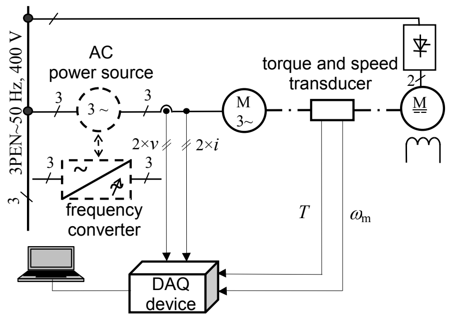

Fig.1. Block diagram of testing system

Experimental efficiency measurement

It is difficult to take into account all physical phenomena act in the motor under non-sinusoidal conditions because a real motor is a complex, non-linear system. For this reason it is more efficient to make precise experimental efficiency measurements in compliance with the requirements of standard [2] and then if it is necessary to determine dividing losses [9] or equivalent parameters of the motor.

To verify influence of the total harmonic voltage distortion level (THD_v) [7] on the motor efficiency the motor was fed by the ACPS with adjusted levels of THD_v equal to 0%, 2%, 4%, 6% and 8% respectively. Measurement results are depicted in Fig. 2 and labelled in the legend of the graph for constant motor load expressed in p.u. of the rated motor torque. As it can be seen the motor efficiency decreases with the THD_v level approximately linearly but with different slopes depending on motor load. The slope of the lines lies between values of -0.040% and -0.055% of the efficiency per 1% of the THD_v. Therefore, it is evident that the voltage distortion limit prescribed in EN 50160:2007 [10] does not significantly reduce the motor efficiency.

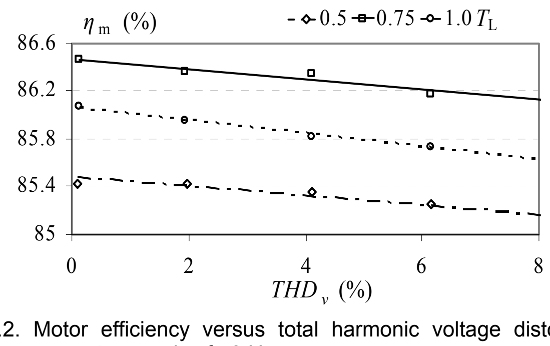

Fig.2. Motor efficiency versus total harmonic voltage distortion, frequency motor supply of 50 Hz

For comparison, there were performed both the sinusoidal and converter motor feeding measurements at motor electrical frequencies 40 Hz, 45 Hz, 50 Hz, 55 Hz and 60 Hz respectively. For the given frequency the same Volts per Hertz ratio as on the converter were adjusted on the ACPS. The motor efficiency dependencies on the motor load for Volts per Hertz control are depicted in Fig. 3a for the converter and in Fig. 3b for the ACPS and in the same way for field weakening control in Fig. 4a and in Fig. 4b. As can be seen from figures the additional losses caused by inverter feeding are visibly larger in the Volts per Hertz control then in the field weakening control. To be more precise, the first of the mentioned control method decreases the motor efficiency up to about 3 % in the frequency range of 30 - 50 Hz and the second one about 1.5% above frequency of 50 Hz. Thus, differences in motor efficiencies are affected by the control method but they may be caused by measurement uncertainty [11] as well.

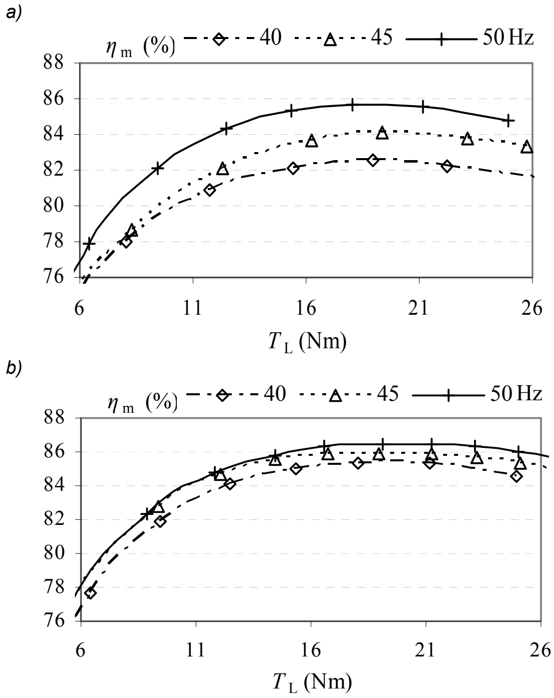

Fig.3. Motor efficiency versus motor load, Volts per Hertz control, *a)* converter, *b)* ACPS

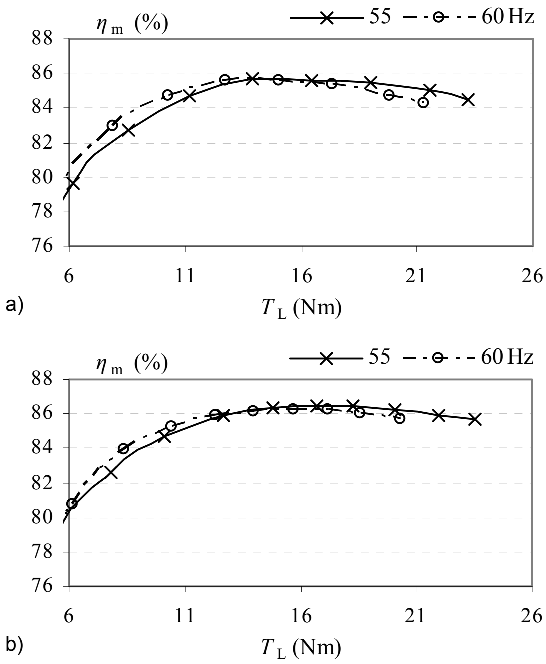

Fig.4. Motor efficiency versus motor load, field weakening control, *a)* converter, *b)* ACPS

It is worth noting that the lower values of the motor efficiency at converter feeding and full loads in Fig. 3a and Fig. 4a are caused by voltage sag on DC bus.

It is well-known that for the phase active power holds roughly $P = P_{(1)}$ at converter feeding with a higher switching frequency. It means that the efficiencies given by (3) and (4) have got practically the same values and graphs as in Fig. 3a and Fig. 3b, because the phase harmonic powers are negligible and that additional losses should be nearly zero. However, performed measurements have turned up that it is not quite true. Although harmonic powers caused by voltage distortion at the ACPS feeding are very small, so their values match well with additional losses as it can be seen from graphs of the motor efficiency in Fig. 2. The same results have been confirmed by simulation, but they are not presented due to limited length of the paper.

Simulation model

For the purpose of simulation, the steady-state conventional T-model of the induction motor was used, whose cross section has been modelled by parallel combination of both the constant resistance R_{Fe} representing core losses and the non-linear magnetizing inductance L_m, whose characteristic has been determined from no load characteristic of the induction motor under the test. The motor equivalent parameters were provided by manufacturer: R_1 = 1.25 Ω, R'_2 = 1.07 Ω, $X_{1\sigma}$ = 4.24 Ω, $X'_{2\sigma}$ = 1.67 Ω, X_m = 64 Ω where rotor parameters are referred to stator.

The simulation was performed for sinusoidal and distorted voltage at the rated frequency. The simulated and measured efficiency of the motor in dependence on its load are shown in Fig. 4 for sinusoidal voltage. As it can be seen excluding light loads the simulated motor load efficiency characteristic is quite close to the motor one. To achieve a better match of that the resistance R_{Fe} could not be constant. Correspondence between the motor model parameters and the real parameters was verified by calculation of per phase equivalent resistance R_{1e} and equivalent reactance X_{1e} as well.

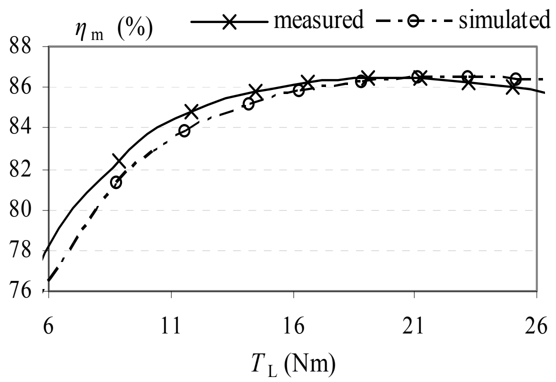

Fig.5. Motor efficiency versus motor load, frequency motor supply of 50 Hz, sinusoidal voltage

Conclusion

This paper has dealt with the experimental efficiency assessment of a low-voltage three-phase motor of the rated power of 4 kW and the new efficiency class IE1. Since 16th June 2011 only low-voltage motors of minimum efficiency class IE2 or greater can be put onto the market in Europe to save energy cost and to protect environment. In particular, it has been focused on impact of the non-sinusoidal motor feeding on the motor efficiency load characteristic, namely, feeding of motor from a distorted voltage source and from a frequency converter operating in the Volts per Hertz and field weakening control mode.

Distorted voltage measurements showed that the efficiency of the motor under the test in dependence on THD_v is approximately linear decreasing for standardized THD_v values of voltage in distribution network.

Comparison measurements between the sinusoidal and converter feeding of the motor under the test with the same Volts per Hertz ratio showed that the motor efficiency is decreasing in dependence on motor load at the converter feeding, in worst case, up to 3% in the Volts per Hertz control and up to 1.5% in the field weakening control mode at the given switching frequency of 16 kHz and modulation strategy.

Finally, simulations confirmed the necessity to consider non-linear characteristics of both the magnetizing inductance and the iron core resistance of the induction motor model and the temperature dependence of the rotor resistance to achieve closer relation between the measured and simulated motor load efficiency characteristic not only in steady-state but also in transient state, which is our future goal.

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