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DESIGN STRATEGIES, NEW MATERIALS AND TECHNOLOGIES TO IMPROVE INDUCTION MOTORS EFFICIENCY

ABSTRACT *The paper presents a comparison between four different design strategies with the aim to improve the efficiency of three-phase induction motors: substitution of die-caste copper cage for aluminium cage with standard and "premium" electrical steels; design optimisation of copper cage motor by changing the stator winding and the stack length only; design optimisation of copper cage motor by changing the stator winding, the stack length and the stator and rotor slot shapes. The comparison is based on the actual efficiency improvements, the arrangement of the motors respect to the European Classification Scheme (EC/CEMEP), the contribution of each material and innovative technology. The results concern with 4 pole, 50 Hz, 400 V, TEFC, 3 and 15 kW induction motors.*

1. INTRODUCTION

Electric Drive Systems have a significant impact on the consumption of electricity and induction motors are one of the components involved, which can contribute to energy savings. While sensitive and technically ready, the

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motor industry is under increasing price competition from low cost low efficiency motors. New ranges of high efficiency motors require accurate motor design, the adoption of new materials (e.g. premium steel) and innovative technologies (e.g. copper rotor cage die-casting). The challenge is to develop high efficiency motors without substantial additional cost. That could be achieved by choosing among several design strategies each of one presents different cost for the manufacturer.

In the paper the following design strategies have been investigated:

1. *Substituting copper cage for aluminium cage and standard electrical steel, without changing any motor dimension.*
   It is well known that incorporation of copper for the rotor bars and end rings in place of aluminium would result in attractive improvements in motor energy efficiency [1], [2]. Copper die-cast rotor construction does not differ significantly from the aluminium one and, in essence, the manufacturing details are identical. The additional manufacturing challenges are increased temperatures and pressures required to die-cast copper: the main technical barrier was the inadequate die life of the mould. Recently suitable high temperature mould materials have been successfully identified demonstrating that operating the dies and shot sleeve at elevated temperatures could substantially extend tooling life [3], [4]. Also, the French company, FAVI SA (Fonderie et Atelier du VImeu), has applied its considerable experience and know-how in die casting copper alloys to production of the copper rotors for a number of European motor manufacturers [5].
2. *Substituting copper cage for aluminium cage and high performance electrical steel, without changing any motor dimension.*
   The magnetic material plays a significant role in the improvement of the motor performance [6]. Respect to this goal, its main features are the magnetic permeability and the specific losses. Moreover, the choice of a “suitable” electrical steel depends on several aspects such as cost, workability, annealing (when needed), “business tradition” and storehouse demands.
3. *Design optimisation of copper cage motor by changing the stator winding and the stack length only [7].*
4. *Design optimisation of copper cage motor by changing the stator winding, the stack length and the stator and rotor figures.*

The aim of the project was the comparison between the above mentioned design strategies respect to:

- the efficiency improvements;

- the arrangement of the motors respect to the European Classification Scheme (EC-CEMEP);
- the contribution of each material and innovative technology to the efficiency improvements.

The paper presents the results obtained using the considered design strategies when "premium steel" and copper rotor cage are used instead of standard steel and aluminium cage, with standard and higher stack length. The considered motors are typical 4 pole, 50 Hz, 400 V, TEFC, 3 and 15 kW industrial three-phase induction motors.

2. RESEARCH PROJECT DEVELOPMENT

To evaluate the efficiency improvements, two standard motors have been chosen as "reference motors": they are commercial motors with aluminium rotor cage and standard electrical steel belonging to the efficiency classes Eff3 (3 kW motor) and Eff2 (15 kW motor). However, taking into account the tolerance on efficiency measurements, the 3 kW motor could be classified in the Eff2 class.

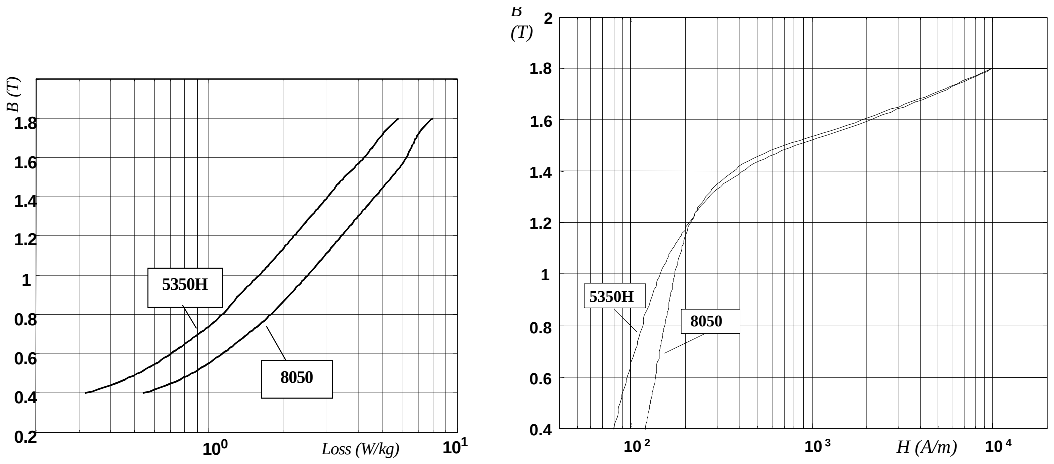

Fig. 1. Specific losses and B-H curves of 8050 and 5350H steels

The standard electrical steel used in the reference motor construction is labelled 8050. The chosen alternative electrical steel is labelled 5350H. It represents a good compromise between specific loss and permeability. In fact, frequently better magnetic materials from the losses point of view have worse permeability. As a consequence, the increase of magnetizing current and corresponding Joule losses reduce the benefit of lower iron losses. Actually, the electrical steel 5350H can be define “premium steel” because combines low specific losses (3.5 W/kg at 1.5 T respect to 5.5 of the 8050, Fig. 1) with high permeability (better than 8050 under 1.2 T, a little bit worse over).

2.1. Motor Prototypes

The motor prototypes have been realized according to the following combinations (1...3 for the 15 kW size, 1...6 for the 3 kW one) :

1. Aluminium cage and standard steel 8050 (commercial “reference motor”); the corresponding prototype is labelled “Al 8050”.
2. Copper cage and standard steel 8050; the prototype is labelled “Cu 8050”.
3. Copper cage and premium steel 5350H; the prototype is labelled “Cu 5350H”.
4. Copper cage, standard steel 8050, new stator winding and Higher Stack Length (HSL); the new stack length is consistent with the standard housing; the prototype is labelled “HSL Cu 8050”.
5. Copper cage, premium steel 5350H, new stator winding and Higher Stack Length (HSL); the new stack length is the same of case 4); the prototype is labelled “HSL Cu 5350H”.
6. Copper cage, premium steel 5350H, higher stack length, new stator winding and new stator and rotor slot shapes (Optimised Design OD); the new stack length is the same of case 4); the prototype is labelled “OD Cu 5350H”.

The motor prototypes could be divided in two groups:

- the first one (combinations 1...3, 3 an 15 kW motor sizes) includes the standard motor and the alternative ones with copper cage and premium steel with the same stator winding and stack length; they represent the cheapest way to increase the efficiency using high quality materials and innovative technology;
- the second group includes the prototypes with higher stack length, new stator winding, copper rotor cage, premium steel (combinations 4 and 5) and new stator and rotor figures (case 6); the inner and outer stator diameters are the same of the standard motor ones. For cases 4) and 5) the cost of tooling is effectively the same of the standard design since the need for costly new lamination punch tools or stator housing tools are avoided (except the additional cost for copper die-casting).

All new motors have been designed by a suitable design procedure that combine a performance analysis model with an optimisation algorithm.

2.2. Design Procedure

The physical description of the motor is reduced to equivalent parameters such as resistances and inductances: the adopted analytical model takes into account the influence of saturation on stator and rotor reactances and the influence of skin effect on rotor parameters. The effects of temperature on motor resistances are computed on the basis of a detailed thermal network. The validity of the model has been verified by means of experimental tests on several three-phase induction motors [8].

The design optimisation integrates the analytical motor model into an automated process. The optimisation problem is to minimise (or maximise) a function $F=F(X)$, with $X=(x_1, x_2, \ldots x_n)$; the function F is called "objective function" (OF) and the vector X represents the set of independent variables. Each variable might be constrained explicitly by upper/lower bounds ($x_{li} < x_i < x_{ui}$ i=1,2,3,…n). The introduction of p constraints $g_i(X)$ that concern typical motor performance makes the optimisation a constrained problem. The distinguishing features of such an optimisation problem are that:

(i) an explicit mathematical representation of the objective function and of constraint functions is not available;
(ii) he constraints $g_i\,(X) \leq 0,\ \ i=1,..p,$ are not very restrictive, namely it is relatively easy to find a feasible point and to remain in the feasible region;
(iii) different local minimum points lie beside global minimum points.

The approaches proposed in literature to tackle induction motor design optimisation, use one or both the following strategies:

- the constraints $g_i\ (X) \leq 0,\ i=1,..p$, are eliminated by adding to the objective function an interior penalty term which goes to infinity at the boundary of the set;
- the (possibly modified) objective function is minimized over the box $x_{li} \leq x_i \leq x_{ui}$ by adopting a derivative-free unconstrained local optimisation method; such an algorithm is able to find a stationary point of the objective function, without using first order derivatives (e.g. simplex method or the Hooke-Jeeves algorithm).

The optimisation algorithm proposed by the authors [9] does not use any penalty function; instead, because of feature (ii) of the original problem, it is able to produce directly feasible points. Another interesting feature is that it is a modification of a method which was defined to locate the global minimum of a function and therefore it does not get trapped in local minima.

In the project, the optimisation procedure to design new prototypes has been applied only to the 3 kW motor and it has been formulated as constrained maximisation of the objective function “rated efficiency”. The list of the independent variables and the design constraints with their bounds are shown in Table 1 and Table 2 respectively. Table 3 presents the main dimensions and weights of the prototypes (reference motors and new prototypes, 3 and 15 kW sizes) while Fig. 2 shows a view of the copper rotors.

TABLE 1
Design independent variables with upper and lower bounds. 3 KW motor

Independent Variables	Min	Max
(*) Stack length (mm)	130	160
(*) Stator wire size (mm^2)	0.90	1.30
(*) Air-gap average flux density (T)	0.45	0.60
Stator tooth width (mm)	3.7	4.3
Stator tooth height (mm)	15.0	19.0
Rotor tooth width (mm)	3.7	4.8
Rotor tooth height (mm)	15.0	18.0

(*) cases 4) and 5)

TABLE 2
Design Constraints with upper/lower bounds. 3 kW motor

Constraints	
Power factor	≥ 0.75
Temperature of stat. wind. (°C)	≤ 90
Temperature of rotor cage (°C)	≤ 100
Breakdown torque (Nm)	≥ 60
Locked rotor torque (Nm)	≥ 48
Locked rotor current (A)	≤ 50
Flux density in the stat. tooth (T)	≤ 1.8
Flux density in the rot. tooth (T)	≤ 1.8
Rated slip %	≤ 2.5
Stator slot fullness	≤ 0.46

TABLE 3
Prototypes main dimensions and weights

3 kW			**HSL**	**OD**
	Al 8050	**Cu 8050 Cu 5350H**	**Cu 8050 Cu 5350H**	**Cu 5350H**
Stack length (mm)	130	130	155 (+19%)	155 (+19%)
Out. stator diam. (mm)	152	152	152	152
In. stator diam. (mm)	90	90	90	90
St. winding weight (kg)	2.45	2.45	2.82 (+15 %)	3.46 (+41%)
Rotor cage weight (kg)				
Al	0.74			
Cu		2.43	2.73 (+12%)	2.89 (+19%)
Gross iron (kg)	22.4	22.4	26.8 (+20%)	26.8 (+20%)

15 kW	**Al 8050**	**Cu 8050 Cu 5350H**
Stack length (mm)	220	220
Out. stator diam. (mm)	250	250
In. stator diam. (mm)	160	160
St. winding weight (kg)	14.5	14.5
Rotor cage weight (kg)		
Al	3.0	
Cu		9.8
Gross iron (kg)	220	220

3. RESULTS

In order to evaluate the copper rotor and premium steel effects on each loss category and to obtain an accurate efficiency measurement, a loss segregation method is required. IEEE 112-B and CSA C390-98 methods are true input vs output power efficiency tests that segregate losses into five categories: Iron Losses, Stator Resistance, Rotor Resistance, Friction and Windage (F&W) and Stray Load Losses (SLL). The first four are measured directly and the remainder is the “stray load” category. The experimental results presented in the paper refer to the Standard CSA C390-98.

Fig. 2. View of the copper rotors

Table 4 shows the comparison between 15 kW standard stack length new prototypes (Cu 8050 and Cu 5350H) and commercial motor Al 8050: the efficiency and loss segregation test results are presented.

Comparison between motors Al 8050 and Cu 8050 allows to evaluate the improvements achievable with copper rotor only. The comparative tests have been carried out by adopting the same stator core and winding: in this way any difference in performance due to the production process has been avoided. Motor Cu 5350H results show the effects of the premium steel (in comparison with motor Cu 8050) and the improvements respect to the standard motor (in comparison with motor Al 8050).

TABLE 4
CSA C390-98 Efficiency and Loss Segregation Test Results. 15 kW motor

15 kW	Al 8050	Cu 8050	Cu 5350H
η %	90.1	91.0	91.9
Σlosses (W)	1634	1473	1316
Stator wind.	481	470	477
Rotor cage	385	232	202
Iron	434	424	327
SLL	238	256	219
F&W	96	91	91

Copper rotor (Cu 8050) yielded an average 44 % reduction in measured rotor losses while the overall losses were reduced by 10 %. With premium steel and copper rotor (Cu 5350H), iron losses were reduced by 24 % and the overall losses by 20 % and 11 % respect to the standard motor and the copper motor. In comparison with standard motor, the efficiency improvements were 0.9 points with copper rotor and 1.8 points with premium steel and copper rotor. For the 15 kW copper motor, it is interesting to remark that the tolerance on the efficiency could classify this motor as Eff1. With the adoption of premium steel and copper rotor, the 15 kW motor is fully in Eff1 class. Therefore no any other action has been adopted to improve its efficiency.

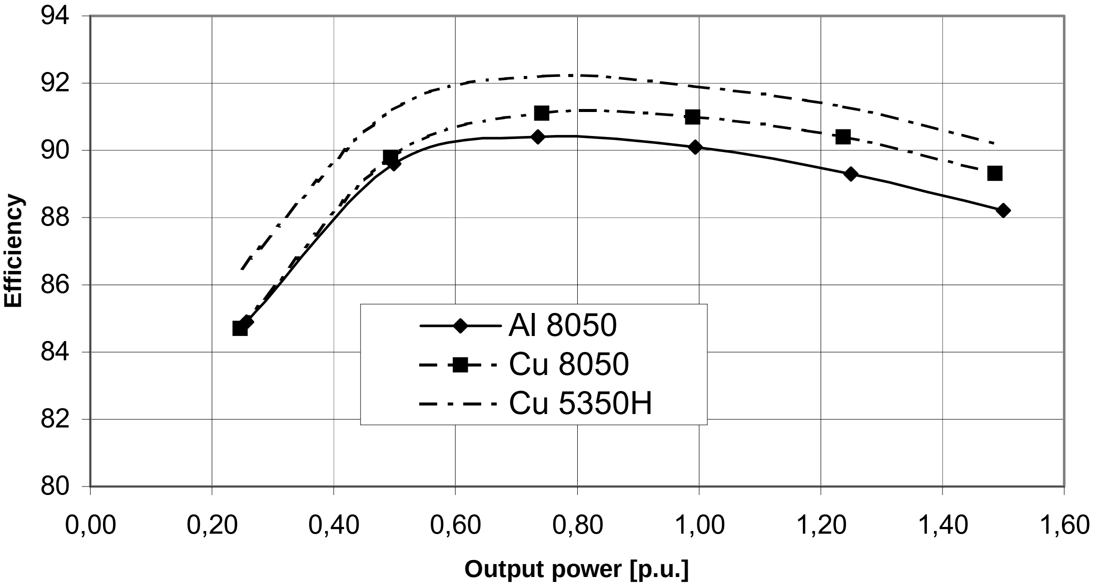

Fig. 3. Efficiency - output power curves. 15 kW motors

Figure 3 shows the dependence of efficiency on output power. The effects of premium steel and copper rotor cage are evident: premium steel improves the efficiency at partial load while copper cages increase the efficiency at rated and over load, maintaining good efficiency in an extended range (0.5...1.3 p.u.).

Tables. 5 and 6 show the 3 kW motors test results.

The substitution of copper as rotor material (Table 5) has allowed to move the 3 kW motor in the Eff2 class (efficiency > 82.6), while the use of the 5350 H electrical steel does not give rise any further efficiency class movement. As expected, the most significant loss reduction is in the rotor cage while iron losses reduction is 20 % with premium steel.

Further improvement on motor performance has been achieved with copper rotor and premium steel adoptions combined with higher stack length, new stator winding (motors HSL Cu 8050 and HSL Cu 5350H) and new stator and rotor slot shapes (motors OD Cu 5350H). Table 6 shows test results of the 3 kW higher stack length prototypes.

TABLE 5
CSA C390-98 Efficiency and Loss Segregation Test Results. 3 kW standard stack length motors

3 kW	**Al 8050**	**Cu 8050**	**Cu 5350H**
η %	82.0	84.1 (+2.1)	84.5(+2.5)
Σlosses (W)	655	563 (-14%)	545 (-17%)
Stator wind.	351	327	337
Rotor cage	153	83 (-46%)	83(-46%)
Iron	117	124	94(-20%)
SLL	13	13	8
F&W	21	16	23

TABLE 6
CSA C390-98 Efficiency and Loss Segregation Test Results. 3 kW Higher Stack Length motors

3 kW	**HSL Cu 8050**	**HSL Cu 5350H**	**OD Cu 5350H**
η %	86.0	86.5	87.7
Σlosses (W)	486	465	418
Stator wind.	265	265	186
Rotor cage	73	77	67
Iron	113	99	134
SLL	15	9	8
F&W	20	15	23

With standard steel 8050 the measured efficiency is 2 points higher respect to the corresponding copper rotor motor with standard stack length and 4 points higher respect to the commercial aluminium rotor motor (Table 5). With premium steel 5350H the measured efficiency is 2 points higher respect to the corresponding copper rotor motor with standard stack length and 4.5 points higher respect to the commercial aluminium rotor motor. The most significant losses reduction is in the stator winding. The HSL motors remain in the Eff2 class, but could be labelled Eff1 motors if the tolerance is taken into account.

The best results have been achieved when the adoption of new materials and technologies have been associated with a more complete, accurate optimised motor design (OD Cu 5350H motor) that allows to exploit the advantages of copper cage and premium steel: the motor is fully in Eff1 class (efficiency > 87.4). Stator winding losses are considerably reduced, only partially compensated by the iron losses increasing; moreover, further rotor cage losses reduction has been obtained.

A complete comparison between the 3 kW motor series is shown in the next figures.

Figure 4 shows the dependence of efficiency on output power. It is easy to individuate four groups of motors: standard motor with aluminium; motors where aluminium are simply substituted by copper; motors with higher stack length; motor completely redesigned. The effects of materials (premium steel and copper) and design strategies are evident. Curves corresponding to copper cages are almost flat, maintaining good efficiency in an extended range (0.6...1.2 p.u.) of output power respect to aluminium motor (0.6...1.0 p.u). That result is important due to frequent partial load operations and shows good overload capabilities of copper rotor motors.

Figure 5 presents the voltage-no load current curves. It points out the effect of the design optimisation exploiting the quality of the premium steel.

Figs. 6 shows the comparison between other important motor performance.

Stator winding temperature rise reduction confirms the total losses trend and it is between 30 °C and 40 °C for the new design motors. That is a very important feature because temperature rise is significant in the life expectancy of the motor and lower temperatures mean that smaller cooling fans can be used: this has a significant effect in reducing the friction and windage losses.

Power factor is almost constant for all motors with the exception of the OD Cu 5350H optimised design one.

Copper substitution for aluminium keeps nearly constant the breakdown torque. Higher stack length and new stator winding permit to increase it by 15 %.

Focusing on starting conditions, the substitution of copper for aluminium leads to decreased starting torque (-13...-20 %, but still above two times the rated one) and slight higher starting current (+14 %). Higher stack length and new stator winding assure the same standard motor locked rotor torque with about 40...45 % higher currents.

4. CONCLUSIONS

The paper presents test results concerning several prototypes of 3 and 15 kW induction motors with die-cast copper rotor cage and premium electrical steel. Four design strategies have been investigated:

1. substituting copper cage for aluminium cage with standard electrical steel, without changing any motor dimension;
2. substituting copper cage for aluminium cage with high quality electrical steel, without changing any motor dimension;
3. design optimisation of copper cage motor by changing the stator winding and the stack length only;
4. design optimisation of copper cage motor by changing the stator winding, the stack length and the stator and rotor figures.

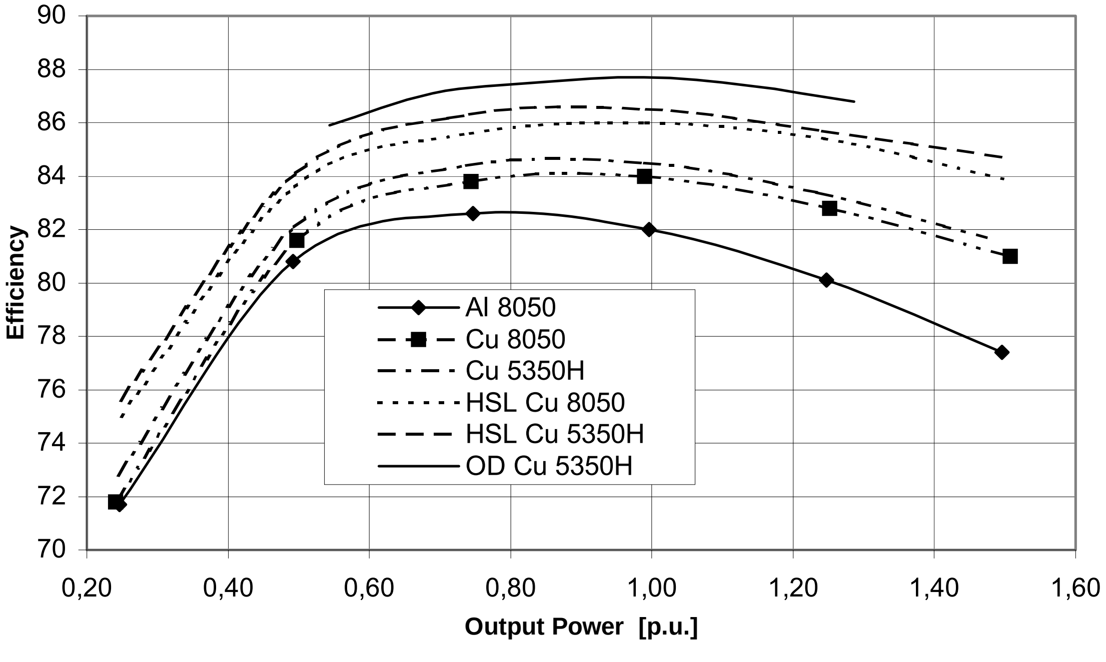

Fig. 4. Efficiency - output power curves. 3 kW motors

For the 15 kW size, the tolerance on the efficiency permits to classify the copper rotor motor as Eff1. With the adoption of premium steel and copper rotor, the 15 kW motor is fully in Eff1 class. Therefore no any other action has been adopted to improve its efficiency.

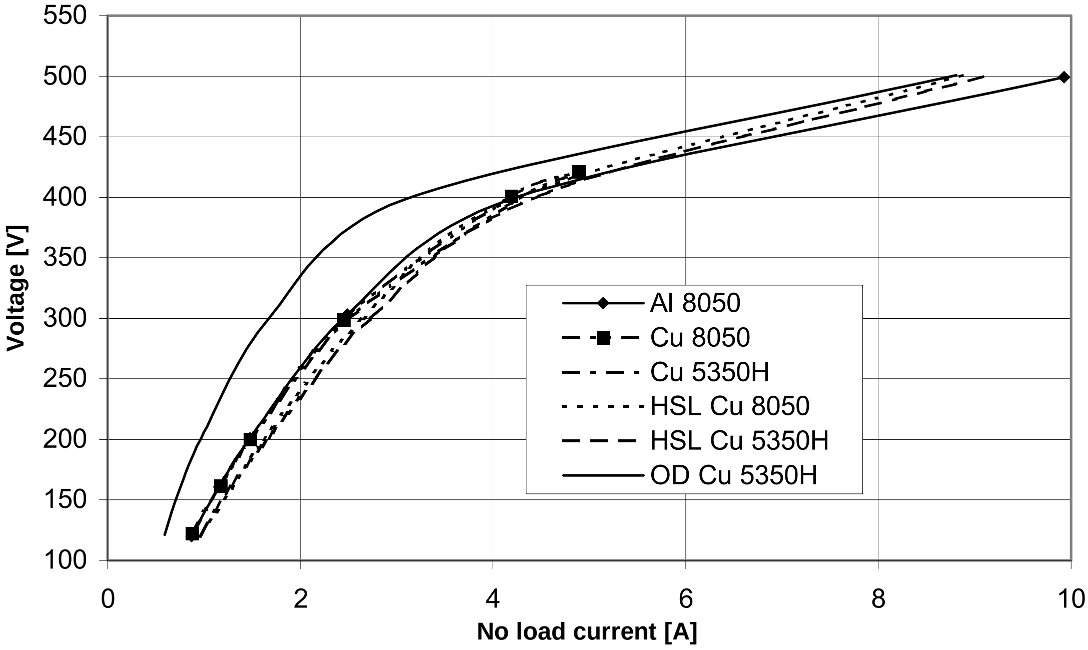

Fig. 5. Voltage - no load current curves. 3 kW motors

The substitution of copper for aluminium has allowed to move the 3 kW motor in the Eff2 class.

Motors with higher stack length and optimised new stator winding (HSL series) remain in the Eff2 class, but could be labelled Eff1 motors if the tolerance is taken into account.

The 3 kW motor is fully in Eff1 class if new stator and rotor slot shapes are adopted, when an accurate optimisation allows to exploit the advantages of copper cage and premium steel.

All copper rotor motors assure flat efficiency-output power. Motors with new design guarantee lower stator winding temperature, higher breakdown torque and constant locked rotor torque. New lamination adds higher power factor.

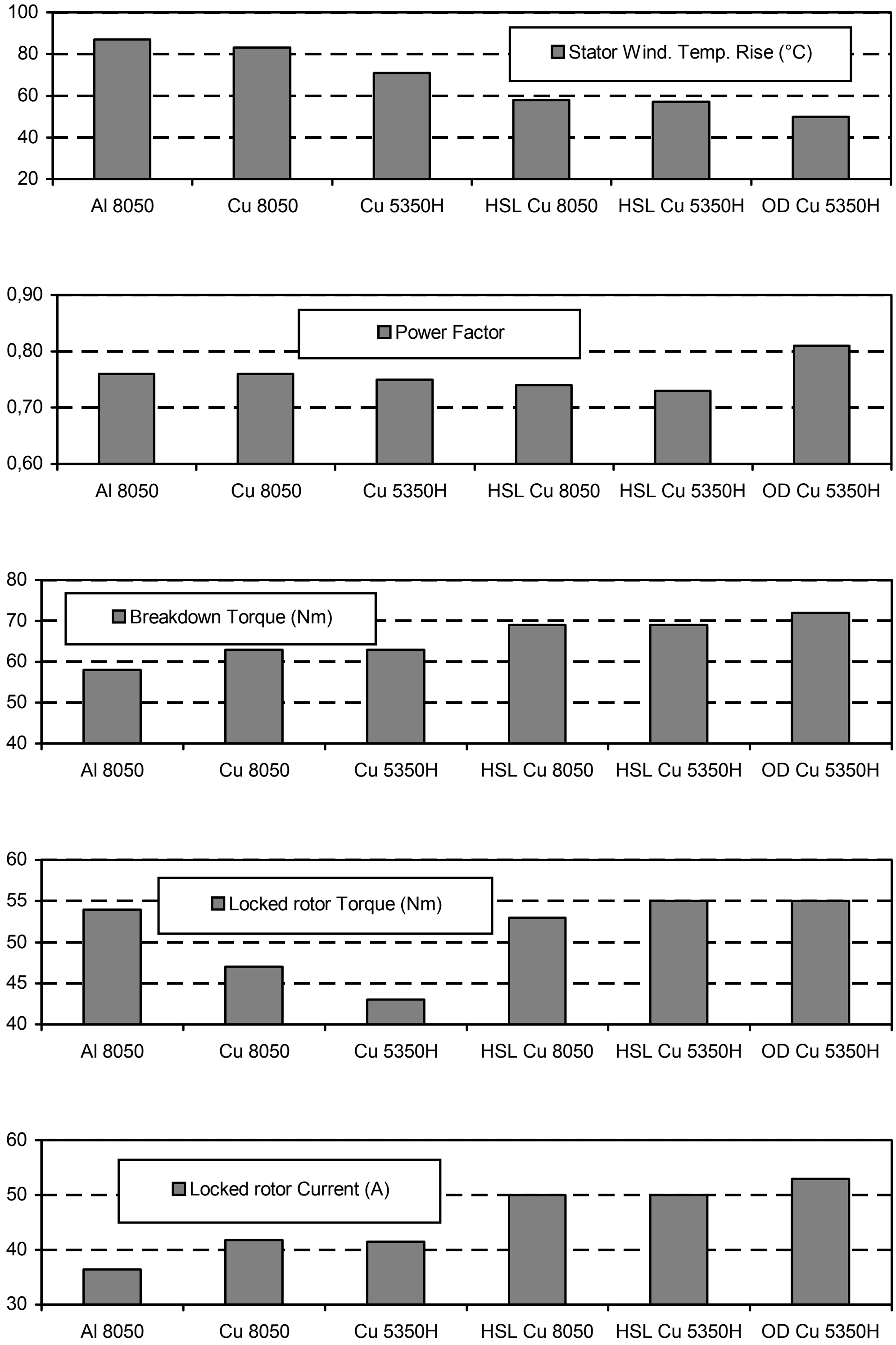

Fig. 6. Comparison between the 3 kW motor series

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STRATEGIE PROJEKTOWANIA, NOWE MATERIAŁY I TECHNOLOGIE POWIĘKSZAJĄCE SPRAWNOŚĆ SILNIKÓW INDUKCYJNYCH

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STRESZCZENIE *W referacie przedstawiono porównanie pomiędzy następującymi różnymi strategiami projektowania, których celem jest powiększenie sprawności trójfazowych silników indukcyjnych: zastępowanie klatek aluminiowych odlewanymi klatkami miedzianymi w silnikach standardowych i silnikach wysokosprawnych; optymalizacja klatki miedzianej silnika tylko poprzez zmianę uzwojenia stojana oraz długości pakietu; optymalizacja klatki miedzianej silnika poprzez zmianę uzwojenia stojana, długości pakietu oraz kształtu żłobków stojana i wirnika. Porównanie jest oparte na aktualnych ulepszeniach sprawności, zaprojektowaniu silników zgodnie z wymaganiami EC/CEMEP, znaczeniu materiałów i nowej technologii. Wyniki dotyczą silników 4-ro biegunowych, 50 Hz, 400 V, 3 i 15 kW.*