AN APPROACH TO IMPROVE THE PERFORMANCE OF THREE-PHASE INDUCTION MOTORS FROM IE2 TO IE3 AND IE4 CLASSES

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The paper presents an optimizing method of energy parameters of three-phase induction motor in order to improve their efficiency class from IE2 to IE3 or IE4. These efficiency classes are defined in the European standard IEC 60034-30-1:2014. The optimization is performed using specific software by successively adjusting the geometry and the technology. The results have been validated by experiments within the UMEB SA laboratories. The three-phase induction motor that has been analyzed has a rated output of 45 kW, 380V (delta connection), rated speed 1475 rot/min and squirrel-cage rotor type.

Keywords: induction motor, energy efficiency class, optimisation

1. Introduction

The three-phase induction motors represent the main power energy consumers within the industrial field. The global industrial trend is to employ high efficiency induction motors due to the restrictions on the energy consumption and environment's protection directives.

In addition to cutting energy cost the high efficiency motors cut the operating costs due to their high reliability, which leads to lower maintenance costs.

At the same time, as the motor has less power losses its heating and temperature are lower and better behaviour in abnormal operating conditions [1], [2].

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In the past, in Europe the high efficiency low voltage three-phase induction motors were divided in EFF3, EFF2 and EFF1 efficiency classes.

In time contrasts have arisen between various national systems regarding the efficiency classes. In effect the International Electrotechnical Commission (IEC) has stated unified principles.

Some of the efficiency assessment methods have been improved and a new standard has been defined, namely IEC 60034-30-1:2014 [3]. This defines the following efficiency classes for low voltage three-phase induction motors at international level: IE1 (Standard Efficiency), IE2 (High Efficiency), IE3 (Premium Efficiency) and IE4 (Super Premium Efficiency).

Induction motors absorb about 70% of energy consumed by the industrial field. The total amount of consumed electric energy for one year associated with three-phase induction motors is about 1,000,000,000 MWh, thus CO_2 emissions of about 425,000,000 tones per year.

It is estimated that by the end of 2020 the electric energy total consume for one year for induction motors will be about 1,250,000,000 MWh. For this reason it is also spotted a total reduction of greenhouse gases by 20%.

The estimated energy savings for 2020 are of 135,000,000 MWh corresponding to a yearly reduction of 63,000,000 tones of CO_2 and a total savings of 9 milliard Euros.

The last unified standard IEC 60034-30-1:2014 defines four international efficiency classes for low voltage three-phase induction motors. A second part of this standard series (IEC 60034-30-2) will be prepared for motors rated for variable voltage and frequency supply, such as synchronous motors.

The second part will also provide for harmonic voltage losses in motors capable of line operation when fed by frequency converters.

In Fig. 1 [4] is presented the efficiency of induction motors in relation with the output power for each of the 4 efficiency classes, from IE1 to IE4 in accordance with unified standard IEC 60034-30-1:2014.

Based on the data within the graphic in Fig. 1 the IE1 class ranges about 72% to 94%, IE2 class ranges about 80% to 95%, IE3 class ranges about 82% to 95% while IE4 class ranges about 85% to 96%. Thus a major efficiency improvement is found for lower powers. For example, in case of 0.75kW the improvement of the efficiency is about 18% from IE1 class to IE4.

The electric motors qualified as IE4 efficiency class results in energy savings of up to 14% versus IE1 type.

In comparison to IE3 class the IE4 saves energy up to 3%. Moreover, the efficiency class becomes an important parameter when considering the energy cost for the majority of electric motors, knowing that the initial buying cost is covered in just about 6 months of operation.

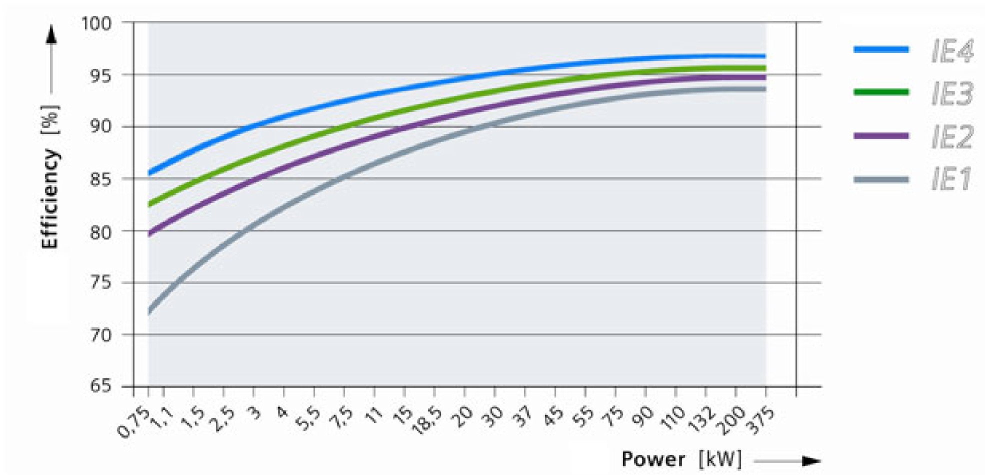

Fig. 1. Efficiency classes IE1 to IE4 according to IEC 60034-30-1:2014

Siemens and ABB provide IE4 alternating current electric motors [5], [6]. These motors have the same shaft height as IE1, IE2 and IE3 motors, for the same power rating. Thus the replacement of one motor with another one is always available regardless the efficiency class.

It must be underlined that for induction motors the most important feature is the energy savings.

Other important operating features are: starting torque, breaking torque, reliability, life time [7 - 10]. When the environment impact is considered then manufacturing technologies are also important being in direct contact with EcoDesign principles.

2. Three-phase induction motor design optimization

In order to design a high efficiency induction motor the starting point was an already existing IE2 type motor manufactured at UMEB SA. The plate data are ASA motor series, rated power 45 kW, rated speed 1500 rev/min, rated voltage 380V, delta connection, and squirrel-cage rotor. The motor has been successively improved based on combined designing and manufacturing processes until IE3 efficiency level has been obtained.

The elements involved during the optimization process are: deeper rotor and stator slots, thinner ferromagnetic sheets, less air-gap, careful manufacturing technology, improved cooling, efficient self-ventilation, high performance ball-bearings (less mechanical losses and increased reliability) [11] [12].

For the ferromagnetic core, based on the IE3 standard, the chosen sheet was M250-50A (Surahammar) which is one of the best, with specific losses of 2.2 W/kg at 50Hz and 1T.

Using a high performance ferromagnetic sheet the efficiency of the motor is improved [1], [2]. Fig. 2 depicts the magnetizing characteristic of M250-50A sheet. It can be observed that for a flux density of 1.5T the magnetic field intensity is 1400 A/m.

All improvements are obtained following a designing process performed with a sheet calculator program presented in [13] associated with computer simulations.

The program sizes the motor and computes its characteristics based on the input data such as: rated values (power, voltage, frequency, speed), materials properties (magnetizing characteristic, such as shown in Fig. 2), maximum electromagnetic stresses (magnetic flux densities, current densities), geometry (diameters, slots dimensions, shaft, housing), various coefficients (filling factors, geometry factors, proportionality factors), materials sizing's (insulation width, conductors size).

The program evaluates the no-load and rated-load characteristics (efficiency, power factor, current, speed, torque, power losses).

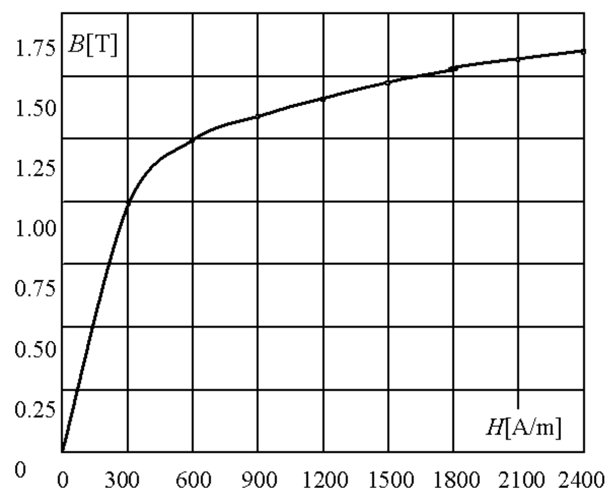

Fig. 2. The magnetizing characteristic of M250-50A sheet

A key parameter for the optimal design of the induction motor in order to be classified as IE3 is the length of the motor's magnetic core.

The conversion from IE2 to IE3 class is performed in two stages.

First one considers the core's length $L_c = 225$ mm that corresponds to IE2 class.

The changes have been performed over the teeth and stator slots, number of rotor slots, stator coils turns, conductor size, squirrel-cage type, skewing angle for rotor bars, bearings type, magnetic sheet. All these parameters change lead to higher motor efficiency.

The second stage maintains all the previous parameters unchanged but various lengths of the magnetic core are considered.

It was concluded that the higher efficiency is obtained for 320mm. The next section presents a study of the motor's performance with the magnetic core length.

In Table I are shown both the initial and final values for the IE2 motor design and IE3 efficiency respectively. The rated values of the motor before and after conversion are the same, i.e. 45kW, 1500rpm, 380V, delta connection.

3. Motor's performances with the magnetic core length

For the optimized motor design (last column in Table 1 - IE3 class) the core length is changed and the influence over various parameters is observed.
The monitored parameters are: rated efficiency, rated power factor, total weight, rated current and rated slip.
The study considers the next five axial lengths for the magnetic core: 225 mm, 250 mm, 280 mm, 320 mm and 360 mm.

Table 1

Parameters for IE3 efficiency level (optimized motor design) versus IE2 efficiency level (initial motor design)

Parameter	IE2	IE3
Stator slot bottom base width b_{1s}	b_{1s} =10.81 mm	b_{1s} =11.8 mm
Stator slot height (tooth height) H_{d1}	H_{d1} = 31.5 mm	H_{d1} = 34 mm
Rotor slots Z_2	Z_2 = 38 slots	Z_2 = 40 slots
Magnetic core length L_c	L_c = 225 mm	L_c = 320 mm
Stator turns (one phase) w_{1f}	w_{1f} = 80 turns	w_{1f} = 68 spire
Raw stator conductor diameter d_c	d_c = 1.4 mm	d_c = 1.18 mm
Insulated stator conductor diameter d_{ci}	d_{ci} = 1.479 mm	d_{ci} = 1.254 mm
Rotor cage	Simple cage with rectangular bars	Double-cage with round cross-section towards air-gap and oval cross-section respectively
Skewing	Unskewed bars	Skewing angle $\alpha = 1^{o}\ 5'$
Bearings	SKF 6313 2Z	E2.6313 2Z (low friction)
Magnetic sheet	M400-50A	M250-50A

Rated efficiency

Based on the results the core length has a major influence over the rated efficiency of the motor. Fig. 3 depicts the dependence between the rated efficiency and the motor's magnetic core length.

It is concluded that the maximum rated efficiency is obtained for a length of 320mm. This length is the one chosen for the IE3 motor prototype.

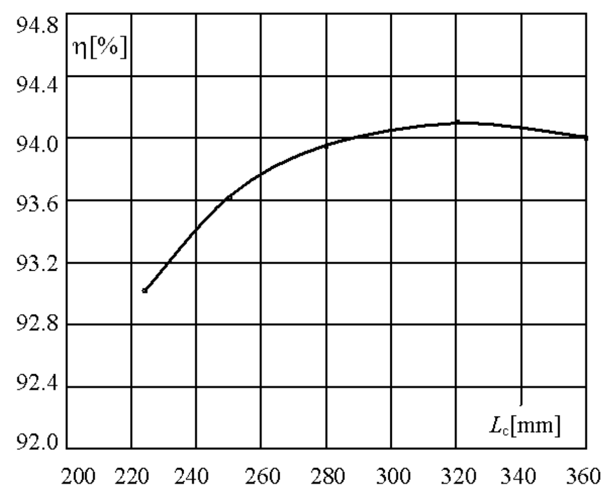

Fig. 3. Motor's rated efficiency variation with magnetic core's length

Power factor

For each of the five core lengths the rated power factor has been obtained. In Fig. 4 is depicted the link between the core length and the obtained rated power factor.

It can be concluded that the rated power factor of the induction motor has a slightly increase with the increase of the magnetic core length.

The increase is sharper for small lengths (below 280 mm).

For larger values of the magnetic core length (over 280 mm) the increase is sharper. One reason for this trend is the higher weight of the end-cap magnetic leakages.

As the core's length increases so does the magnetizing magnetic field while the leakages are almost the same.

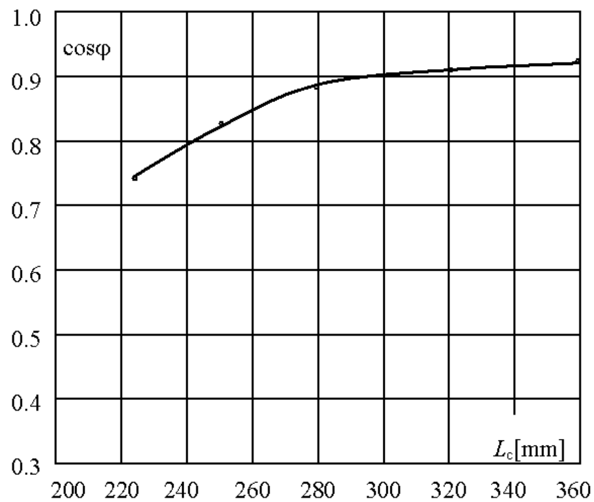

Fig. 4. Motor's rated power factor variation with magnetic core's length

Total weight

Fig. 5 depicts the motor's total weight variation with the magnetic core's length. It can be observed that the length of the magnetic core has a major influence over the motor's total weight.

Although the required number of magnetic sheets is increased the obtained energy savings during the motor's operation are much more important.

The cost for the magnetic material is less than the economy for the saved energy, thus a solution with longer core and more weight is preferred. Moreover, a longer magnetic core means less stator windings, thus less copper. The unit price of copper is larger than the unit price for magnetic core material.

Rated current

The variation with core length of the rated current is presented in Fig. 6. The current value trend is to decrease with the increase of the magnetic core length. The decrease is sharper for small values of the magnetic core length (below 280 mm) followed by an almost flat level.

The rated current decreases because the longer magnetic core (IE3 type) has smaller no-load current with about 20% beside the shorter magnetic core (IE2 type). In other words, the magnetizing component of the no-load current decreases as the length of the magnetic core increases.

Due to the increase of the coils surface the magnetic flux density decreases, thus the motor is less saturated as the magnetic core increases.

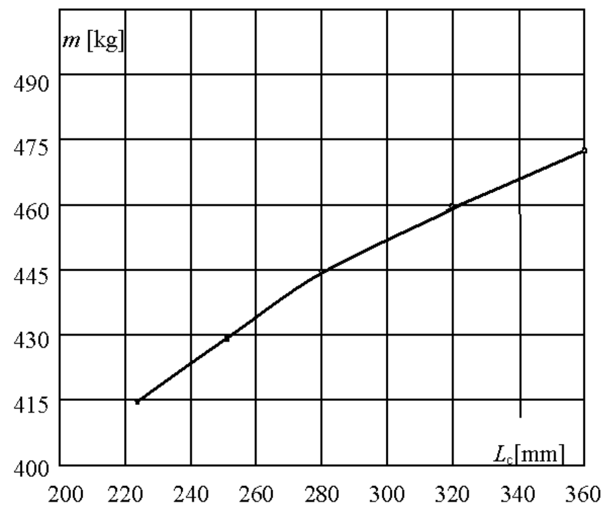

Fig. 5. Motor’s total weight variation with magnetic core’s length.

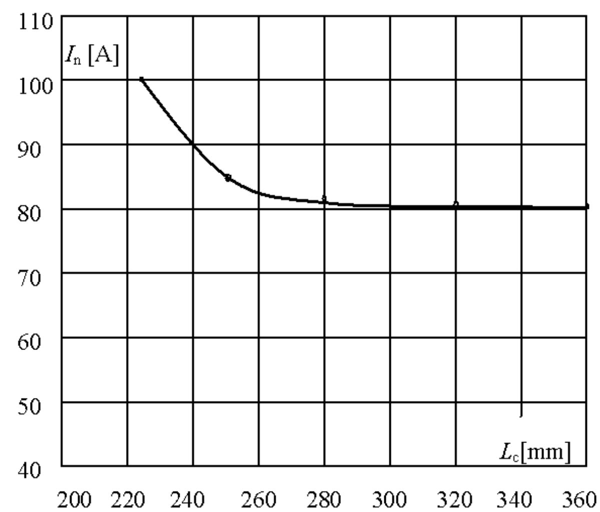

Fig. 6. Motor’s rated current variation with magnetic core’s length

Rated slip

Changing the length of the magnetic core leads to changes of the rated slip. Fig. 7 depicts this dependency. Thus, as the length increases from 225 mm to 360 mm the rated slip also increases from 1.18% to 1.73% respectively.

As the core's length increases the rotor winding's Joule losses increase while the stator winding's Joule losses decrease.

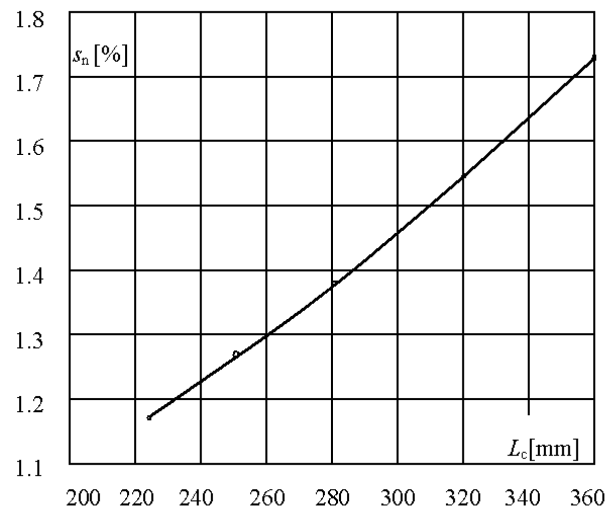

Fig. 7. Rated slip variation with magnetic core's length.

The increase of the rated slip with the length of the magnetic core is easily explainable.

Taking into account the direct link between the rotoric Joule losses and the product between the slip and the electromagnetic power, when the electromagnetic power is constant and equal to its rated value, the increase of the rated rotoric Joule losses leads to the increase of the rated slip.

Looking at the characteristics shown in Fig. 3 and Fig. 6, it can be concluded that for a motor length of 320mm it is obtained the highest efficiency and the lowest rated current. Moreover, the power factor is very close to its maximum value (Fig. 4).

This motor configuration may be considered as IE3 class. Thus, the prototype is manufactured based on the two-step design optimisation process described in sections 2 and 3.

4. Experimental validation

Within the UMEB SA laboratories in Bucharest the motor prototype for the IE3 class has been manufactured, that is ASA motor series, rated power 45 kW, rated speed 1500 rev/min, rated voltage 380V, delta connection, squirrel-cage rotor. Its configuration is optimised as it has been shown. Trials have been performed for the both induction motors IE2 and IE3 types. In Table 2 the obtained experimental results are presented.

All the results presented in sections 2 and 3 are obtained based on computation using the algorithms and methods described in [13]. A comparison between the computed and the measured values for the IE3 motor type are given in Table II. Because the differences are quite low, the experimental results certify the designing algorithm based on computation. The error is computed as follows:

$$error = |measured - computed| / measured \cdot 100 \qquad (1)$$

Moreover, the quantities that have a major influence over the motor energy losses show a low error, that is rated efficiency, rated current and rated power factor.

Table 2

Computed and measured values comparison for the IE3 type induction motor (45 kW, 1500 rpm, 380V, delta connection, squirrel-cage rotor)

Quantity	Computed value	Measured value	Error (%)
Rated efficiency (%)	94	95	1.05
Rated current (A)	84	81.4	3.19
Rated power factor	0.86	0.88	2.27
Rated slip (%)	1.55	1.4	10.7
Stator winding losses (W)	678	584	16.1
Rotor winding losses (W)	716	651	4.15
Stator iron core losses (W)	636	507	25.0
Stator winding over-temperature (°C)	43.3	48.3	10.4
Absorbed rated power (W)	47900	47610	0.61

5. Technology discussion

From thermal point of view, the contact air-gap that exists between the outer surface of the stator iron core and the internal surface of the housing has a major influence. The value of this undesired gap is essentially given by the deviation apart from cylindrical shapes of the stator iron core and the housing. The measurements performed on various induction motors show that even 1/10th millimetre of this gap increases the stator winding temperature with about 10°C.

The rotor core for the type IE3 motor is no longer fixed by the shaft using a key but by warm pressing on the shaft or by a small tapering of the shaft. The key method is not applicable due the skewing of the cage bars. By skewing the bars for the IE3 motor type the cogging torque is reduced.

6. Conclusions

Manufacturing high efficiency induction motors is an up to date matter due to the limited energy resources concern, that it is still present.

The issue becomes more important because the induction motors consume about 70% of the industrial energy and the associated CO_2 emissions are becoming gradually more harmful.

In accordance with Commission Regulation (EC) No 640/2009 of 22 July 2009 implementing Directive 2005/32/EC of the European Parliament and of the Council with regard to eco-design requirements for electric motors, from 01 January 2015 all electric motors with a rated output of 7,5-375 kW shall not be less efficient than the IE3 efficiency level. Thus energy savings are obtained with improved exploitation of electric motors.

In the paper is performed a conversion study of an induction motor ASA type of 45 kW, 1500 rpm, 380V, delta connection, squirrel-cage rotor from IE2 efficiency class to IE3 class. The study has been performed using dedicated computing programs followed by experimental trials and validations performed on a manufactured prototype, which has been successively improved both constructional and technological at UMEB SA.

The main quantities that have been optimised in order to increase the efficiency are: the length of the magnetic core, stator slots and teeth geometry, rotor slots number, stator phase winding turns, rotor cage type, rotor bars skewing angle, ball-baring type, sheet type for the magnetic core. The performed experimental validations have been performed and proved a good accordance between the computed and measured values of the optimising quantities.

Presently, IE4 efficiency class motors are already found on the market, manufactured by well-known players on motors markets [5], [6]. A similar analysis such as the one shown in the article may also be performed for IE4 type.

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