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IE3 Efficiency Induction Motors with Aluminum and Copper Rotor Cage: Technical and Economic Comparison

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Abstract: The aim of this study was to design three-phase induction motors with aluminum and copper cage, in the range 0.75 ÷ 22 kW, to fulfill the IE3 efficiency level according to typical performance and standard constraints. The proposed study has concerned TEFC (totally Enclosed Fan-Cooled), 400 V, 50 Hz, S1 duty three phase squirrel-cage induction motors only. The motors' designs, with Al and Cu cage, have been optimized in order to reach the minimum efficiency level IE3 at lowest active material costs and satisfy the physical and performance constraints of the designs, which are the motor specifications. A suitable optimization procedure has been used which allowed to find the "best design" by chancing the geometric dimensions of the stator, rotor shape, the stator winding and the stack length. In order to guarantee the goodness and feasibility of the optimized designs, several constrains have been imposed.

Key words: Induction motors, efficiency, copper rotor, design optimization.

1. Introduction

The new three-phase induction motors classification scheme (EC (European Commission) Regulation No. 640/2009) has introduced two efficiency levels [1]: "high efficiency" IE2 and "premium efficiency" IE3, totally new for Europe and corresponding to the American "Nema Premium". Its coming dates open new settings for electric motors manufacturers, which will have to adapt their production cycle and invest on development strategies for innovative and high efficient motors. The improvement of induction motor efficiency requires the use of innovative technological solutions [2] and the optimization of the motor design [3], keeping construction restrictions typically adopted for these motors classes. The use of die-cast copper rotor cage [3-6] would result in attractive improvements in motor energy efficiency and could represent a valid alternative to traditional (and low cost) aluminum cage.

This paper presents a study on new induction motor designs with aluminum and copper rotor, specially developed to reach the IE3 efficiency level. A comparison on technical and economic aspects will be shown. Five motor sizes have been selected: 1.5 kW-6 pole, 3 kW-4 pole, 7.5 kW-4 pole, 15 kW-4 pole and 22 kW-2 pole, squirrel-cage, TEFC, 400 V, 50 Hz, S1 duty. Table 1 shows, for each size, the IE3 minimum efficiency levels according to the EC Regulation No. 640/2009.

The motors' designs have been optimized in order to reach the minimum efficiency level IE3 at lowest active material cost and satisfy the physical and performance constraints of the designs, which are the motor specifications. The study does not take into account the costs for the die-casting and stamping processes and the tooling cost. For the active material cost calculation, three different scenarios have been considered with different "Cu/Al" price ratio.

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Table 1 The IE3 minimum efficiency levels for the considered motor sizes.

Rated power (kW)	Poles	Frame size	Efficiency IE3
1.5	6	100 L	82.5%
3	4	100 L	87.7%
7.5	4	132 M	90.4%
15	4	160 L	92.1%
22	2	180 M	92.7%

A suitable optimization procedure has been used [7, 8] which allowed to find the "best design" by chancing the geometric dimensions of the stator, rotor shape, the stator winding and the stack length, in order to obtain a final optimized design whose dimensions are consistent, when possible, with the standard commercial frames.

Motor performance has been evaluated by a "lumped parameter model". The adopted model takes into account magnetic saturation, skin effect on rotor parameters and thermal analysis. The validity of the mathematical model has been verified by means of experimental tests on several three-phase induction motors.

The paper presents the results of the IE3 optimized designs, with Al and Cu cage; these solutions have been compared in terms of performance, active material costs and advantage in size (diameter/stack length) and total weight. Moreover, it has been possible to verify if the Al and Cu technologies allow to go beyond IE3 efficiency level and correspond with standard dimensions compatible with commercial housings.

2. Optimization and Design Procedure

The optimization procedure is synthesized in the flow-chart shown in Fig. 1, where X represents the set of motor design variables and $F(X)$ the objective function (active material cost) to minimize.

Starting from a "preliminary design" (Initial design), the optimization algorithm iteratively updates the set of design variables (X) and try to identify an "optimal" motor by making a trade-off between the different parameters of the machine.

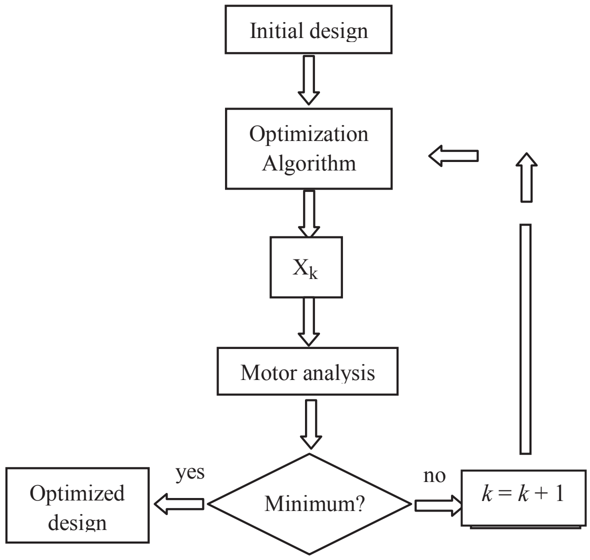

Fig. 1 Design optimization procedure.

The block "motor analysis" evaluates the motor performance, the objective function and the constraints values. The physical description of the motor is reduced to equivalent parameters such as resistance and inductances: the adopted model takes into account the influence of saturation on stator and rotor reactances and the influence of the skin effect on rotor parameters. The effects of the temperature on motor resistances are computed on the basis of a detailed "thermal network". The validity of the mathematical model has been verified by means of experimental tests on several three-phase induction motors.

The motors designs, with Al and Cu cage, have been optimized in order to reach the minimum efficiency level IE3 at lowest active material costs and satisfy the physical and performance constraints of the designs, which are the motor specifications.

The active material cost is defined as follows:

$$ACM = (Wfe \times Cfe) + (Ws \times Ccu_W) + (Wrc \times Cm) \quad (1)$$

where,

Wfe: weight of gross iron (kg);

Ws: weight of stator winding (kg);

Wrc: weight of rotor cage (kg);

Cfe: cost of premium steel (€/kg);

Ccu_W: cost of copper wire (€/kg);

Cm: cost of raw material (Al or Cu) (€/kg).

These costs do not take into account the die-casting process, the stamping process, the tooling and the structure costs. In order to guarantee the goodness and feasibility of the optimized designs, several constrains have been introduced that concern:

- the rated efficiency (minimum efficiency level for IE3, Table 1);
- the power factor;
- the starting performance (starting torque and starting current);
- the breakdown torque, the stator winding temperature rise and rotor bars temperature rise;
- the slot fill factor.

The values of these constraints have been fixed with reference to commercial motors of the same size of the investigated motors.

The considered design variables set is shown in Fig. 2 and concerns the geometric dimensions of the stator and rotor shape (inner and outer stator diameters, tooth width, slot high), the stator winding (number of turns per phase, wire size) and the stack length. Each variable has been varied between an upper and a lower limit according to Manufacturers suggestions, in order to obtain a final optimized design whose dimensions are consistent, when possible, with standard commercial frames. One small and one big housing company have been considered as reference. The dimensions (L and D in Fig. 3) of their commercial housings (type B3) are shown in Tables 2 and 3.

3. Design Assumptions

The following design assumptions have been made. For each size, the motors with Al and Cu cage have the same:

- number of stator and rotor slots;
- air-gap length;
- slot fill factor;
- stator slot opening;
- rotor skewing;
- shaft diameter;
- winding distribution and "winding factor";
- stator slot insulation and thermal coefficients (for the thermal network);
- percentage for the Stray Losses calculation (2% the output power).

About the active materials, the following unit price have been imposed (2012):

- premium steel Cfe 0.91 (€/kg);
- raw material for Al cage Cm_Al 1.76 (€/kg).

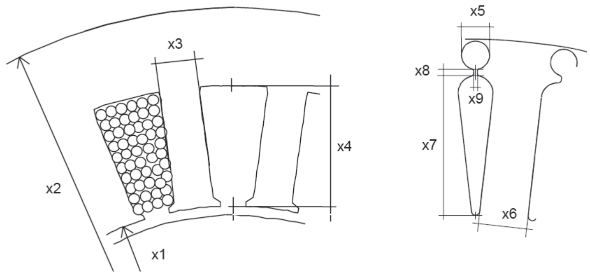

Fig. 2 Geometric design variables.

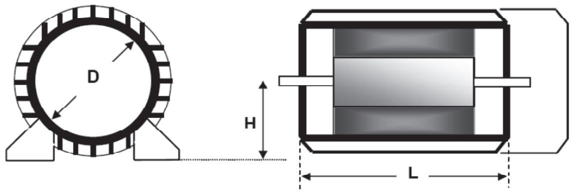

Fig. 3 Schematic commercial housing.

Table 2 Small company commercial housing dimensions.

Frame size	Length *L* (mm)	Inner diameter *D* (mm)
90 L	230	138
100 L	255	165
112 M	282	175
132 M	320	210
160 M	278	260
160 L	322	260
180 M	317	290
180 L	355	290
200 L	385	327

Table 3 Big Company commercial housing dimensions.

Frame size	Length *L* (mm)	Inner diameter *D* (mm)
90 L	192	130
100 L	198	155
112 M	214	175
132 M	268	210
160 M	270	260
160 L	314	260
180 M	317	290
180 L	355	290
200 L	375	327

The copper wire (Ccu_W) is 15% higher than the cost of Cu raw material.

The cost of raw material for the copper has been related to the aluminum one, and the following three scenarios have been introduced by imposing a different "Cu/Al" price ratio:

- Scenario 1—$€_{CU}$/ $€_{AL}$ = 3.0

Raw material for Cu cage: Cm_Cu = 5.28 (€/kg);
Copper wire: Ccu_W = 6.07 (€/kg);

- Scenario 2—$€_{CU}$ / $€_{AL}$ = 3.5;

Raw material for Cu cage: Cm_Cu = 6.16 (€/kg);
Copper wire: Ccu = 7.08 (€/kg);

- Scenario 3—$€_{CU}$ / $€_{AL}$ = 4.0;

Raw material for Cu cage: Cm_Cu = 7.04 (€/kg);
Copper wire: Ccu_W = 8.10 (€/kg).

The motors have been optimized with reference to the Scenario 2. The commercial "premium steel" 330-50 AP (0.5 mm thickness) has been chosen for the new designs, and the main magnetic characteristics are presented in the Table 4.

4. Results

The results of the optimized designs are shown in the Tables 5-9 and Figs. 4-8. That includes the motor main dimensions, the motor performance and the active material weights and costs for the three scenarios, calculated according to the Eq. (1); for each size, some comments have been included.

4.1 1.5 kW, 6-Pole Motor

Table 5 shows the 1.5 kW, 6-pole motor main dimensions while Figs. 4a-4d show losses, rated current and torque (*Ir*, *Tr*), starting current and torque (*Ist*, *Tst*), maximum torque (*Tmax*), active material weights and costs.

Both designs have the same rated efficiency (82.5%) and the performance are quite similar and consistent with typical performance of a commercial Al motor of the same size.

In Table 5, it is important to highlight that the outer stator diameter of the Al motor allows to use commercial housing produced by a small company only and not the housings of the big company (Table 3): in this case (*) a new (out of line) and more expansive housing is needed.

Table 4 Magnetic characteristics of the "premium" steel 330-50 AP (50 Hz).

B (T)	H (A/m)	Losses (W/kg)
1.0	121	1.31
1.5	946	2.86

Table 5 1.5 kW, 6 pole-motor main dimensions.

η = 82.5% (IE3)		Al	Cu
Stack length	(mm)	130	126
Outer stator diameter	(mm)	160 (*)	152
No. of turns *x* phase		342	342
Wire size	(mm^2)	0.830	0.688
Stator slot area	(mm^2)	81.9	68.5
Rotor slot area	(mm^2)	50.2	38.0

The Cu motor is compatible with all commercial housings (small and big company, see Tables 2 and 3) and presents an advantage in size (diameter/stack length) with a total weight reduction of about 9%. Moreover, the slots area are smaller respect the Al solution, with a reduction of about 16% for the stator slot and 24% for the rotor slot (and rotor bar). Although this significant reduction on the rotor slot area, the weight of the Cu rotor cage is twice over the Al cage and this is due to the different specific weight of the two metals.

The total copper weight in the Cu motor (stator winding and rotor cage) is about 48% higher than the copper weight (stator winding) in the Al motor.

The Cu cage motor is slightly more expensive, with an increase on the active material cost of 3 Euro for the Scenario 1 and about 6 Euro for the Scenarios 3: this difference could be reduced if the Al motor needs a new (out of line) housing.

4.2 3 kW, 4-Pole Motor

Table 6 shows the 3 kW, 4-Pole motor main dimensions while Figs. 5a-5d show losses, performance and active material weights and costs.

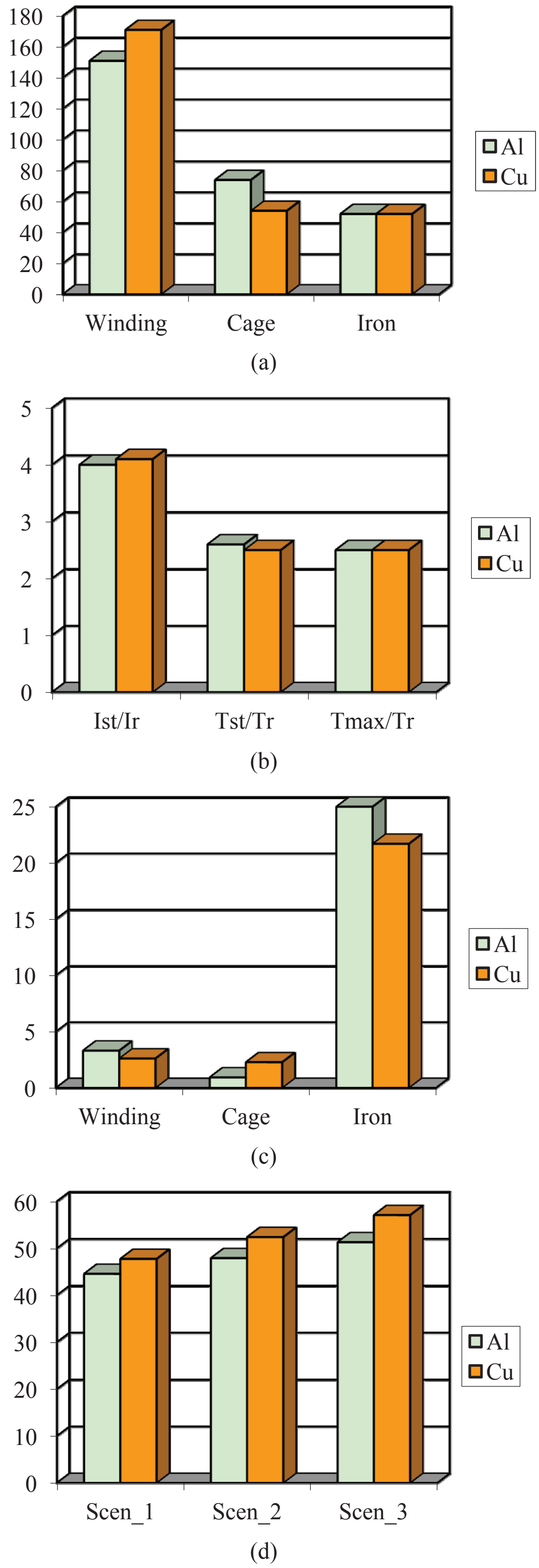

Fig. 4 (a) 1.5 kW—losses; (b) 1.5 kW—performance; (c) 1.5 kW—active material weight (kg); (d) 1.5 kW—active material cost (€).

Table 6 3 kW, 4-pole motor main dimensions.

η = 87.7% (IE3)		Al	Cu
Stack length	(mm)	155	150
Outer stator diameter	(mm)	165 (*)	160 (*)
No. of turns *x* phase		186	186
Wire size	(mm^2)	1.645	1.31
Stator slot area	(mm^2)	125	102
Rotor slot area	(mm^2)	93.8	58.6

Both designs have the same rated efficiency (87.7%) and the performance are quite similar and consistent with typical performance of a commercial Al motor of the same size.

The outer stator diameters of both designs allow to use commercial housings produced by the small company only (see Table 6 (*)).

The Cu motor presents an advantage in size (diameter/stack length) with a total weight reduction of about 6%. The comparison points out a significant reduction of stator and rotor slot area (rotor bar), for the Cu motor, of 18% and 37%.

The total copper weight in the Cu motor (stator winding and rotor cage) is about 42% higher than the copper weight (stator winding) in the Al motor. The Cu cage motor is slightly more expensive, with an increase on the active material cost for all cases, in the range between 4 Euro and 7 Euro.

4.3 7.5 kW, 4-Pole Motor

Table 7 shows the 7.5 kW, 4-pole motor main dimensions while Figs. 6a-6d show losses, performance and active material weights and costs. Both designs have the same rated efficiency (90.4) and the performance is quite similar and consistent with typical performance of a commercial Al motor of the same size. It is difficult to go beyond IE3 with Al technology because of limitations in housing and inability to fit with standard dimensions for the small and big company. The outer stator diameter of the Al cage needs a new (out of line) and more expansive housing (Table 7 (*)). The Cu motor can use commercial housings produced by small and big

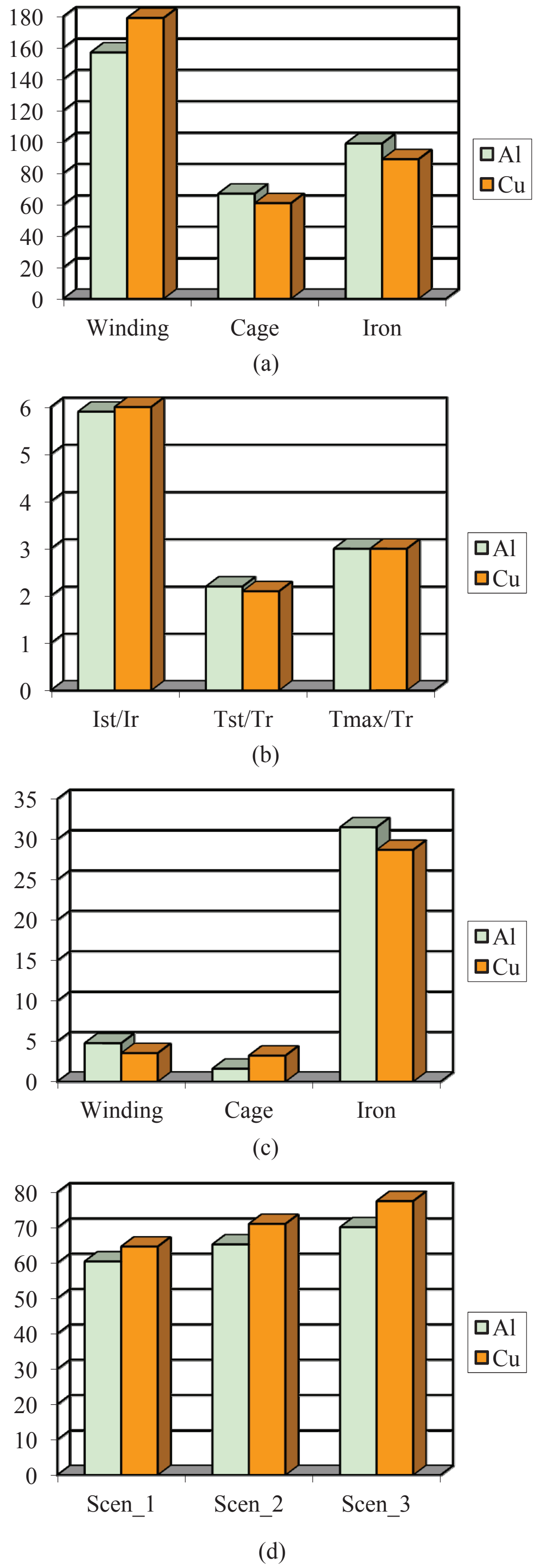

Fig. 5 (a) 3 kW—losses; (b) 3 kW—performance; (c) 3 kW—active material weight (kg); (d) 3 kW-active material cost (€).

Table 7 7.5 kW, 4-pole motor main dimensions.

η = 90.4% (IE3)		Al	Cu
Stack length	(mm)	200	190
Outer stator diameter	(mm)	215 (*)	210
No. of turns x phase		114	108
Wire size	(mm^2)	4.80	4.15
Stator slot area	(mm^2)	205	168
Rotor slot area	(mm^2)	115	52.5

company and presents an advantage in size (diameter/stack length) with a total weight reduction of about 9%: this percentage tends to increase when a bigger housing is used for the Al cage motor. The slots area are smaller respect the Al solution, with a reduction of about 18% for the stator slot and 54% for the rotor slot (and rotor bars) but the weight of the Cu rotor cage is 50% higher than the Al cage. The total copper weight in the Cu motor (stator winding and rotor cage) is about 22% higher than the copper weight (stator winding) in the Al motor.

The Cu motor has an active material cost lower respect to the Al motor for the Scenario 1: for the other two cases the difference are very small. If the cost of the new housing for the Al motor is taken into account, the Cu motor is certainly more convenient (excluded the cost of die-casting process).

4.4 15 kW, 4-Pole Double-Cage Motor

Table 8 shows the 15 kW, 4-pole motor main dimensions while Figs. 7a-7d show losses, performance and active material weights and costs. Both designs have the same rated efficiency (92.1%) and the performance are quite similar and consistent with typical performance of a commercial Al motor of the same size. Both designs can use commercial housings produced by small and big company.

The Cu motor presents an advantage in size (diameter/stack length) with a total weight reduction of about 11%.

The comparison points out a significant reduction of stator and rotor slot area (rotor bar) of about 18% and

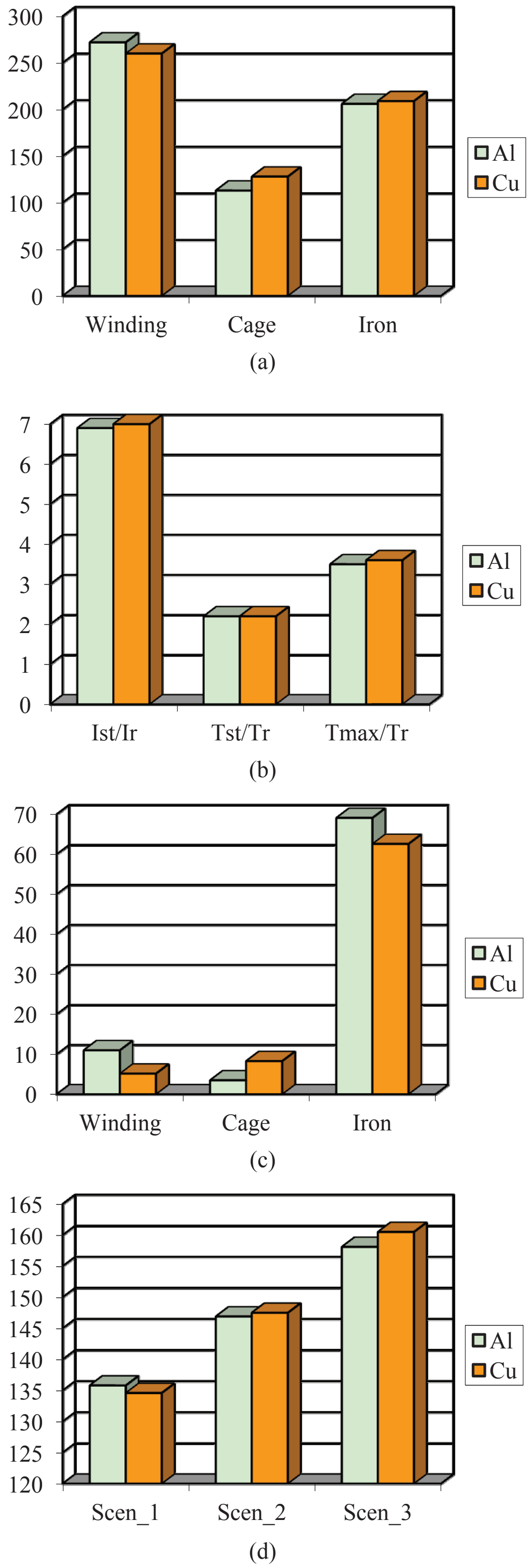

Fig. 6 (a) 7.5 kW—losses; (b) 7.5 kW—performance; (c) 7.5 kW—active material weight (kg); (d) 7.5 kW—active material cost (€).

Table 8 15 kW, 4-pole motor main dimensions

η = 92.1% (IE3)		Al	Cu
Stack length	(mm)	225	215
Outer stator diameter	(mm)	255	245
No. of turns x phase		78	78
Wire size	(mm^2)	7.90	5.60
Stator slot area	(mm^2)	228	182
Rotor slot area	(mm^2)	83	65

37%, respectively: the weight of the Cu rotor cage is twice over the Al cage. The total copper weight in the Cu motor (stator winding and rotor cage) is about 13% higher than the copper weight (stator winding) in the Al motor.

The motor with copper cage allows a reduction on the active material cost in all cases, from 8 to 10 Euro (excluded the cost of die-casting process).

4.5 22 kW, 2-Pole Double-Cage Motor

Table 9 shows the 22 kW, 2 pole motor main dimensions while Figs. 8a-8d show losses, performance and active material weights and costs.

Both designs have the same rated efficiency (92.7%) and the performance are quite similar and consistent with typical performance of a commercial Al motor of the same size.

The outer stator diameters of both designs allow to use commercial housings produced by small and big company.

The Cu motor presents an advantage in size (diameter/stack length) with a total weight reduction of about 8%. The reduction of stator and rotor slot area (rotor bar) are about 18% and 32%, respectively and the weight of the Cu rotor cage is twice over the Al cage.

The total copper weight in the Cu motor (stator winding and rotor cage) and Al motor (stator winding) is equal, making the steel weight the difference to the benefit of copper rotor solution.

Moreover, the motor with copper cage allows a reduction on the active material cost in all cases of about 16 Euro (excluded the cost of die-casting process).

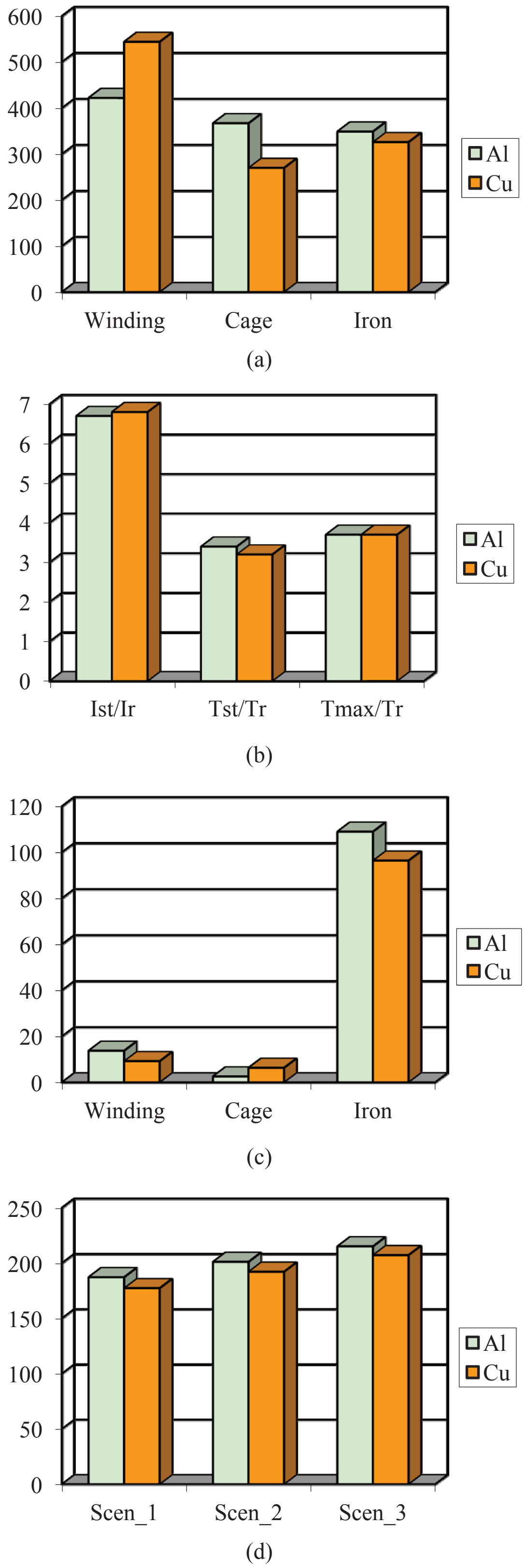

Fig. 7 (a) 15 kW—losses; (b) 15 kW—performance; (c) 15 kW—active material weight (kg); (d) 15 kW—active material cost (€).

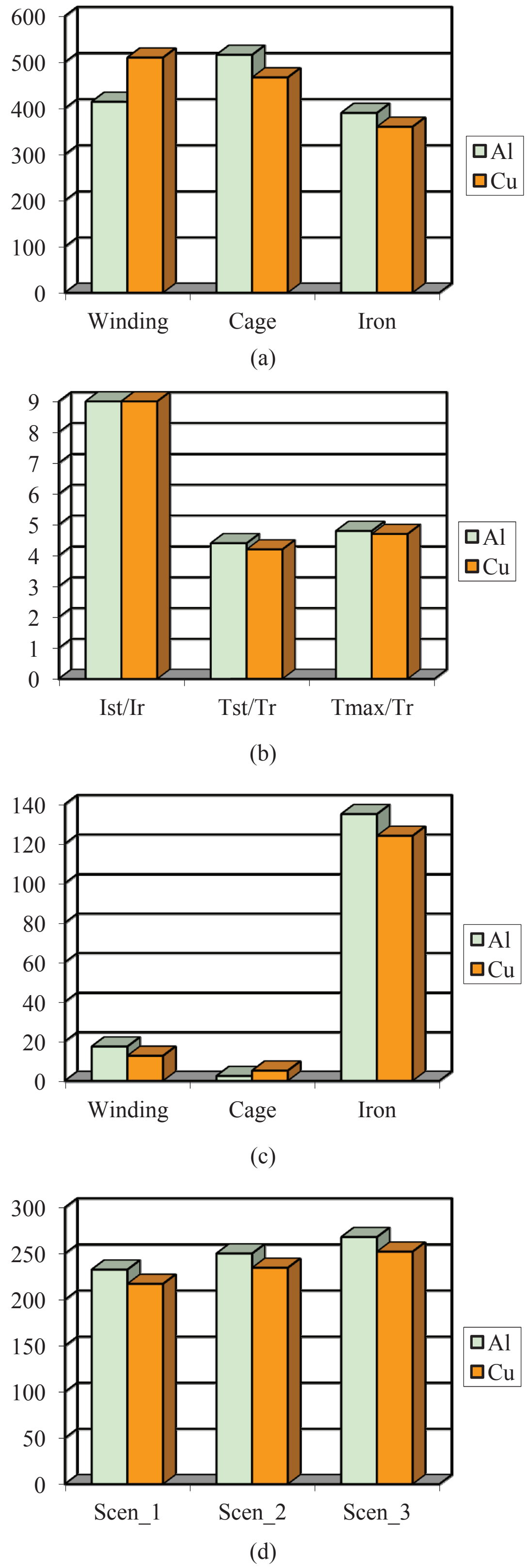

Fig. 8 (a) 22 kW—losses; (b) 22 kW—performance; (c) 22 kW—active material weight (kg); (d) 22 kW—active material cost (€).

Table 9 22 kW 2-pole double-cage motor main dimensions.

η = 92.7% (IE3)		Al	Cu
Stack length	(mm)	215	205
Outer stator diameter	(mm)	290	285
No. of turns *x* phase		84	84
Wire size	(mm^2)	6.36	4.80
Stator slot area	(mm^2)	200	164
Rotor slot area	(mm^2)	122	83

Table 10 Cu rotor motors active material cost variations (in Euro and %) respect to Al rotor motors.

kW	Scen_1	Scen_2	Scen_3
1.5	+3.2 ∈ +7.2%	+4.5 ∈ +9.4%	+5.8 ∈ +11.3%
3	+4.2 ∈ +7.0%	+5.8 ∈ +8.9%	+7.4 ∈ +10.5%
7.5	-1.2 ∈ -1.0%	+0.6 ∈ +0.4%	+2.4 ∈ +1.5%
15	-9.9 ∈ -5.3%	-8.9 ∈ -4.4%	-7.8 ∈ -3.8%
22	-15.4 ∈ -6.6%	-15.5 ∈ -6.2%	-15.8 ∈ -5.9%

5. Conclusions

In conclusion, the following remarks could be pointed out.

The performance of IE3 efficiency motors with Al and Cu cage are quite similar and consistent with typical performance of commercial Al motors of the same size.

The Cu motors present always an advantage in size (diameter/stack length) and total weight.

The total copper weight in the Cu motors (stator winding and rotor cage) is higher than the copper weight (stator winding) in the Al motors, difference reducing from small to large sizes (in case of 22 kW one, they are similar).

It is difficult to go beyond IE3 with Al technology because of limitations in housing and inability to fit with standard dimensions for the small and/or big company.

Table 10 shows the Cu rotor motors active material cost variations (in Euro and %) respect to Al rotor motors.

For the small sizes (1.5 kW and 3 kW), the Cu cage motors are slightly more expensive respect to the Al motor while for the 7.5 kW the difference on the active material cost is very small; this difference could be reduced if the Al motor needs a new (out of line) housing.

For the big sizes (15 kW and 22 kW), the Cu cage motors present active material costs lower than the IE3 Al motors for all scenarios (excluded the cost of die-casting).

Copper rotor motors are proving a cost-effective way of meeting the new high efficiency IE4 standards.

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