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Dept. of Industrial and Information
Engineering and Economics

New induction motor designs with Aluminum and Copper rotor specially developed to reach the IE3 efficiency level

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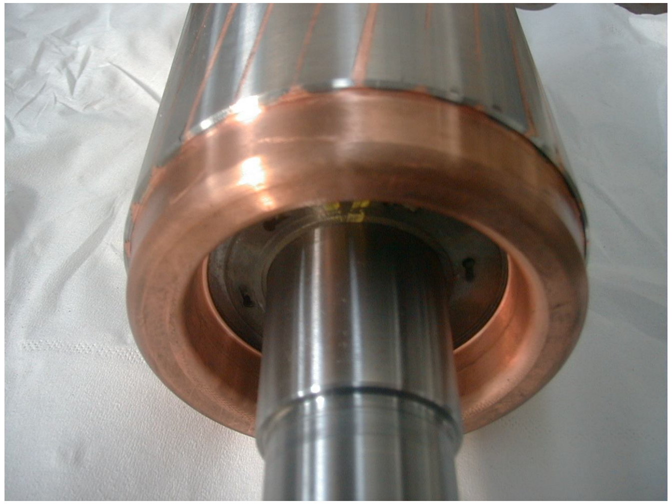
Aim of the study

The aim 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.

Vs



Sizes

Five sizes have been selected (in the range 0.75÷22 kW):

1.5 kW	**6 pole**
3 kW	**4 pole**
7.5 kW	**4 pole**
15 kW	**4 pole**
22 kW	**2 pole**

squirrel-cage, TEFC, 400 V, 50 Hz, S1 duty.

The sizes 1.5, 3 and 7.5 kW are “single-cage” motors, while 15 and 22 kW “double-cage” motors.

Minimum efficiency levels for IE3

Power kW	Poles	Frame size	Efficiency %
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

According to the EC Regulation No. 640/2009.

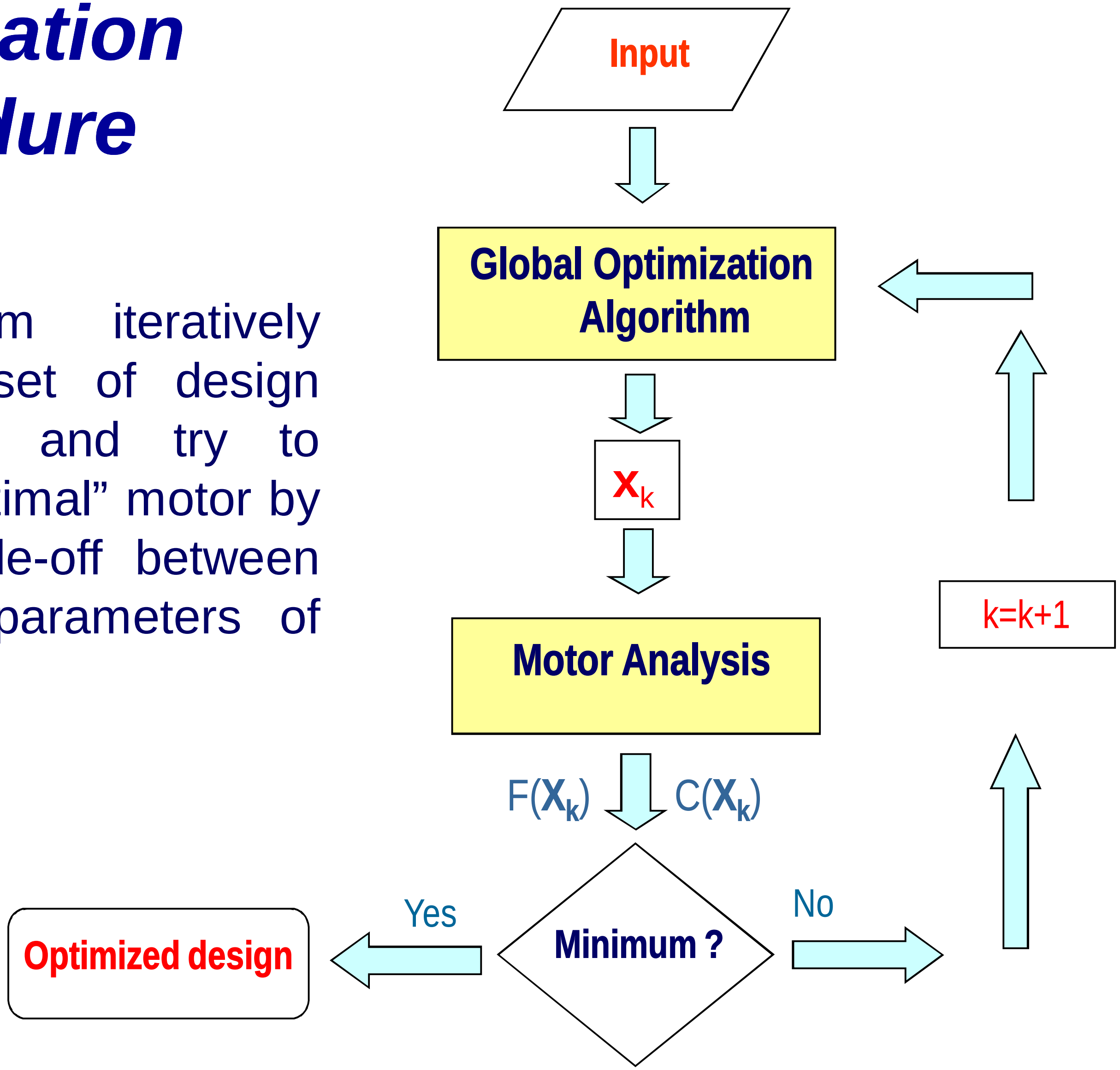
Motors designs

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, that are the motor specifications.

A suitable Optimization Procedure has been used that has allowed to find the “best design” by chancing the geometric dimensions of the stator and rotor shape, the stator winding and the stack length.

Optimization procedure

The 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.



Motor analysis

The block "Motor Analysis" evaluates the motor performance, by a "lumped parameter model".

⬇

The adopted model takes into account:

- Magnetic saturation
- Skin effect on rotor parameters
- Thermal analysis

The validity of the mathematical model has been verified by means of experimental tests on several three-phase induction motors.

Objective function

The motors have been optimized by minimizing the active material costs (AMC), in order to avoid excessive motor oversizing.

$$\mathbf{AMC = (Wfe*Cfe) + (Ws*Ccu_W) + (Wrc*Cm)} \qquad (\in)$$

- 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 for rotor cage (Al or Cu)	(∈/kg)

These costs do not take into account the die-casting process, the stamping process, the tooling and the structure costs.

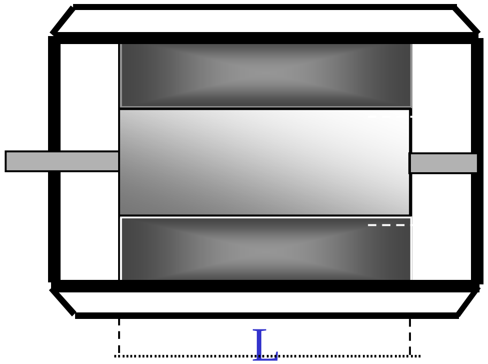
Constraints

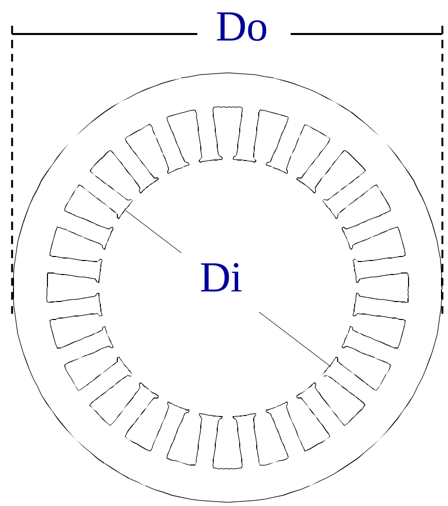
In order to guarantee the goodness and feasibility of the optimized designs, several constrains have been introduced

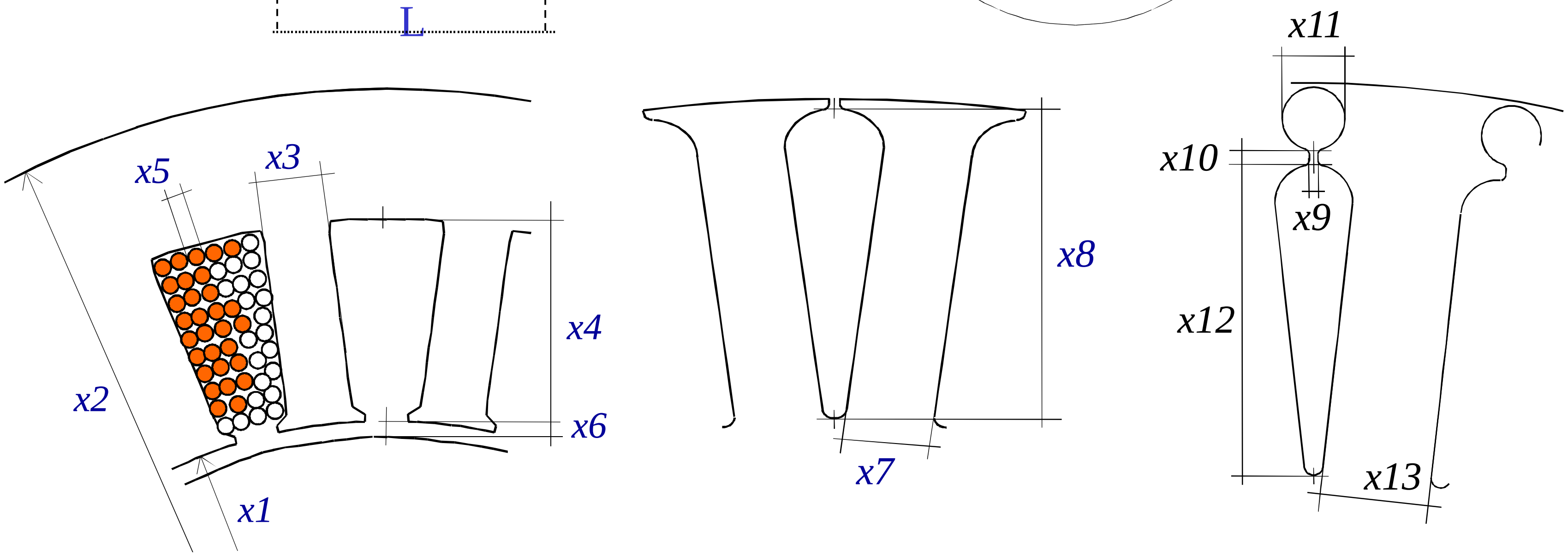
- **Slot fill factor;**
- **Temperatures;**
- **Power factor;**
- **Starting performance** (start. Torque and Current);
- **Breakdown torque;**
- **Rated efficiency** (minimum efficiency level for IE3)

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

Design variables



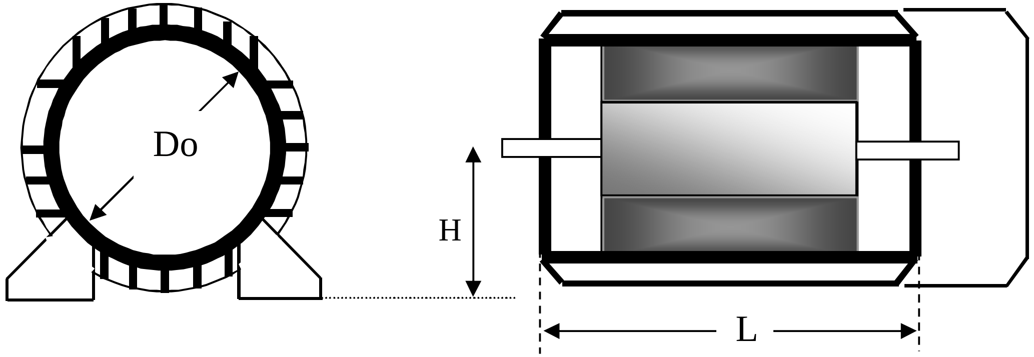




Each variable has been varied between an upper and a lower limit according to the Manufacturers suggestions, in order to obtain a final optimized design whose dimensions are **consistent, when possible, with the standard frame**.

Standard frames

Dimensions of commercial housings produced by Chinese small and big Companies (⇨ max outer stator diameters).



Frame size H	Small Company: Length L (mm)	Small Company: Inner diameter Do	Big Company: Length L (mm)	Big Company: Inner diameter Do
90 L	192	130	230	138
100 L	198	155	255	165
112 M	214	175	282	175
132 M	268	210	320	210
160 M	270	260	278	260
160 L	314	260	322	260
180 M	317	290	317	290
180 L	355	290	355	290
200 L	375	327	385	327

The proposed procedure has allowed to optimize the 5 motor sizes to fulfill the IE3 efficiency level and to compare the optimized designs with Al and Cu rotor.

These assumptions have been made:

Assumptions (1)

For each size, the motors with Al and Cu cage have the same:

- premium steel 330-50 AP (0.50 mm thickness);
- number of stator and rotor slots;
- air-gap length, stator slot opening, rotor skewing;
- slot fill factor;
- winding distribution and “winding factor”;
- stator slot insulation and thermal coefficients;
- the same percentage for the Stray Losses calculation.

Assumptions (2)

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

- premium steel **0.91** (∈/kg)

- raw material for Al cage **1.76** (∈/kg)

- copper wire **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 3 Scenarios have been introduced by imposing a different “Cu/Al” price ratio.

Scenarios

Different Metal Exchange quotations

Scenario_1 $€_{CU}/€_{AL}$ **= 3.0**	- raw material	Al = 1.76 Cu = 5.28 (€/kg)
	- copper wire	6.07 (€/kg)
(*) Scenario_2 $€_{CU}/€_{AL}$ **= 3.5**	- raw material	Al = 1.76 Cu = 6.16 (€/kg)
	- copper wire	7.08 (€/kg)
Scenario_3 $€_{CU}/€_{AL}$ **= 4.0**	- raw material	Al = 1.76 Cu = 7.04 (€/kg)
	- copper wire	8.10 (€/kg)

(*) The motors have been optimized with reference to the Scenario 2.

Results

The results of the optimized designs, with Al and Cu cage, are shown in the following Tables and Figures, that include the main motor dimensions, the motor performance and the active material costs for the 3 Scenarios.

Moreover, the “Torque-Speed” and “Efficiency-Load” curves have been added.

1.5 kW, 6 pole (100 L)

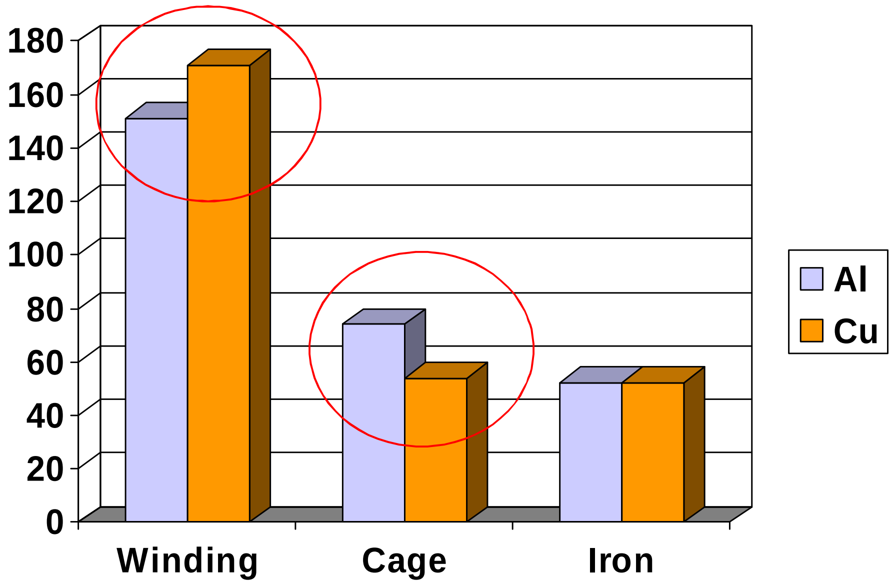
$\eta = 82.5\%$

		Al	Cu
Stack length	mm	**130**	**126**
Outer stat. diameter		**160 (*)**	**152**
N. of turns x phase		342	342
Wire size	mm^2	0.830	0,688
Stat slot area	mm^2	81.9	68.5
Rot. slot area	mm^2	50.2	38.0
Phase current	A	3.68	3.65
Speed	rpm	954	966
Power factor		0.716	0.720
Winding. temper.	°C	65	66
Rotor cage temper.	°C	76	75

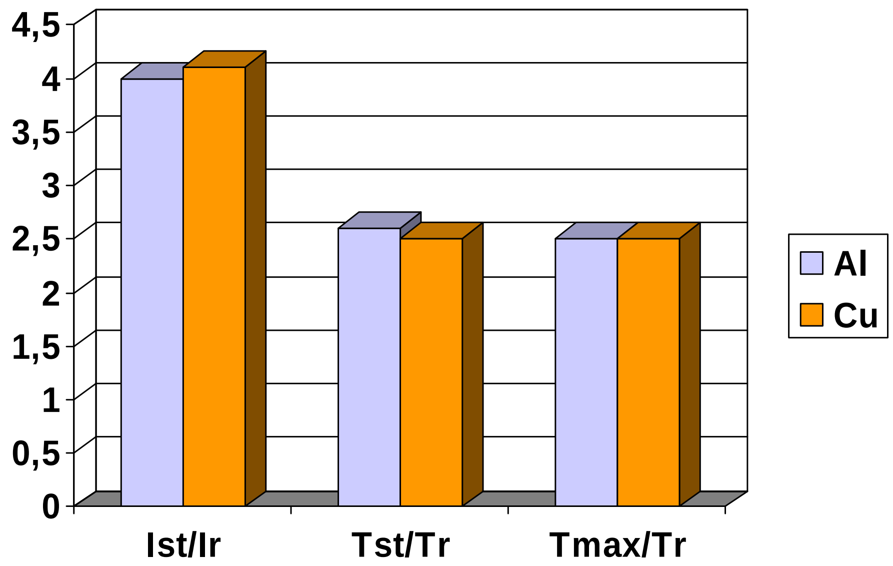
(*) not suitable for the standard housings of the big company.

1.5 kW, 6 pole (η = 82.5%)

Losses (W)



Performance p.u.



Ist = Starting current

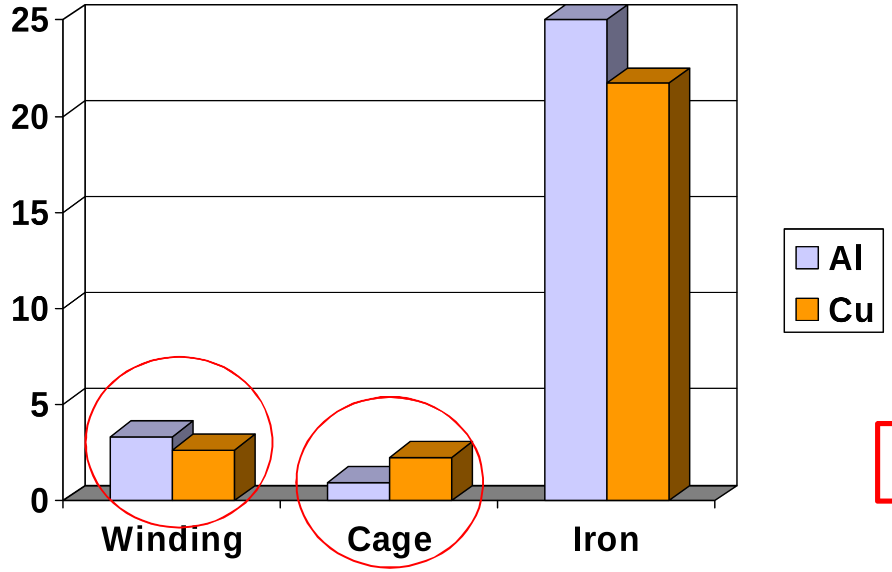
Tst = Starting torque

Tmax = Max torque

Ir, Tr = Rated current, torque

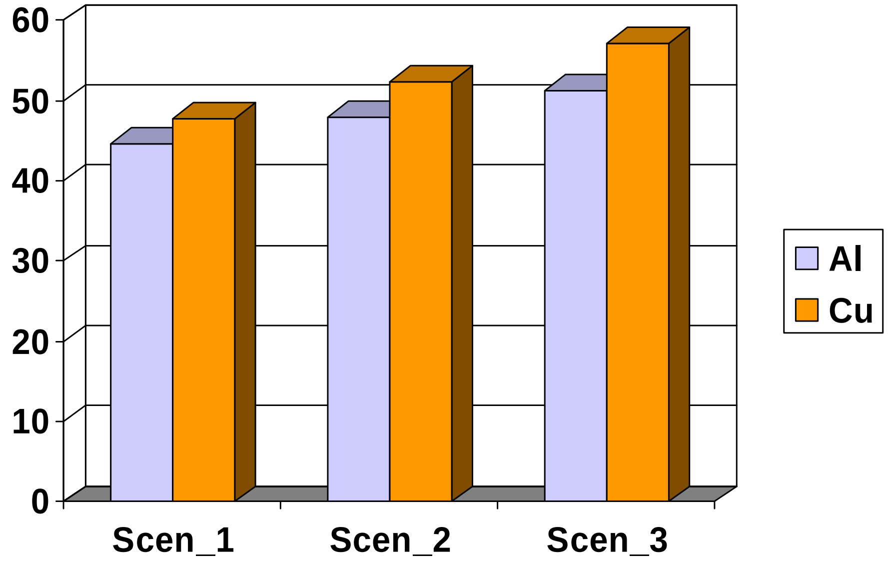
1.5 kW, 6 pole (η = 82.5%)

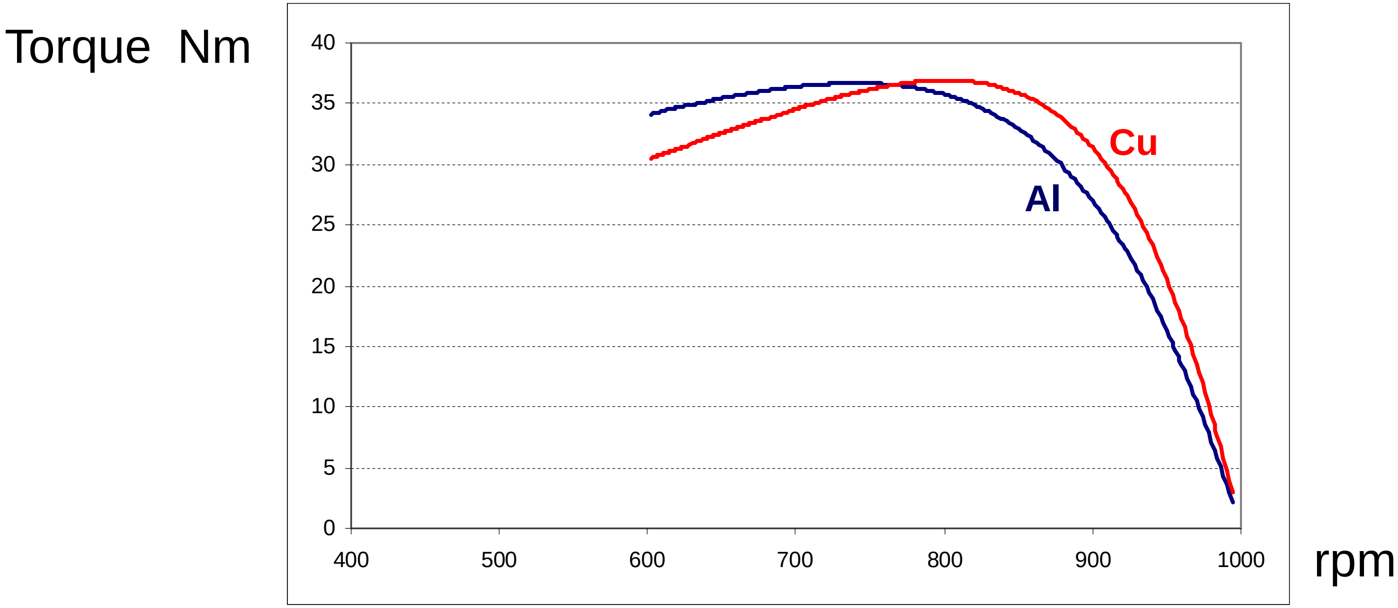
Weight (kg)

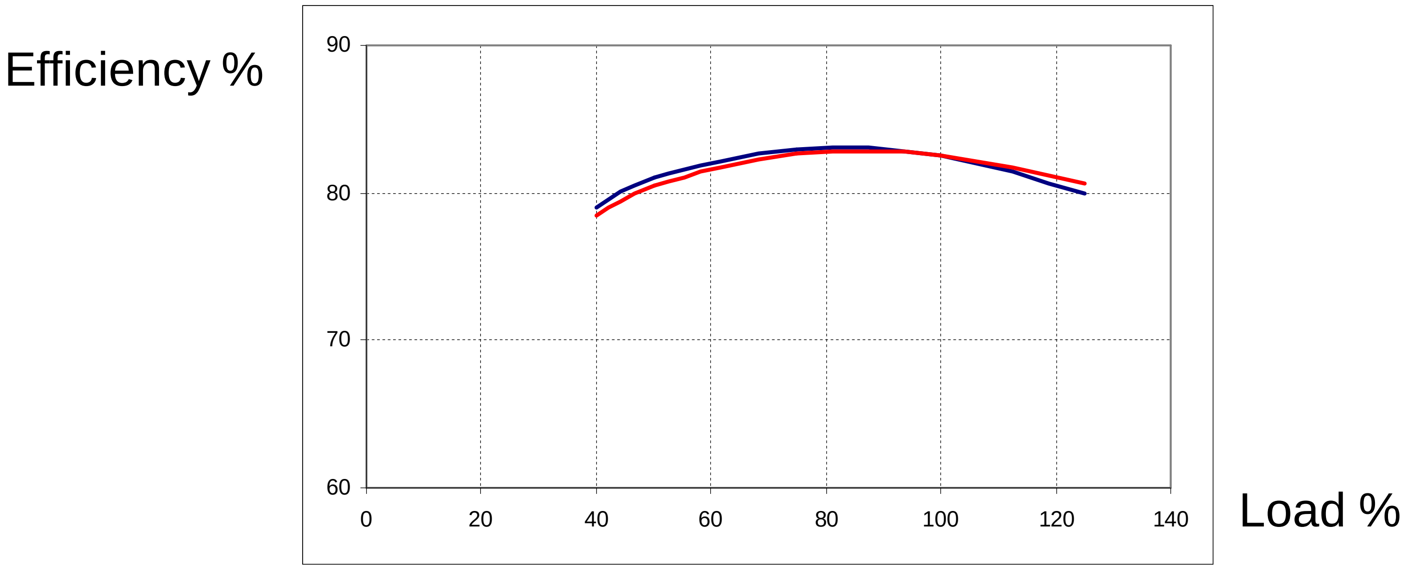


+ 48 % Cu

Active Material Cost (€)




Torque Nm
40
35
30
25
20
15
10
5
0
400
500
600
700
800
900
1000
rpm
Cu
Al


Efficiency %
90
80
70
60
0
20
40
60
80
100
120
140
Load %

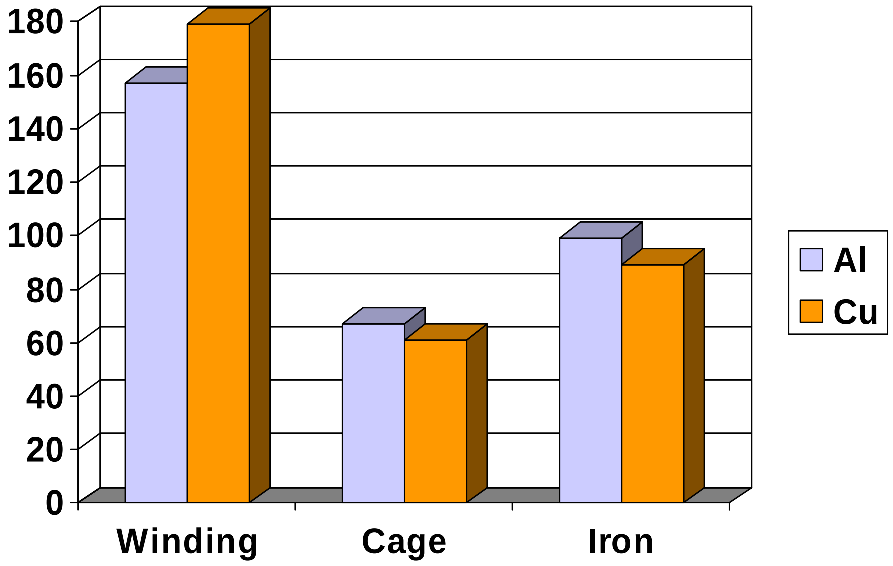
3 kW, 4 pole (100 L) $\eta = 87.7\%$

		Al	Cu
Stack length	mm	**155**	**150**
Outer stat. diameter		**165 (*)**	**160 (*)**
N. of turns x phase		186	186
Wire size	mm^2	1.645	1.31
Stat slot area	mm^2	125	102
Rot. slot area	mm^2	93.8	58.6
Phase current	A	6.28	6.19
Speed	rpm	1468	1471
Power factor		0.78	0.79
Winding. temper.	°C	57	58
Rotor cage temper.	°C	64	65

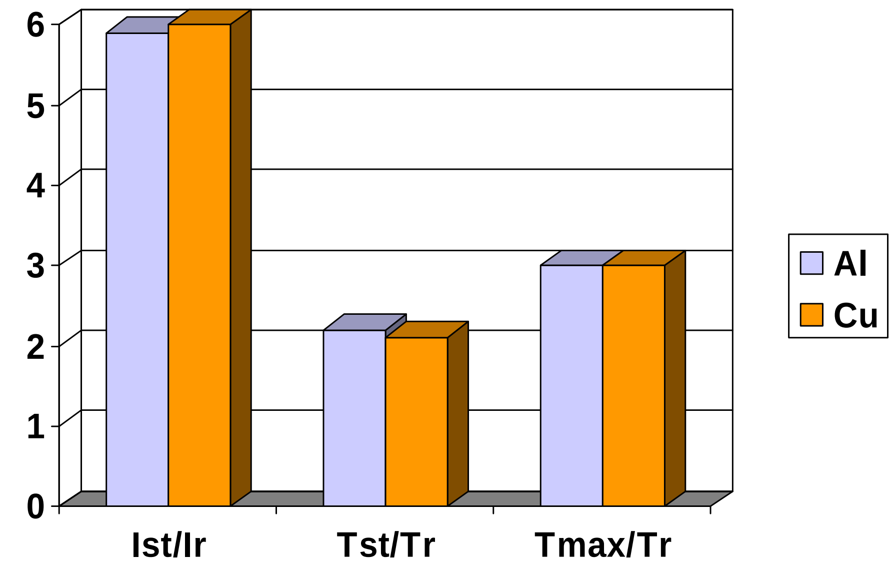
(*) not suitable for the standard housings of the big company.

3 kW, 4 pole (η = 87.7%)

Losses (W)

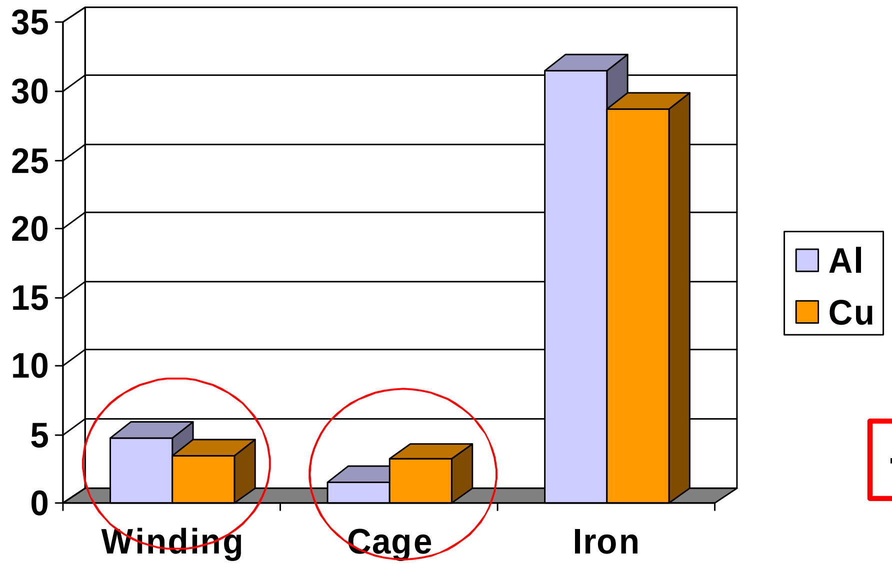


Performance p.u.



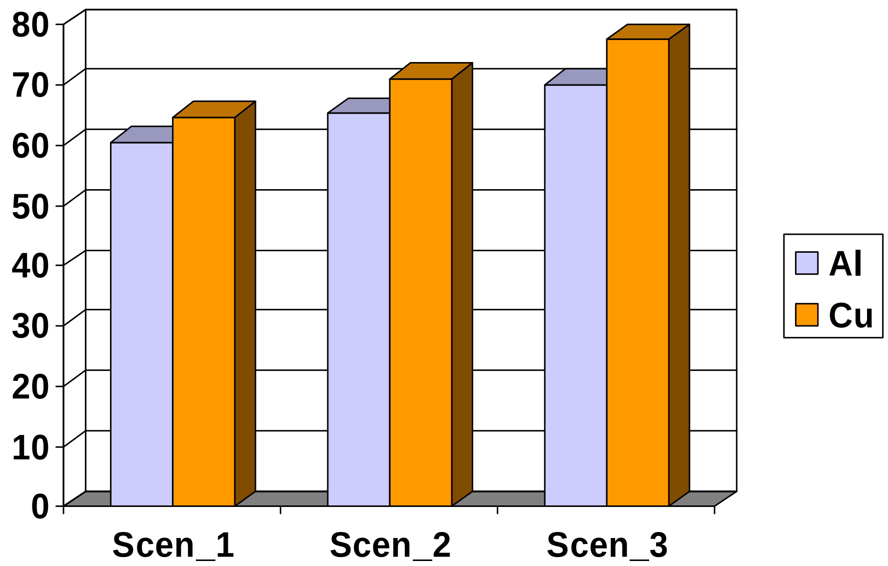
3 kW, 4 pole (η = 87.7%)

Weight (kg)

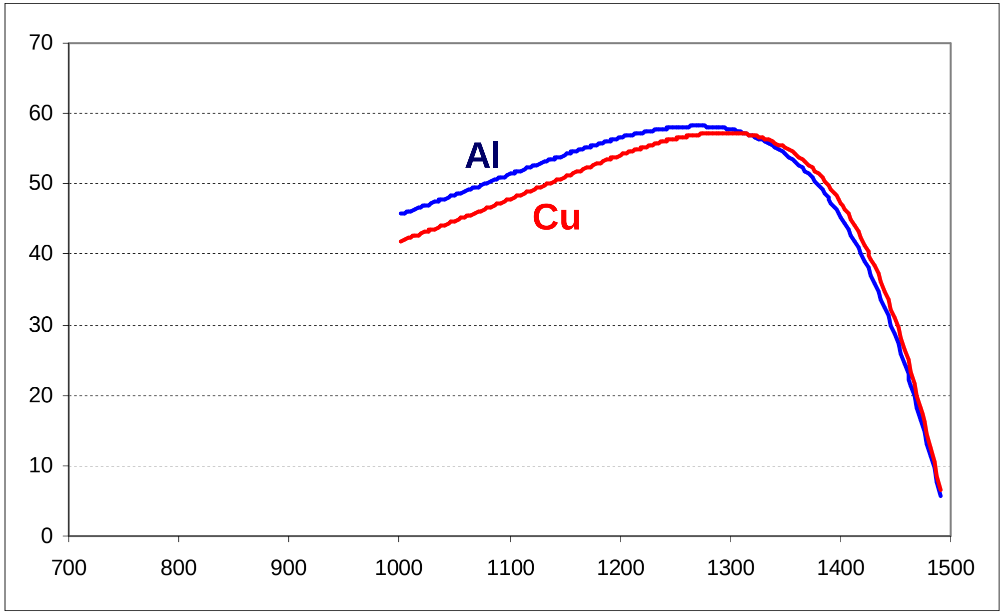


+ 42 % Cu

Active Material Cost (∈)

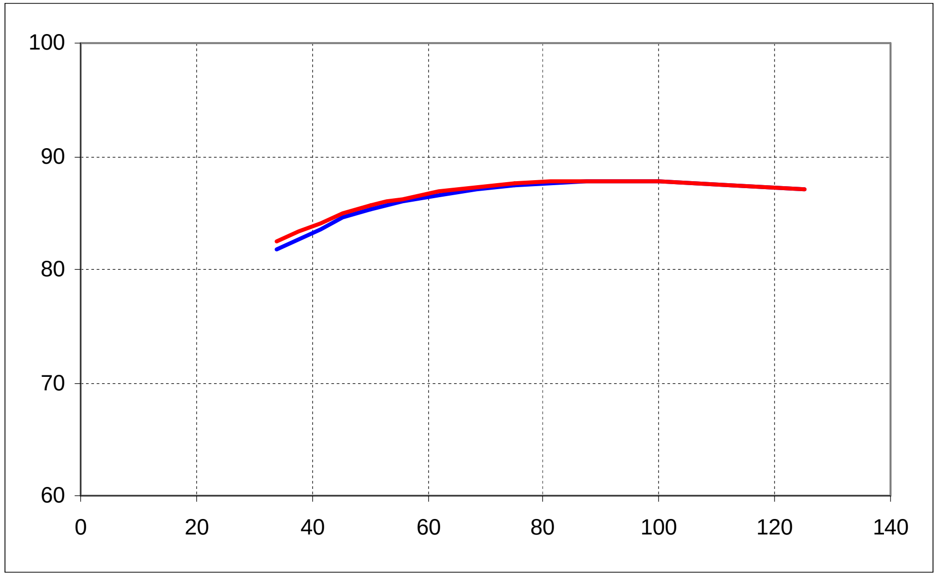


Torque Nm



rpm

Efficiency %



Load %

7.5 kW, 4 pole (132 M)

$\eta = 90.4\%$

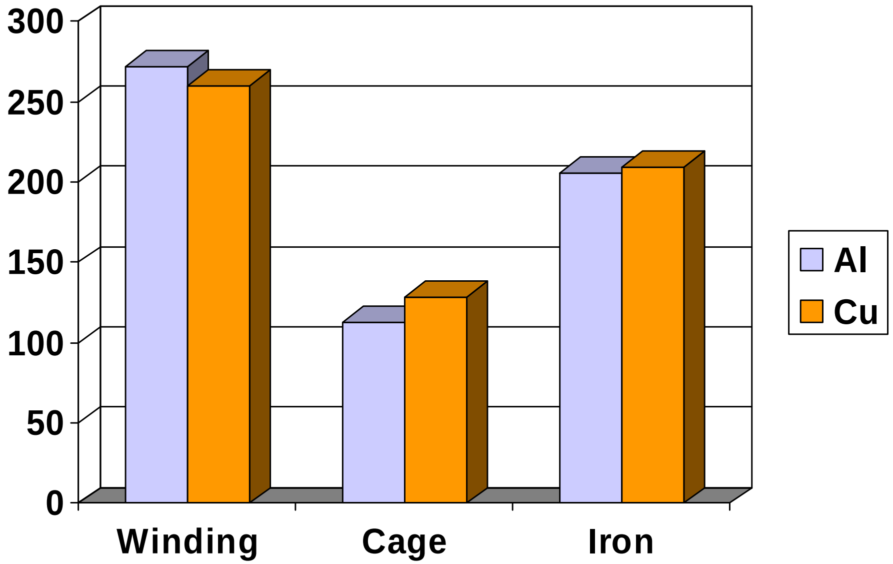
		Al	Cu
Stack length	mm	**200**	**190**
Outer stat. diameter		**215 (*)**	**210**
N. of turns x phase		114	108
Wire size	mm^2	4.80	4.15
Stat slot area	mm^2	205	168
Rot. slot area	mm^2	115	52.5
Phase current	A	15.41	14.96
Speed	rpm	1478	1475
Power factor		0.78	0.81
Winding. temper.	°C	71	73
Rotor cage temper.	°C	82	85

- 55 %

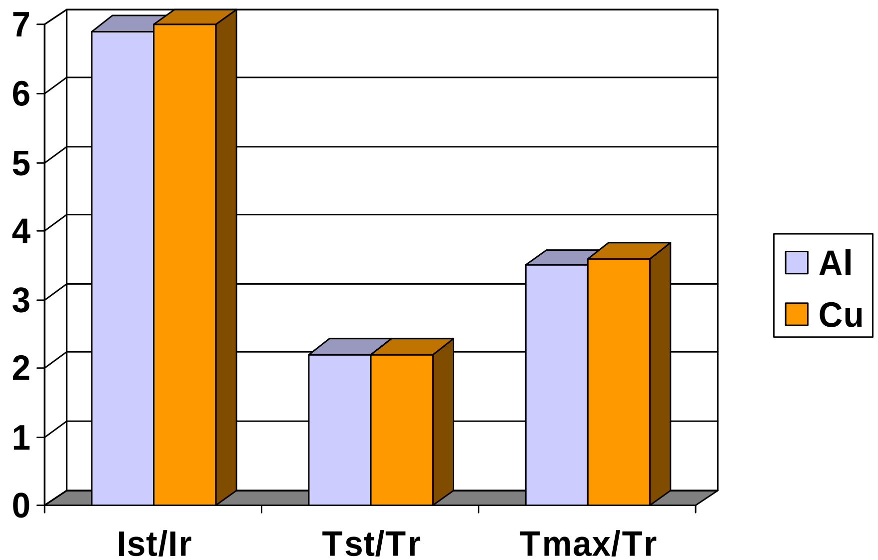
(*) not suitable for the standard housings of the small and big company.

7.5 kW, 4 pole (η = 90.4%)

Losses (W)

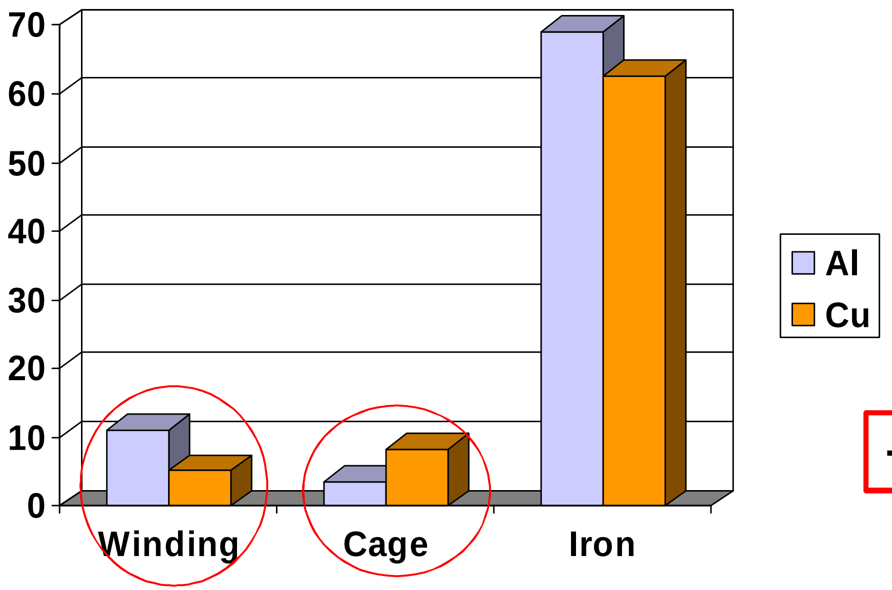


Performance p.u.



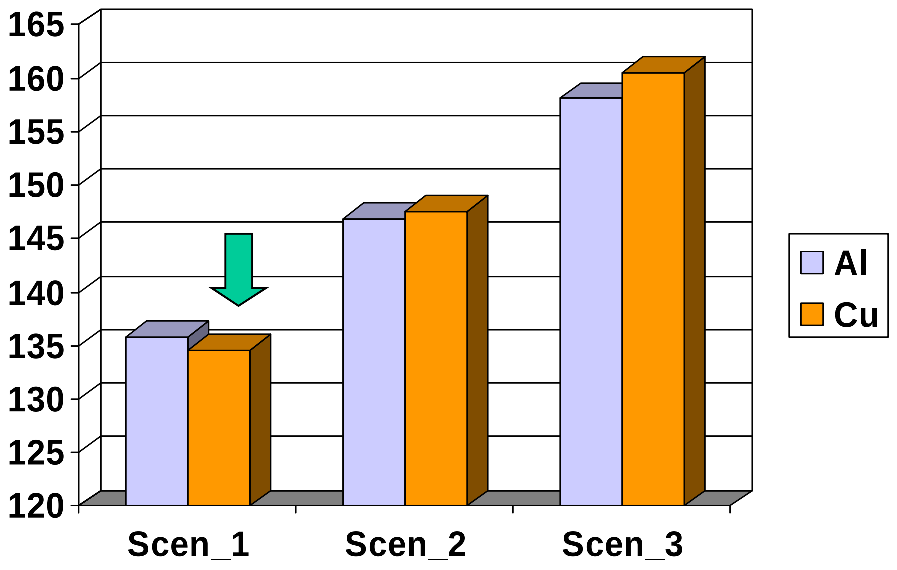
7.5 kW, 4 pole (η = 90.4%)

Weight (kg)

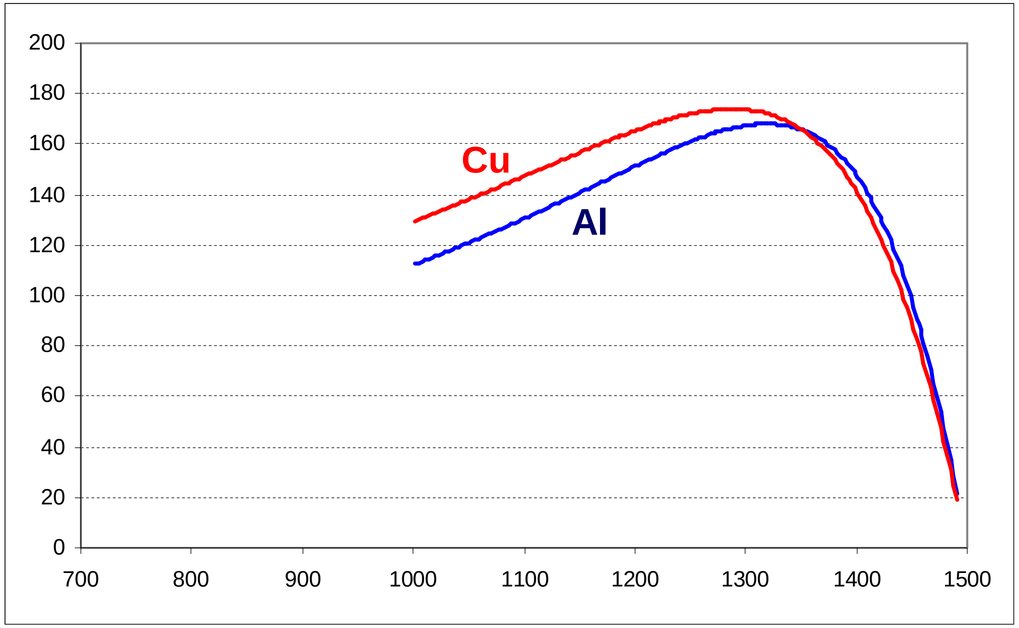


+ 22 % Cu

Active Material Cost (€)

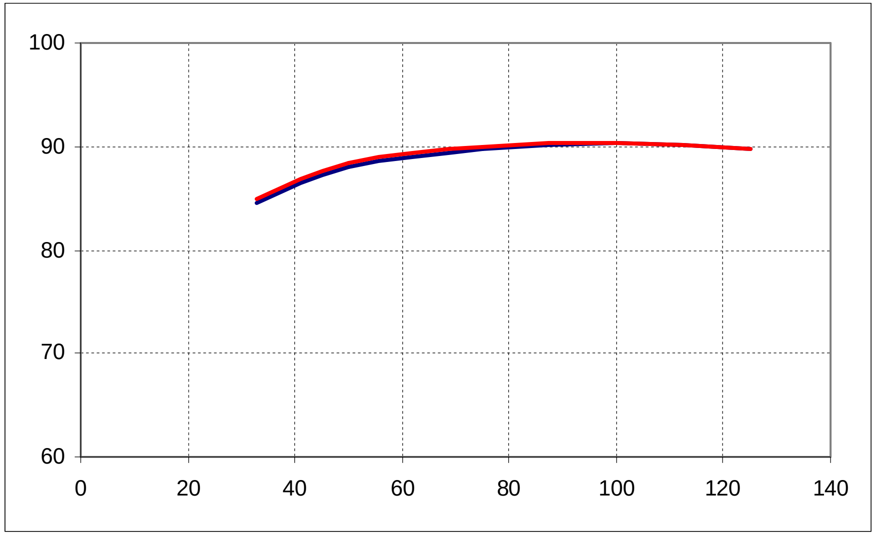


Torque Nm



rpm

Efficiency %



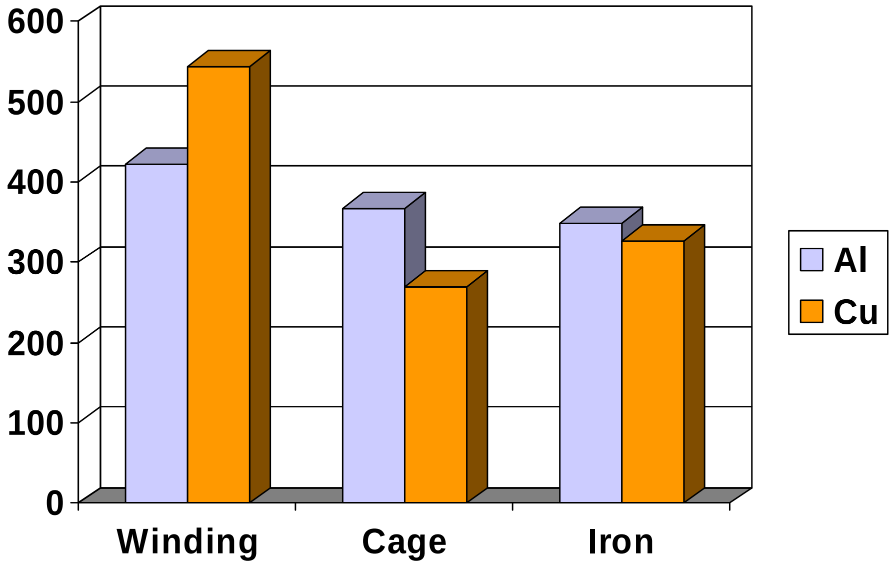
Load %

15 kW, 4 pole (160 L) $\eta = 92.1\%$

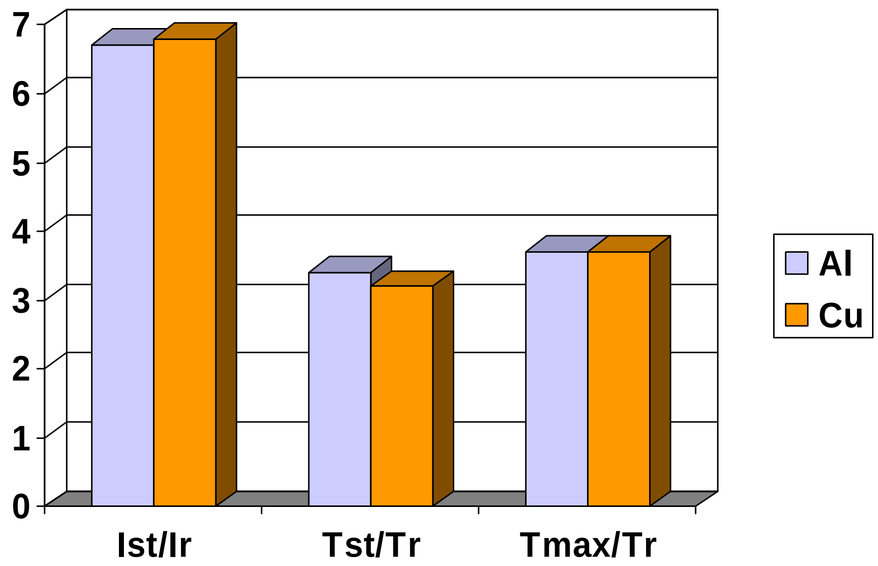
		Al	Cu
Stack length	mm	**225**	**215**
Outer stat. diameter		**255**	**245**
N. of turns x phase		78	78
Wire size	mm^2	7.90	5.60
Stat slot area	mm^2	228	182
Rot. slot area	mm^2	83	65
Phase current	A	28.1	27.4
Speed	rpm	1465	1474
Power factor		0.84	0.86
Winding. temper.	°C	70	73
Rotor cage temper.	°C	82	84

15 kW, 4 pole (η = 92.1%)

Losses (W)

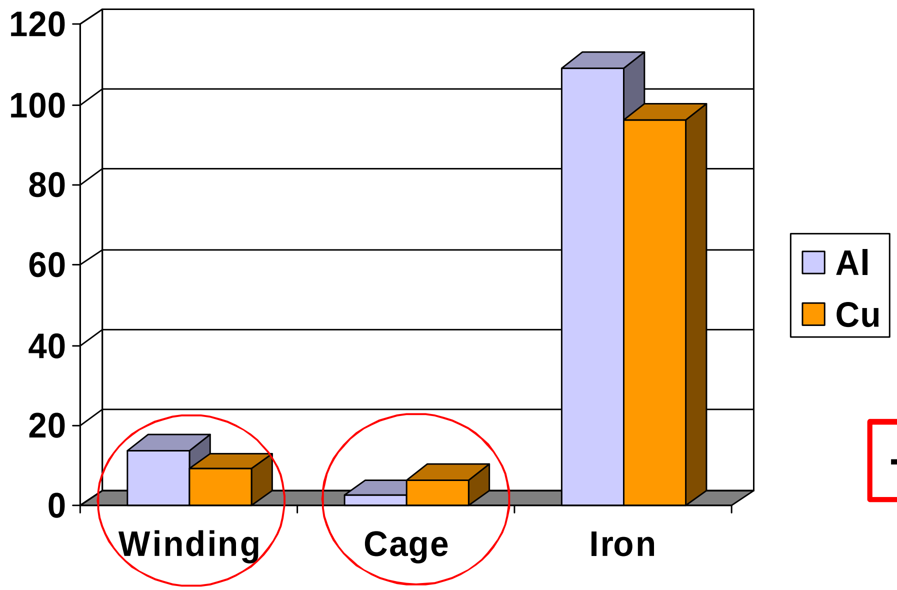


Performance p.u.



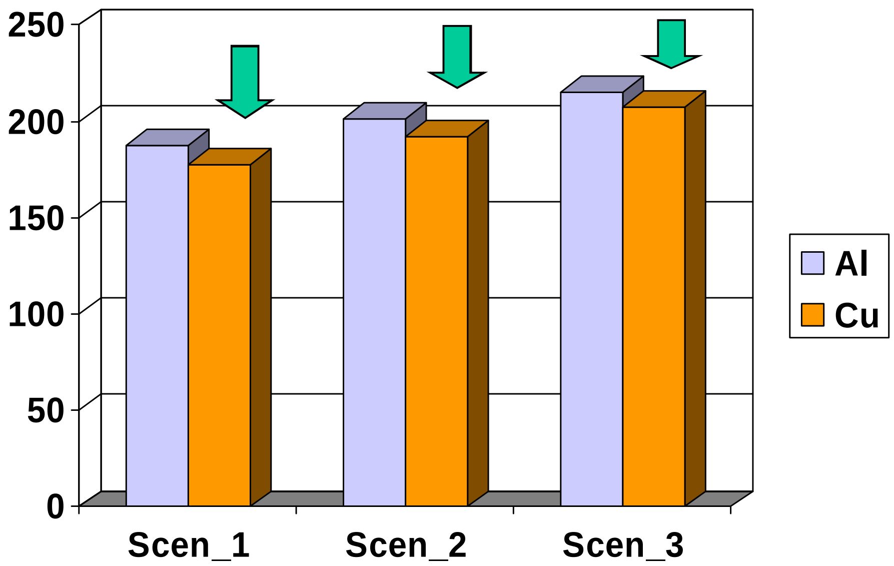
15 kW, 4 pole (η = 92.1%)

Weight (kg)

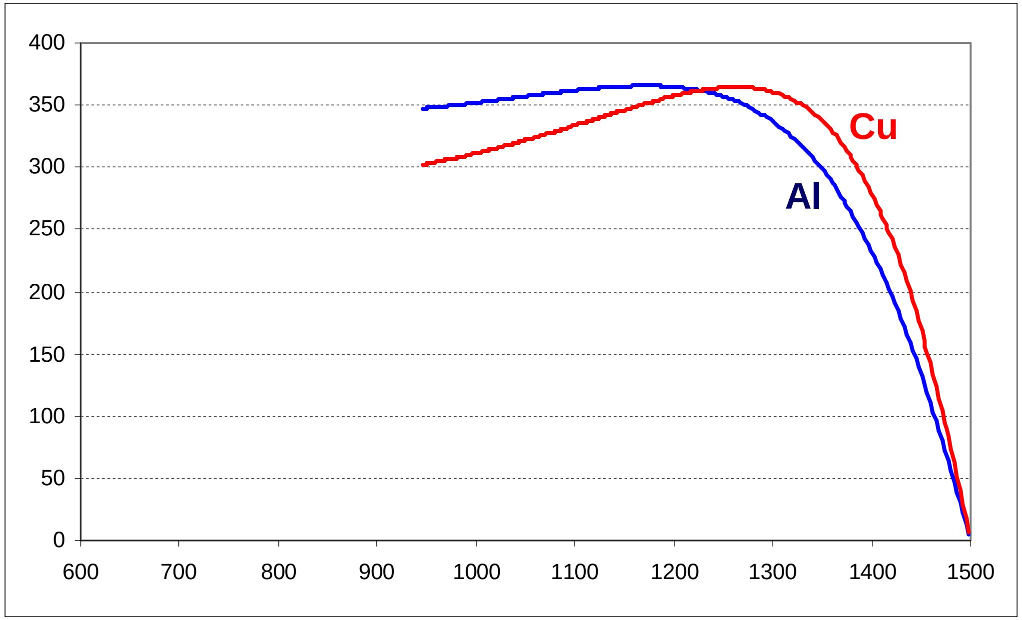


+ 13 % Cu

Active Material Cost (∈)

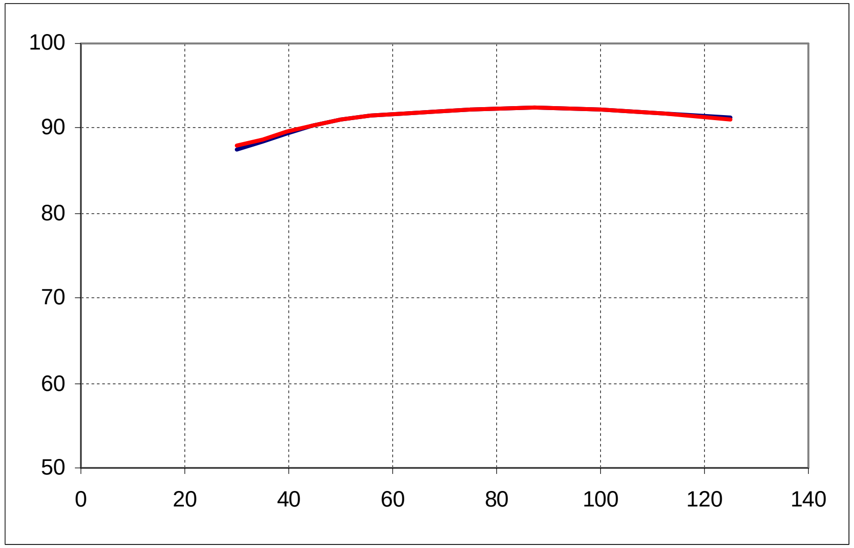


Torque Nm



rpm

Efficiency %



Load %

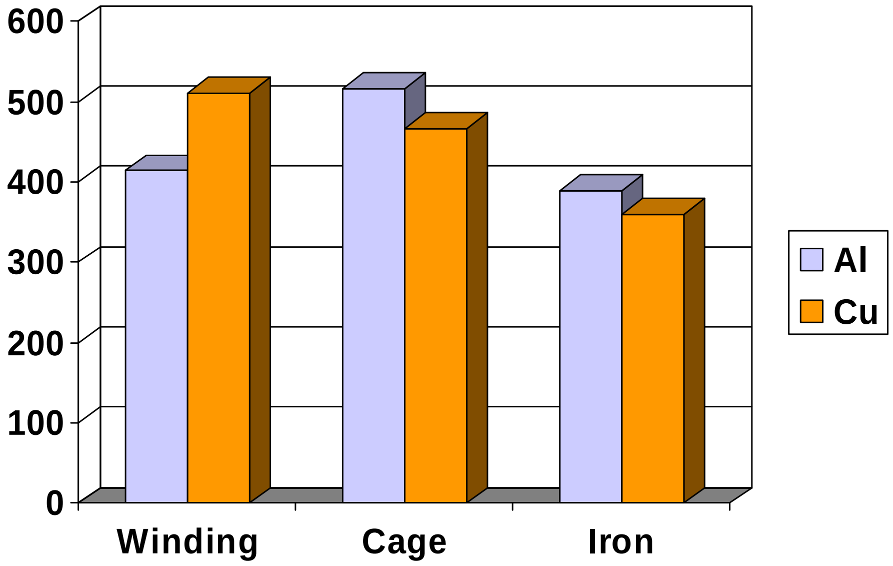
22 kW, 2 pole (180 M)

$\eta = 92.7\%$

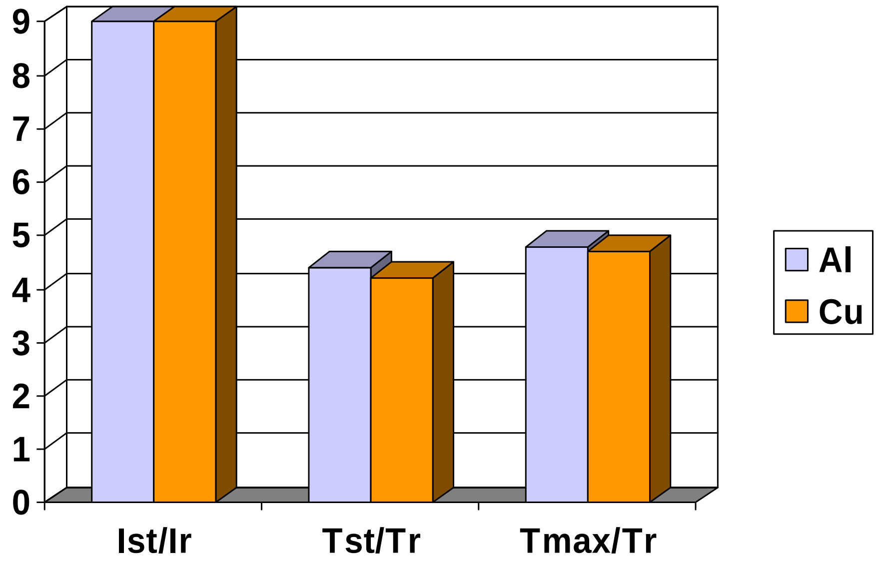
		Al	Cu
Stack length	mm	**215**	**205**
Outer stat. diameter		**290**	**285**
N. of turns x phase		84	84
Wire size	mm^2	6.36	4.80
Stat slot area	mm^2	200	164
Rot. slot area	mm^2	122	83
Phase current	A	20.3	20.2
Speed	rpm	2933	2939
Power factor		0.93	0.93
Winding. temper.	°C	60	62
Rotor cage temper.	°C	70	72

22 kW, 2 pole (η = 92.7%)

Losses (W)

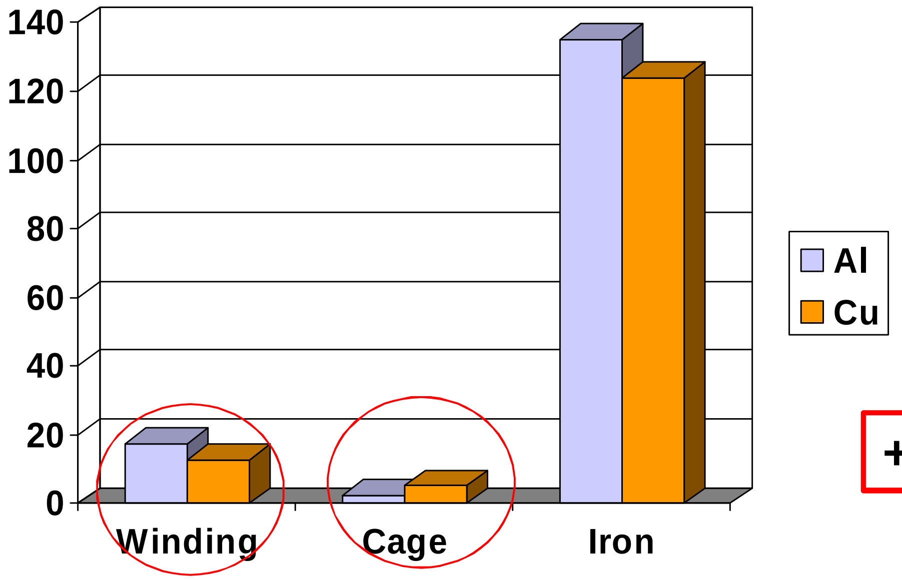


Performance p.u.



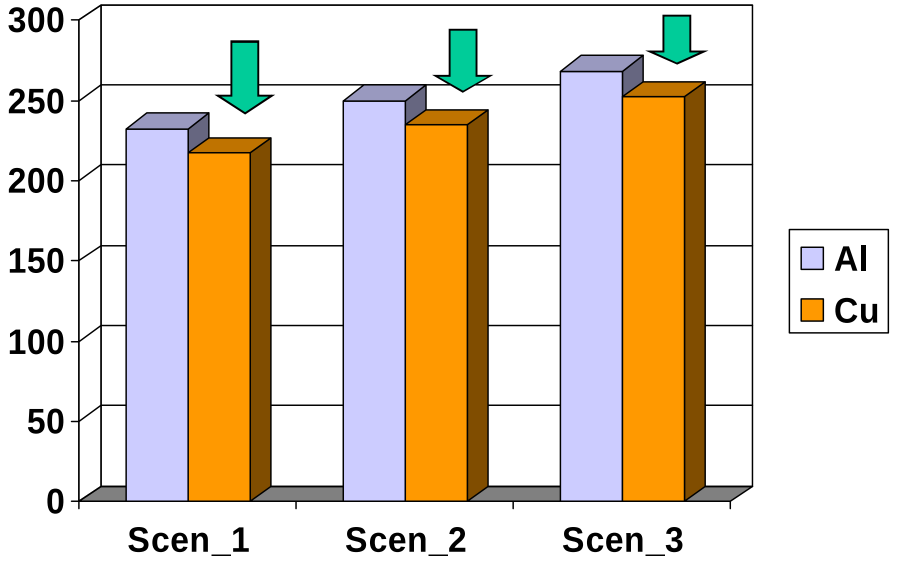
22 kW, 2 pole (η = 92.7%)

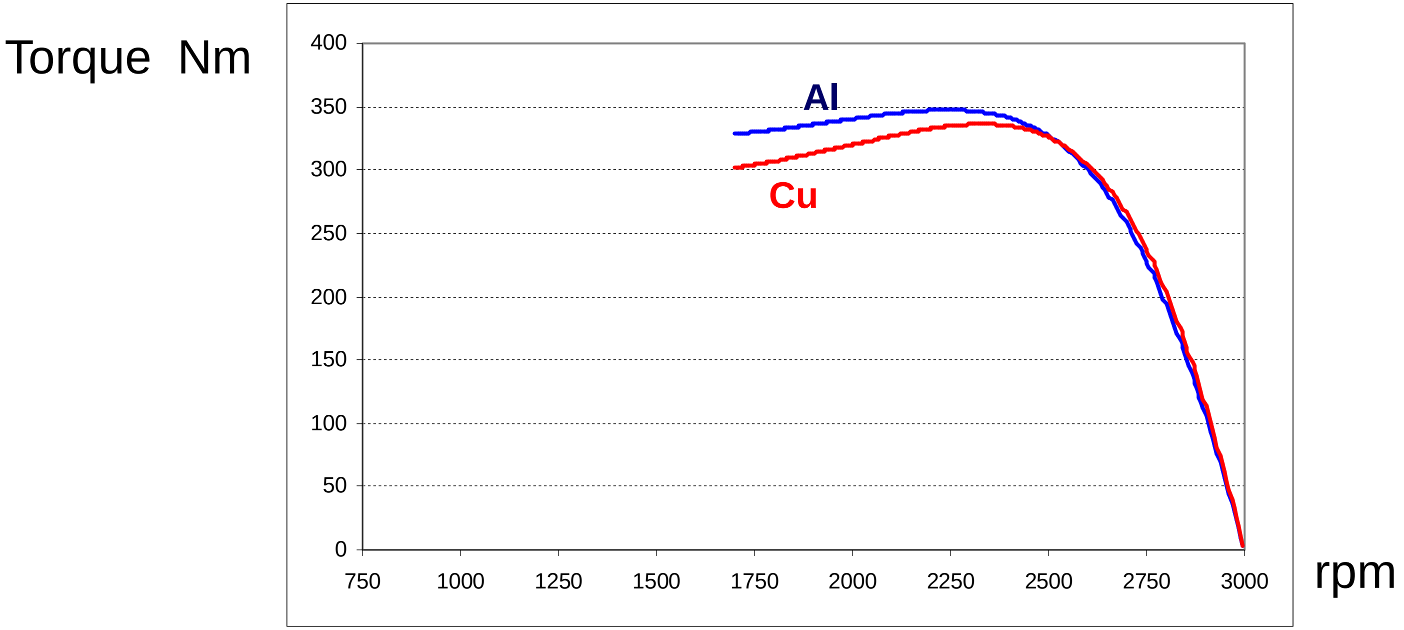
Weight (kg)

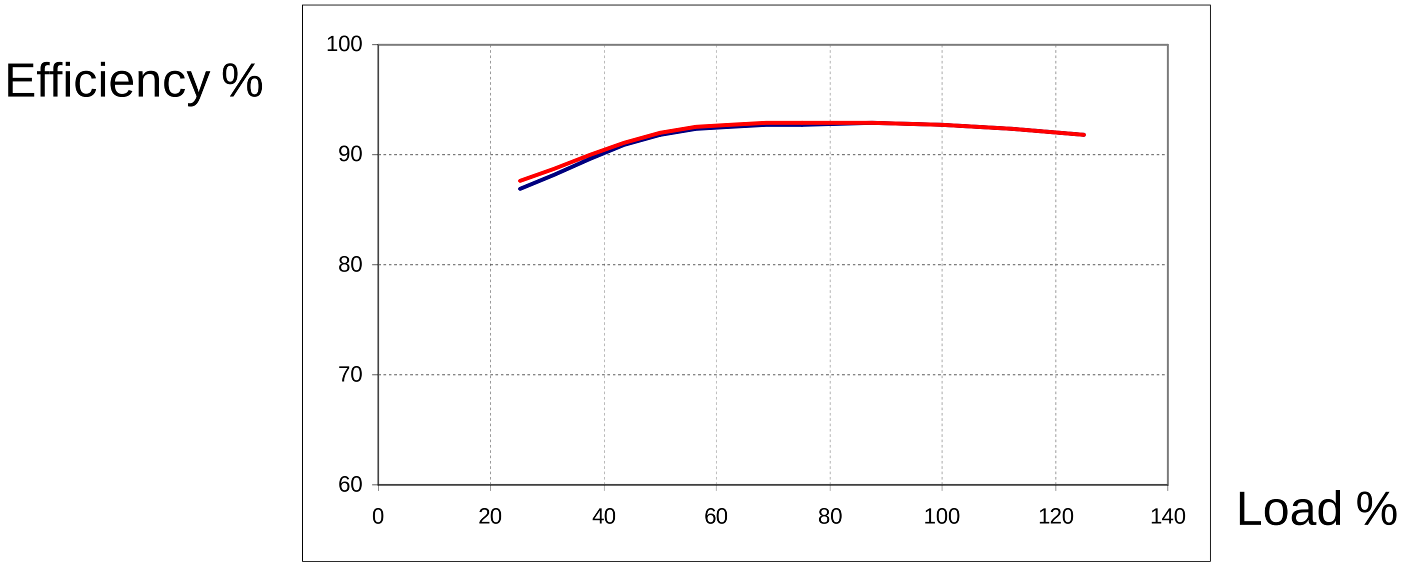


+ 3 % Cu

Active Material Cost (∈)




Torque Nm
400
350
300
250
200
150
100
50
0
750
1000
1250
1500
1750
2000
2250
2500
2750
3000
Al
Cu
rpm


Efficiency %
100
90
80
70
60
0
20
40
60
80
100
120
140
Load %

Copper rotor motors

Active Material Cost variations (in Euro and %) respect to Al rotor motors

Power 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%

For the small sizes (1.5, 3 and 7.5 kW), these variations could be reduced if the Al motors need new (out of line) housings.

Conclusions

The motors with **Al** and **Cu** cage have the same minimum efficiency levels for IE3, according to the EC Regulation No. 640/2009.

The performance of both designs 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.

Difficulty 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.

The IE3 **Cu** motors are always compatible with all commercial housings.

For the small sizes (1.5 and 3 kW), the **Cu** cage motors are slightly more expensive respect to the **Al** motor but this difference could be reduced if the **Al** motor needs a new (out of line) housing.

For the large sizes (15 and 22 kW), the **Cu** cage motors present the active material costs lower respect to 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.