

New Materials and Innovative Technologies to Improve the Efficiency of Three-phase Induction Motors. A Case Study

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Abstract - The paper presents the results of a research project whose aim was the investigation of the efficiency improvement of industrial three-phase induction motors when high quality electrical steel is adopted in combination with die cast copper rotor cage, in order to define the design strategies; to verify the actual efficiency improvements; to verify the arrangement of the motors respect to the European Classification Scheme (EC-CEMPEP). The results are related to the cheapest design strategies when "premium steel" and copper rotor cage are used instead of standard steel and aluminum cage, with standard and higher stack length. The considered motor sizes are 3 and 7.5 kW, 4 pole, 50 Hz, 400 V, TEFC.

I. INTRODUCTION

The European Scheme to designate energy efficiency classes for low voltage AC motors has been in operation since 1999. It is based on a voluntary agreement between the European Commission and CEMEP, the European Committee of Manufacturers of Electrical Machines and Power Electronics [1]. This Scheme classifies induction motors into three efficiency bands, from Eff3 (lowest) to Eff1 (highest). This agreement should stimulate the Manufacturers in the development of new ranges of high efficiency motors that requires an accurate motor design, the adoption of new materials (e.g. premium steel) and innovative technologies (e.g. copper rotor cage die-casting).

The magnetic material plays a significant role in the improvement of the motor performance [2]. 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. Developing new ranges of high efficiency motors, the choice of the magnetic material is today an "open problem".

On the other hand, it is well known that incorporation of copper for the rotor bars and end rings in place of aluminum would result in attractive improvements in motor energy efficiency [3], [4].

Up today, only small numbers of very large motors utilize copper in the rotors by mechanical fabrication. Such fabrication involves intensive hand labour and therefore is expensive [5], [6].

Die casting is widely recognized as a low cost rotor cage manufacturing process. For these reason, die-casting has become the fabrication method of choice and aluminum the conductor of choice in all but the largest frame motors. Copper die-cast rotor construction does not differ significantly from the aluminum one and, in essence, the manufacturing details are identical. The additional manufacturing challenges are increased temperatures and pressures required to die-cast copper. The primary reason copper die-cast rotors are not

commonplace yet is because it requires specialized equipment (investment) and know how in this field.

Aim of the proposed paper is to investigate the improvement of the efficiency of industrial three-phase induction motors when high quality electrical steel is adopted in combination with die cast copper rotor cage.

This activity falls in a research program partially supported by the MIUR (Italian Ministry for Education, University and Research) and concerning the study of motors and drives energy efficiency increase in industrial and civil applications.

The project has been developed in co-operation with three important European companies:

- ThyssenKrupp ES Acciai Speciali Terni, Italy, European leader in the production of electrical steels for electromechanical applications; Acciai Speciali Terni has provided several electrical steels that have been used in the new prototypes;
- LAFERT S.p.A., one of the most important Italian manufacturer of induction motors; LAFERT has provided the stator and rotor cores and stator windings and has assembled the prototypes with copper rotor cages;
- FAVI (Fonderie et Atelier du Vlmeu), French company specialized in copper alloy pressure die-casting; FAVI has co-operated manufacturing a line of high-temperature moulds and several copper rotor cages.

The aim of the project was the analysis and the construction of several prototypes of induction motors by using the above mentioned innovative technological solutions, in order:

- to define the design strategies;
- to verify the actual efficiency improvements;
- to verify the arrangement of the motors respect to the European Classification Scheme (EC-CEMPEP).

The analysis concerns with industrial low voltage three-phase induction motors, 4 pole, 50 Hz, 400 V, TEFC, in the 0.75÷22 kW power range.

In order to obtain high efficiency motors making use of die-cast copper rotor cage and premium steel, the following design strategies have been investigated:

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

The paper presents the results related to the cheapest design

strategies 1), 2) and 3) when “premium steel” and copper rotor cage are used instead of standard steel and aluminum cage, with standard and higher stack length. The considered motor sizes are 3 and 7.5 kW.

II. RESEARCH PROJECT DEVELOPMENT

The minimum nominal efficiencies for these motors according with the EC-CEMEP standard are show in Table I.

To evaluate the efficiency improvements, two standard motors have been chosen as “reference motor”: they are commercial motors with aluminum rotor cage and standard electrical steel belonging to the low efficiency class Eff3 (Fig. 1). Taking into account the tolerance on efficiency measurements standards, the 3 kW motor could be classified in the Eff2 class.

Table I EC-CEMEP Minimum Efficiency Standard for 4-pole Motors

kW	Eff2	Eff1
3	82.6	87.4
7.5	87.0	90.1

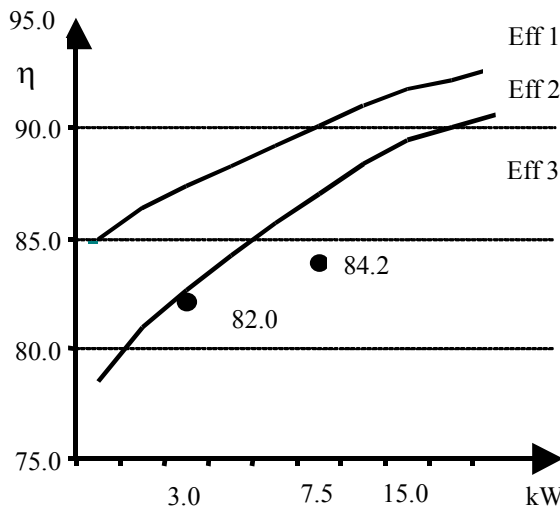


Figure 1. Standard motors placements in the EC-CEMEP Classification Scheme.

A. Choice of the electrical steel

Concerning the choice of the electrical steel, we compared the standard one used in the reference motors, labeled 8050, with several alternative electrical steels classified as:

- low loss electrical steels: 5350 and 3150;
- high permeability electrical steels: 8050H, 5350H.

Their main characteristics are summarized in Fig. 2.

The influence of the considered electrical steels and copper rotor cage on motor performance have been evaluated by simulations. The results have been compared with commercial motor ones in order to evaluate the achievable improvement due to the use of “premium steels” and copper cage only without affecting the design of standard motors.

Frequently better magnetic materials from the losses point of view have worse permeability (in Fig. 2 see electrical steels 3150 and 5350 in comparison with 8050). Electrical steel 5350H represents the most suitable choice because combines

low specific losses (Fig. 3) with high permeability (better than 8050 under 1.2 T, a little bit worse over, Fig. 4).

On the base of these preliminary analyses and the material hardness, the high permeability steel 5350H has been chosen as “premium steel”.

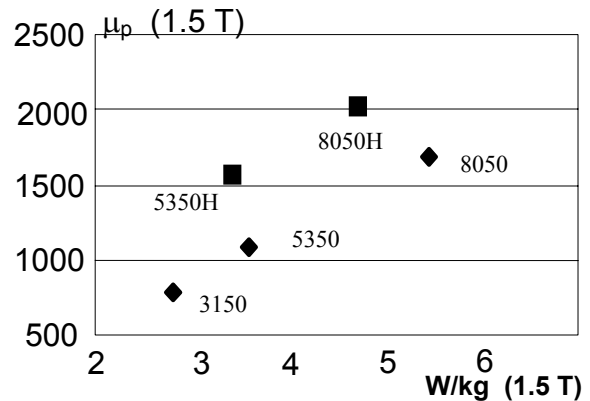


Figure 2. Permeability and loss at 1.5 T of the considered steels

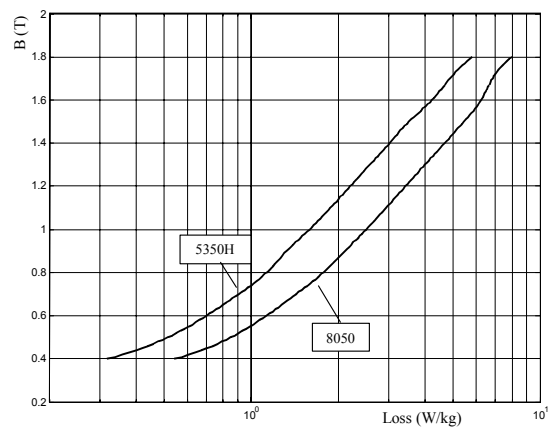


Figure 3. Specific losses curves of 8050 and 5350H steels

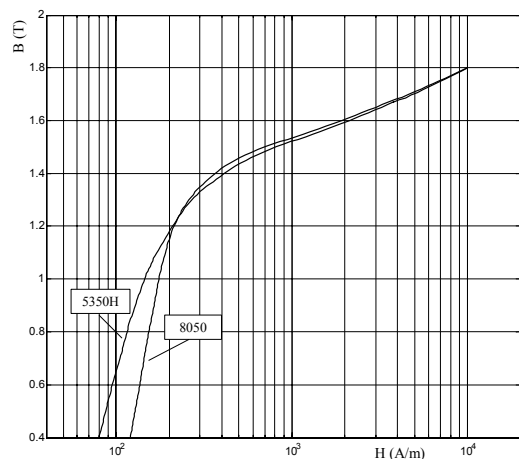


Figure 4. B-H curves of 8050 and 5350H steels.

B. Motor Prototypes

The motor prototypes have been realized according to the following combinations, for each power size:

- aluminum cage and standard steel 8050 (commercial

“reference motor”); the corresponding prototypes are labeled “Al 8050”;

- b) copper cage and standard steel 8050; the prototypes are labeled “Cu 8050”;
- c) copper cage and premium steel 5350H; the prototypes are labeled “Cu 5350H”;
- d) copper cage, standard steel 8050 and higher stack length (HSL); the new stack length is consistent with the standard housing; the prototypes are labeled “HSL Cu 8050”;
- e) copper cage, premium steel 5350H and higher stack length; the new stack length is the same of case d); the prototypes are labeled “HSL Cu 5350H”.

Comparison between motors a) and b) allow to evaluate the improvements achievable with copper rotors 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. Motors c) results will show the effects of the premium steel (in comparison with motors b)) and the improvements respect to the standard motor (in comparison with motors a)). Motors d) and e) results will show the improvements suitable with a low cost re-design strategy, when costly new lamination punch and new stator housing tools should be avoided.

Table II presents the main dimensions and weights of the prototypes (reference motors and new prototypes) while Fig. 5 and Fig. 6 show views of the copper rotors.

Table II Prototypes main dimensions and weights

	3 kW	7.5 kW	3 kW HSL	7.5 kW HSL
Stack length (mm)	130	160	155	180
Out. stator diam. (mm)	152	200	152	200
In. stator diam. (mm)	90	127	90	127
St. winding weight (kg)	2.45	5.40	2.82 (+15%)	5.9 (+7%)
Rotor cage weight (kg)				
Al	0.74	1.45		
Cu	2.43	4.77	2.73 (+12%)	5.20 (+9%)
Gross iron (kg)	22.4	47.8	26.8 (+20%)	53.8 (+12%)



Figure 5. View of standard length copper rotors, 3 and 7.5 kW motors.



Figure 6. View of standard and higher length copper rotors, 3 kW motor.

III. RESULTS

A. Standard test method

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.

B. Motors test results

Table III shows the efficiency and loss segregation test results of the 3 kW motors; the comparison between standard length new prototypes (Cu 8050 and Cu 5350H) and commercial motor Al 8050 is presented.

Table III 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)
Σ losses (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

The substitution of copper as rotor material has allowed to move the 3 kW motor in the Eff2 class, while the use of the 5350 H electrical steel does not give rise any further efficiency class movement.

Concerning the other motors performance (Table IV), with copper rotor and premium steel the stator winding temperature rise ΔT_{SW} is reduced by 16°C and 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 constant while slip is significantly lower for both copper motors: copper motor generates a higher torque at same slip than the aluminum motor one. This implies a very good response on variable frequency drives, but potential problems on variable torque loads like fans and pumps.

Copper motors exhibit substantially constant breakdown torque T_B (+ 8%) but a significant drop in the locked rotor torque T_L (- 18%), due the rotor laminations designed for aluminum.

Table IV 3 kW standard stack length motors performance

3 kW	Al 8050	Cu 8050	Cu 5350H
I (A)	6.86	6.70	6.73
ΔT_{sw} (°C)	87	83 (-4)	71 (-16)
Power Factor	0.76	0.76	0.75
Slip %	4.83	2.69 (↓)	2.7 (↓)
T_B (Nm)	58	63	62
T_L (Nm)	54.4	46.9 (↓)	42.8 (↓)

Concerning temperature, slip and locked rotor torque, tests of 7.5 kW motors (Table V and Table VI) confirm what found for the smaller motors. The efficiency improvements are 3.2 and 3.9 points respectively. Nevertheless, the motors do not move in the Eff1 class, stopping in Eff2.

Table V CSA C390-98 Efficiency and Loss Segregation Test Results. 7.5 kW standard stack length motors.

7.5 kW	Al 8050	Cu 8050	Cu 5350H
η %	84.2	87.4 (+3.2)	88.1 (+3.9)
Σ losses (W)	1401	1077 (-23%)	1035 (-26%)
Stator wind.	466	456	423
Rotor cage	284	141 (-50%)	138 (-50%)
Iron	361	349	338
SLL	237	92	88
F&W	53	39	48

Table VI 7.5 kW standard stack length motors performance

7.5 kW	Al 8050	Cu 8050	Cu 5350H
I (A)	15.0	15.2	14.8
ΔT_{sw} (°C)	104	86 (-18)	80 (-24)
Power Factor	0.86	0.81	0.82
Slip %	3.44	1.82 (↓)	1.79 (↓)
T_B (Nm)	-	155	-
T_L (Nm)	165	110 (↓)	108 (↓)

Further improvement on motor performance can be achieved if copper rotor and premium steel adoptions are combined with higher stack length and new stator winding.

The new motors have been designed by a suitable software that combines a motor simulation model with an optimization algorithm [7]. The new stack lengths are consistent with the standard housings.

Two higher stack length (HSL) copper rotor prototypes have been realized for the 3 kW size, with 8050 and 5350H electrical steels; only one for the 7.5 kW size, with 5350H.

Tables VII and VIII show test results of the 3 kW higher stack length prototypes.

With standard steel 8050 the measured efficiencies are 2 points higher respect to the corresponding copper rotor motor with standard stack length and 4 points higher respect to the commercial aluminum rotor motor (Table III). With premium steel 5350H the measured efficiencies are 2 points higher respect to the corresponding copper rotor motor with standard stack length and 4.5 points higher respect to the commercial aluminum rotor motor. The most significant loss reduction is in the stator winding.

Comparisons between Table IV and Table VIII show relevant temperature reductions, the same locked rotor torque and the increasing of the breakdown torque respect to the standard motor AL 8050.

The new motors remain in the Eff2 class, but could be labeled Eff1 motors if the tolerance is taken into account.

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

3 kW	HSL Cu 8050	HSL Cu 5350H
η %	86.0	86.5
Σ losses (W)	486	465
Stator wind.	265	265
Rotor cage	73	77
Iron	113	99
SLL	15	9
F&W	20	15

Table VIII 3 kW Higher Stack Length motors performance

3 kW	HSL Cu 8050	HSL Cu 5350H
I (A)	6.76	6.79
ΔT_{sw} (°C)	58	57
Power Factor	0.74	0.73
Slip %	2.36	2.49
T_B (Nm)	69	69
T_L (Nm)	53	55

Table IX shows test results of the 7.5 kW higher stack length prototype. Comparison with Tables V and VI show efficiency increasing of 5 and 1 points respect to aluminum and copper rotor standard stack length motors; further decreasing on temperature and slip can be pointed out. However, it is still in Eff2 efficiency class.

Table IX CSA C390-98 Efficiency and Loss Segregation Test Results and motors performance. 7.5 kW Higher Stack Length motor.

7.5 kW		HSL Cu 5350H	
η %	89.0	I (A)	14.7
Σ losses (W)	919	ΔT_{sw} (°C)	59
Stator wind.	334	Power Factor	0.82
Rotor cage	113	Slip %	1.46
Iron	315	T_B (Nm)	-
SLL	110	T_L (Nm)	-
F&W.	47		

C. Summary of the results and comparison with literature data

Table X summarises the overall motor efficiencies experimentally observed in motors fitted with copper rotors where comparisons with aluminum are reported in literature including the data of this study. The range 3÷18.8 kW, 4 poles motors is covered.

Table X Overall motor efficiencies via copper rotors. Data from this study and the literature.

kW	Hz	Efficiency		Reference
		Al	CU	
3	60	83.2	86.4 (*)	4
3	50	82.0	84.1 (*)	This study
3	50		84.5 (x)	This study
3	50		86.0 (+)	This study
3	50		86.5 (o)	This study
7.5	50	84.2	87.4 (*)	This study
7.5	50		88.1 (x)	This study
7.5	50		89.0 (o)	This study
11.2	60	89.5	90.7 (*)	4
15	50	90.1	91.0 (*)	8
18.8	60	90.9	92.5 (*)	4

(*) standard design, standard steel

(x) standard design, premium steel

(+) higher stack length, standard steel

(o) higher stack length, premium steel

IV. CONCLUSIONS

The paper presented test results concerning several prototypes of induction motors with die-cast copper rotor cages and premium electrical steel with the aim to verify the actual efficiency improvements and the arrangement of the motors respect to the European Classification Scheme EC-CEMEP. Two standard motors (3 and 7.5 kW) have been chosen as “reference motor”: they are commercial motor with aluminum rotor cage and standard electrical steel belonging to the low efficiency class Eff3. The efficiency of the 7.5 kW motor is far from the boundary of Eff2 class (2.8 points less than the lower limit) while the 3 kW motor is very close to it: in fact, taking into account the tolerance on efficiency measurements standards, the 3 kW motor could be classified in the Eff2 class. Three design strategies have been investigated:

1. substituting copper cage for aluminum cage and standard electrical steel, without changing any motor dimension;
2. substituting copper cage for aluminum cage and high performance electrical steel, without changing any motor dimension;
3. design optimization of copper cage motor by changing the stator winding and the stack length only.

The substitution of copper for aluminum has allowed to move the 3 and 7.5 kW motors in the Eff2 class. The efficiency

improvements vary from 2.1 points for the 3 kW to 3.2 points for the 7.5 kW.

The use of 5350H electrical steel (premium steel) improves efficiencies of 0.4 and 0.7 points from smaller to larger motors. However, premium steel and copper rotor do not give rise any further movement (from Eff2).

The third series of prototypes have higher stack lengths, but consistent with standard housing, and optimised new stator windings.

In case of 3 kW size, the new motors remain in the Eff2 class, but could be labeled Eff1 motors if the tolerance is taken into account.

In spite of about 5 points gained respect to the standard motor efficiency, the higher stack length 7.5 kW motor is still in the Eff2 class. This result is strongly conditioned by the original standard design (stator and rotor figures are not changed), very poor from efficiency point of view.

In any case, better results could be achieved if the adoption of new materials and innovative technologies are associated with an accurate motor design that allows to exploit the advantages of copper cage and premium steel.

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