*University of L’Aquila*
*Department of Electrical and Information Engineering*

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

## Final Report

Francesco Parasiliti, Marco Villani
University of L’Aquila
Department of Electrical and Information Engineering

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**Introduction**

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.

Five sizes have been selected and particularly: 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.

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

In Table I are shown, for each size, the minimum efficiency levels for IE3 according to the EC Regulation No. 640/2009.

Table I – The minimum efficiency level for IE3.

| 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 % |

The motors designs, with Al and Cu cage, have been optimized in order to reach the minimum efficiency level IE3 at <u>lowest active material costs</u> 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 (inner and outer stator diameters, tooth width, yoke high, 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 the Manufacturers suggestions, in order to obtain a final optimized design whose dimensions are consistent, when possible, with the standard frame (see Annex I and II).

The motors have been optimized by minimizing the active material costs, in order to avoid an excessive motor oversizing. The active material cost is defined as follows:

$$ACM = (Wfe*Cfe) + (Ws*Ccu_W) + (Wrc*Cm) \quad (\in) \qquad (1)$$

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 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.

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), the power factor, the starting performance (starting torque and starting current), the breakdown torque, the stator winding temperature rise, the rotor bars temperature rise and 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 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.

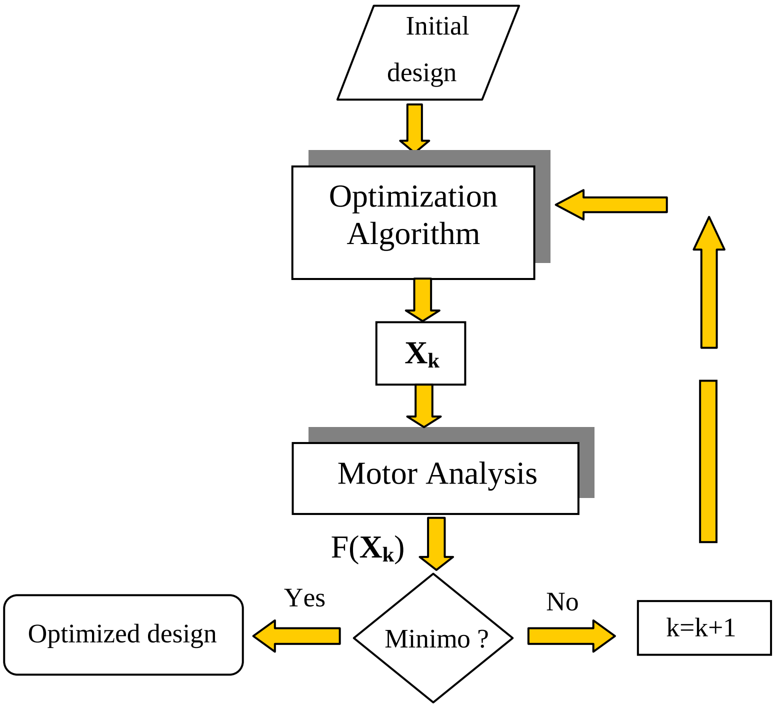



Fig. 1 – Design optimization procedure

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.

The block “Motor Analysis” evaluates the motor performance, the objective function and 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 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.

The following 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) and the same percentage for the Stray Losses calculation (2% the output power).

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

| | | | |
|---|---|---|---|
| - premium steel | Cfe | 0.91 | (∈/kg) (provided by Bourgeois); |
| - raw material for Al cage | Cm_Al | 1.76 | (∈/kg) |
| - copper wire | $(Ccu)_W$ | 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** - $\in_{CU}/\in_{AL} = 3.0$

- raw material for Cu cage Cm_Cu = 5.28 (∈/kg)
- copper wire $(Ccu)_W = 6.07$ (∈/kg)

**Scenario_2** - $\in_{CU}/\in_{AL} = 3.5$

- raw material for Cu cage Cm_Cu = 6.16 (∈/kg)
- copper wire $(Ccu)_W = 7.08$ (∈/kg)

**Scenario_3** - $\in_{CU}/\in_{AL} = 4.0$

- 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 magnetic characteristics are presented in the Annex III.

**Results**

The results of the optimized designs, with Al and Cu cage, are shown in the following Tables, that include the main motor dimensions, the motor performance and the active material costs for the three Scenarios, calculated according to the (1): for each size, some comments have been included. Moreover, the “Torque-Speed” and “Efficiency-Load” curves have been added, to verify the goodness of the proposed designs in terms of performance and efficiency.

The detailed geometric dimensions of the new motors are shown in the Annex IV and include all stator and rotor dimensions.

Some remarks:

- The performance of the 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 except 22 kW one.
- 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 (see Annex I).
- For the small sizes (1.5 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 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).

**1.5 kW, 6 pole (100 L) – 400 V, 50 Hz, TEFC, S1**

| η = 82.5% (IE3) | **Al** | **Cu** |
|---|---|---|
| Electrical steel | 330-50 AP | 330-50 AP |
| Stack length (mm) | 130 | 126 |
| Outer stator diameter (mm) | 160 (*) | 152 |
| N. 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 |
| Phase current (A) | 3.68 | 3.65 |
| Speed (rpm) | 954 | 966 |
| Power factor | 0.716 | 0.720 |
| Temperature (°C): Stat. winding | 65 | 66 |
| Rotor cage | 76 | 75 |
| Joule losses (W) Stat. winding | 151 | 171 |
| Rotor cage | 74 | 54 |
| Iron losses (W) | 52 | 52 |
| Starting Current/Rated Current | 4.0 | 4.1 |
| Starting Torque/Rated Torque | 2.6 | 2.5 |
| Max Torque/Rated Torque | 2.5 | 2.5 |
| Weight (kg); Gross iron | 25 | 21.7 |
| Stator winding | 3.32 | 2.62 |
| Rotor cage | 0.94 | 2.29 |
| Active Material Cost (∊): | | |
| Scenario_1 | 44.56 | 47.74 |
| Scenario_2 | 47.91 | 52.40 |
| Scenario_3 | 51.30 | 57.09 |

| Δcost (∊) |
|---|
| + 3.18 |
| + 4.49 |
| + 5.79 |

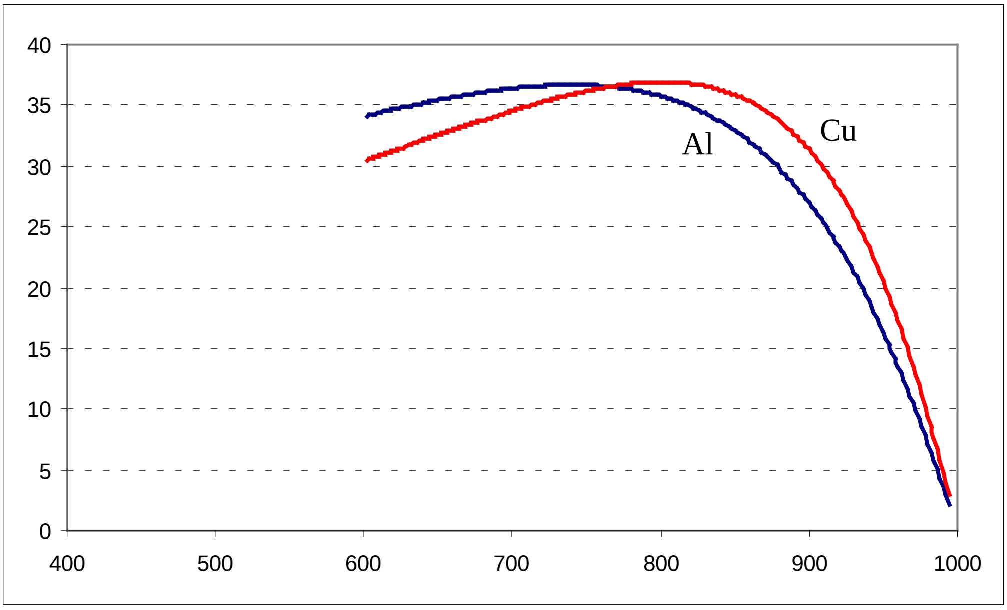
**Comments**

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.
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 (see Annex I) and not the housings of the big company: in this case a new (out of line) and more expansive housing is needed (*).
The Cu motor is compatible with all commercial housings (small and big company, see Annex I) 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. 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.

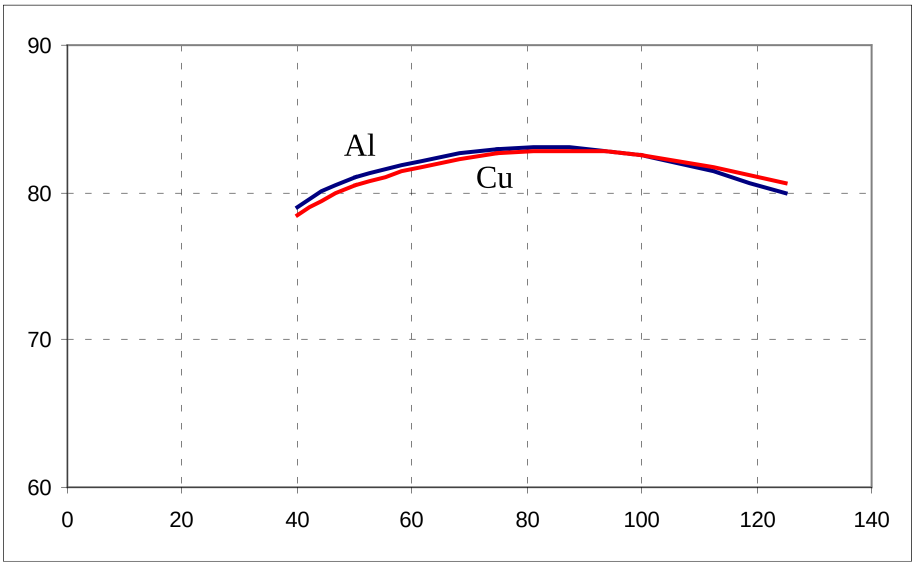
The Cu cage motor is slightly more expensive, with an increase on the active material cost of 3 Euro for the Scenario 1 and about 6 for the Scenarios 3: this difference could be reduced if the Al motor needs a new (out of line) housing.
The following figures show the "Torque-Speed" and "Efficiency-Load" curves. Both designs present good efficiencies also at partial load (e.g. 75%).

**1.5 kW, 6 pole**

Torque (Nm) – Speed (rpm)




Efficiency % - Load %



**3 kW, 4 pole (100 L) – 400 V, 50 Hz, TEFC, S1**

| η = 87.7% (IE3) | | **Al** | **Cu** |
|---|---|---|---|
| Electrical steel | | 330-50 AP | 330-50 AP |
| Stack length | (mm) | 155 | 150 |
| Outer stator diameter | (mm) | 165 (*) | 160 (*) |
| N. 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 |
| Phase current | (A) | 6.28 | 6.19 |
| Speed | (rpm) | 1468 | 1471 |
| Power factor | | 0.78 | 0.79 |
| Temperature (°C): | Stat. winding | 57 | 58 |
| | Rotor cage | 64 | 65 |
| Joule losses (W) | Stat. winding | 157 | 179 |
| | Rotor cage | 67 | 61 |
| Iron losses | (W) | 99 | 89 |
| Starting Current/Rated Current | | 5.9 | 6.0 |
| Starting Torque/Rated Torque | | 2.2 | 2.1 |
| Max Torque/Rated Torque | | 3.0 | 3.0 |
| Weight (kg); | Gross iron | 31.5 | 28.7 |
| | Stator winding | 4.77 | 3.54 |
| | Rotor cage | 1.61 | 3.23 |
| Active Material Cost (€): | | | |
| | Scenario_1 | 60.45 | 64.66 |
| | Scenario_2 | 65.27 | 71.08 |
| | Scenario_3 | 70.14 | 77.53 |

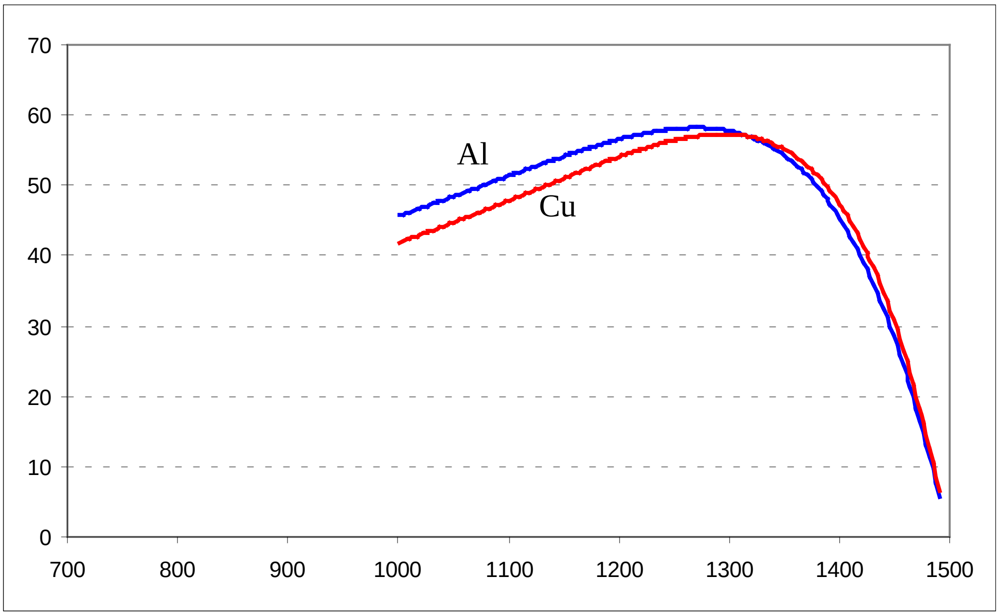
| Δcost (€) |
|---|
| + 4.21 |
| + 5.81 |
| + 7.39 |

**Comments**

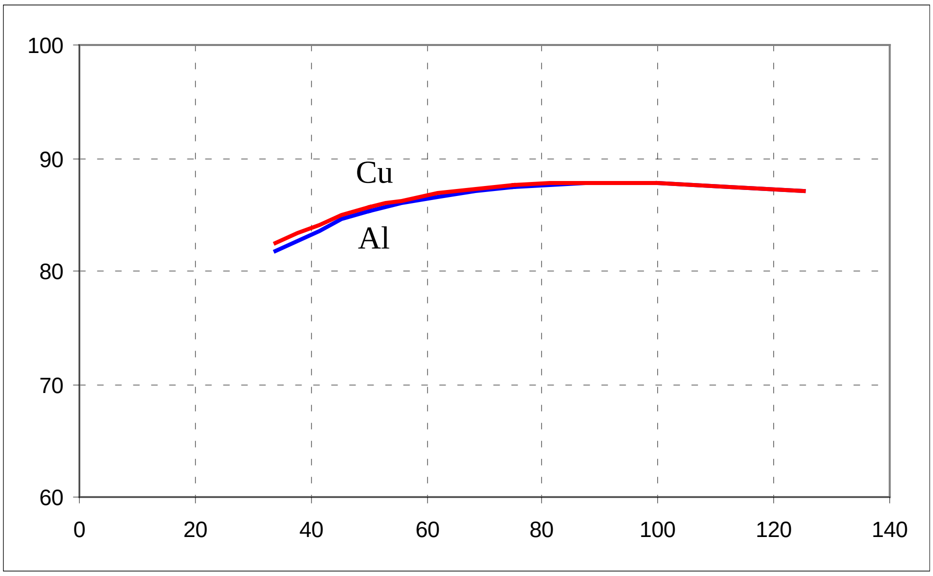
Both designs have the same rated efficiency (87.7%) and the performance are quite similar and consistent with typical performance of a commercial Al motor of the same size.
The outer stator diameters of both designs allow to use commercial housings produced by a small company only (see Annex I) (*).
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 and 7 Euro.
The following figures show the "Torque-Speed" and "Efficiency-Load" curves. Both designs present good efficiencies also at partial load (e.g. 75%).

**3 kW, 4 pole**

Torque (Nm) – Speed (rpm)




Efficiency % - Load %



**7.5 kW, 4 pole (132 M) – 400 V, 50 Hz, TEFC, S1**

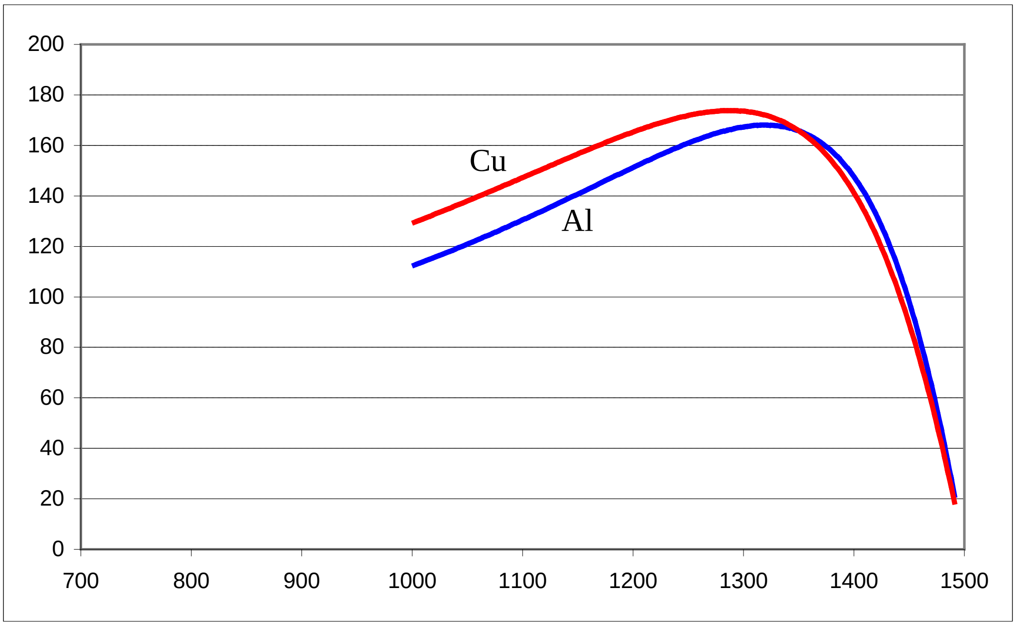
| η = 90.4 % (IE3) | **Al** | **Cu** | |
|---|---|---|---|
| Electrical steel | 330-50 AP | 330-50 AP | |
| Stack length (mm) | 200 | 190 | |
| Outer stator diameter (mm) | 215 (*) | 210 | |
| N. of turns x phase | 114 | 108 | |
| Wire size ($mm^2$) | 4.80 | 4.15 | |
| Stator slot area ($mm^2$) | 205 | 168 | |
| Rotor slot area ($mm^2$) | 115 | 52.5 | |
| Phase current (A) | 15.41 | 14.96 | |
| Speed (rpm) | 1478 | 1475 | |
| Power factor | 0.78 | 0.81 | |
| Temperature (°C): Stat. winding | 71 | 73 | |
| Rotor cage | 82 | 85 | |
| Joule losses (W) Stat. winding | 272 | 260 | |
| Rotor cage | 113 | 128 | |
| Iron losses (W) | 206 | 209 | |
| Starting Current/Rated Current | 6.9 | 7.0 | |
| Starting Torque/Rated Torque | 2.2 | 2.2 | |
| Max Torque/Rated Torque | 3.5 | 3.6 | |
| Weight (kg); Gross iron | 69.1 | 62.6 | |
| Stator winding | 11.0 | 8.30 | |
| Rotor cage | 3.49 | 5.16 | |
| Active Material Cost (∈): | | | Δcost (∈) |
| Scenario_1 | 135.8 | 134.6 | **- 1.20** |
| Scenario_2 | 146.9 | 147.5 | + 0.60 |
| Scenario_3 | 158.1 | 160.5 | + 2.4 |

**Comments**

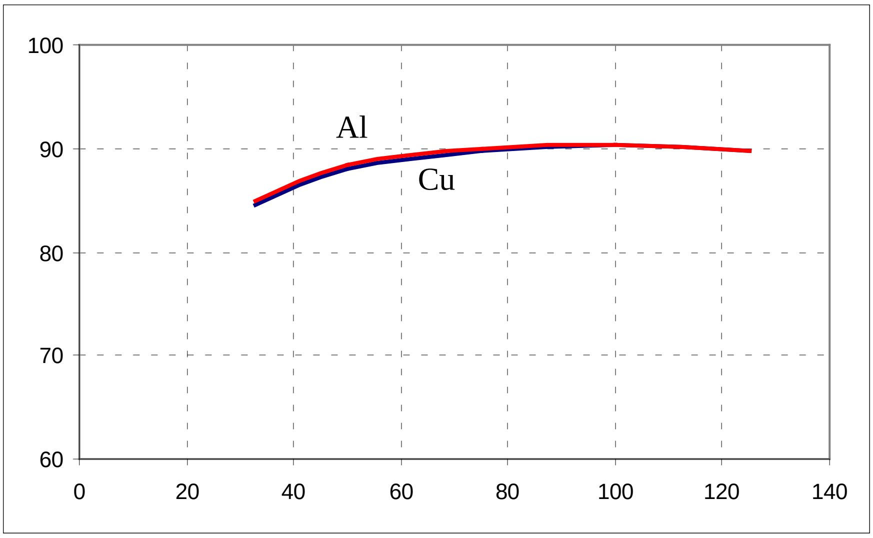
Both designs have the same rated efficiency (90.4) and the performance are quite similar and consistent with typical performance of a commercial Al motor of the same size.
Difficulty to go beyond IE3 with Al technology because of limitations in housing and inability to fit with standard dimensions for the small and big company (see Annex I). The outer stator diameter of the Al cage needs a new (out of line) and more expansive housing (*).
The Cu motor can use commercial housings produced by small and big company (Annex I) 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 we take into account the cost of the new housing for the Al motor, the Cu motor is certainly more convenient (excluded the cost of die-casting process)..
The following figures show the “Torque-Speed” and “Efficiency-Load” curves. Both designs have flat efficiency curves in the range 75%÷100%.

**7.5 kW, 4 pole**

Torque (Nm) – Speed (rpm)




Efficiency % - Load %



**15 kW, 4 pole (160 L) – 400 V, 50 Hz, TEFC, S1 - double-cage**

| η = 92.1% (IE3) | **Al** | **Cu** |
|---|---|---|
| Electrical steel | 330-50 AP | 330-50 AP |
| Stack length (mm) | 225 | 215 |
| Outer stator diameter (mm) | 255 | 245 |
| N. 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 |
| Phase current (A) | 28.1 | 27.4 |
| Speed (rpm) | 1465 | 1474 |
| Power factor | 0.84 | 0.86 |
| Temperature (°C): Stat. winding | 70 | 73 |
| Rotor cage | 82 | 84 |
| Joule losses (W) Stat. winding | 422 | 544 |
| Rotor cage | 367 | 270 |
| Iron losses (W) | 349 | 326 |
| Starting Current/Rated Current | 6.7 | 6.8 |
| Starting Torque/Rated Torque | 3.4 | 3.2 |
| Max Torque/Rated Torque | 3.7 | 3.7 |
| Weight (kg); Gross iron | 109 | 96.4 |
| Stator winding | 13.75 | 9.22 |
| Rotor cage | 2.58 | 6.36 |
| Active Material Cost (€): | | |
| Scenario_1 | 187.2 | 177.3 |
| Scenario_2 | 201.1 | 192.2 |
| Scenario_3 | 215.1 | 207.2 |

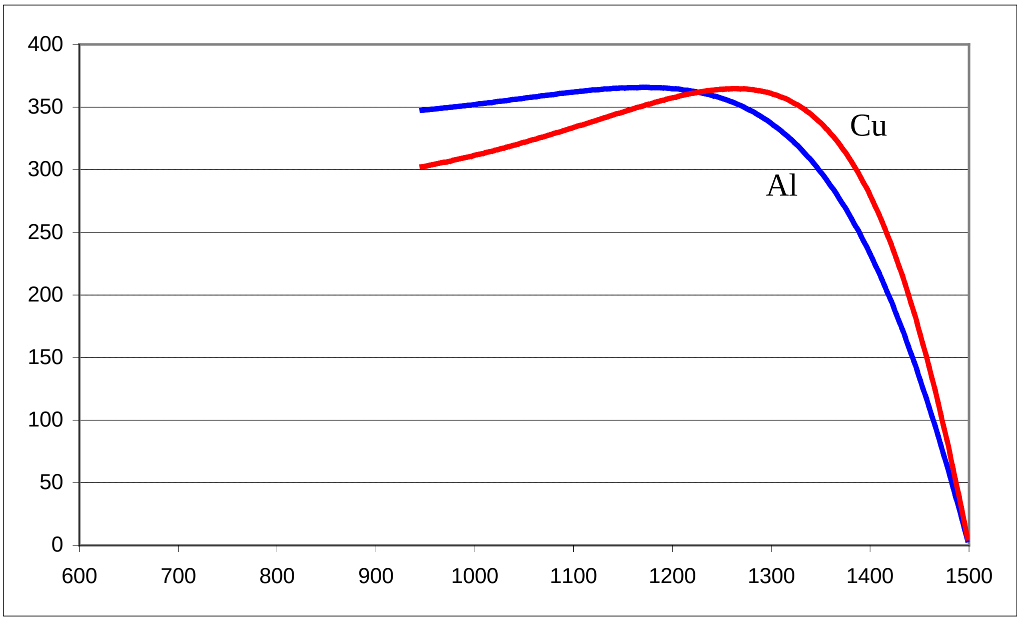
| Δcost (€) |
|---|
| **- 9.9** |
| **- 8.9** |
| **- 7.9** |

**Comments**

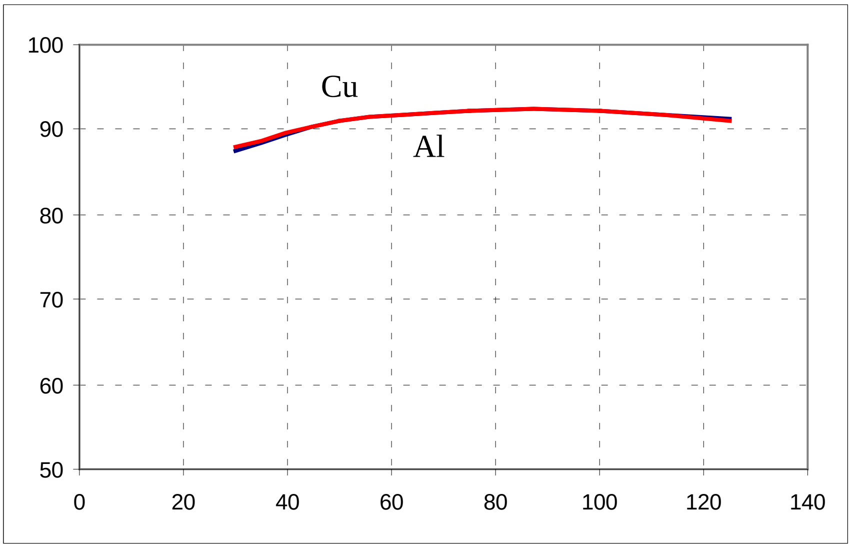
Both designs have the same rated efficiency (92.1%) and the performance are quite similar and consistent with typical performance of a commercial Al motor of the same size.
Both designs can use commercial housings produced by small and big company (see Annex I).
The Cu motor presents an advantage in 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 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).
The following figures show the "Torque-Speed" and "Efficiency-Load" curves. Both designs present good efficiencies also at partial load and a flat efficiency curves in the range 75%÷100%.

**15 kW, 4 pole**

Torque (Nm) – Speed (rpm)




Efficiency % - Load %



**22 kW, 2 pole (180 M) – 400 V, Δ, 50 Hz, TEFC, S1 - double-cage**

| η = 92.7% (IE3) | **Al** | **Cu** |
|---|---|---|
| Electrical steel | 330-50 AP | 330-50 AP |
| Stack length (mm) | 215 | 205 |
| Outer stator diameter (mm) | 290 | 285 |
| N. 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 |
| Phase current (A) | 20.3 | 20.2 |
| Speed (rpm) | 2933 | 2939 |
| Power factor | 0.93 | 0.93 |
| Temperature (°C): Stat. winding | 60 | 62 |
| Rotor cage | 70 | 72 |
| Joule losses (W) Stat. winding | 414 | 510 |
| Rotor cage | 516 | 467 |
| Iron losses (W) | 390 | 360 |
| Starting Current/Rated Current | 9.0 | 9.0 |
| Starting Torque/Rated Torque | 4.4 | 4.2 |
| Max Torque/Rated Torque | 4.8 | 4.7 |
| Weight (kg); Gross iron | 135 | 124 |
| Stator winding | 17.37 | 12.69 |
| Rotor cage | 2.45 | 5.18 |
| Active Material Cost (€): | | |
| Scenario_1 | 232.6 | 217.2 |
| Scenario_2 | 250.1 | 234.6 |
| Scenario_3 | 267.9 | 252.1 |

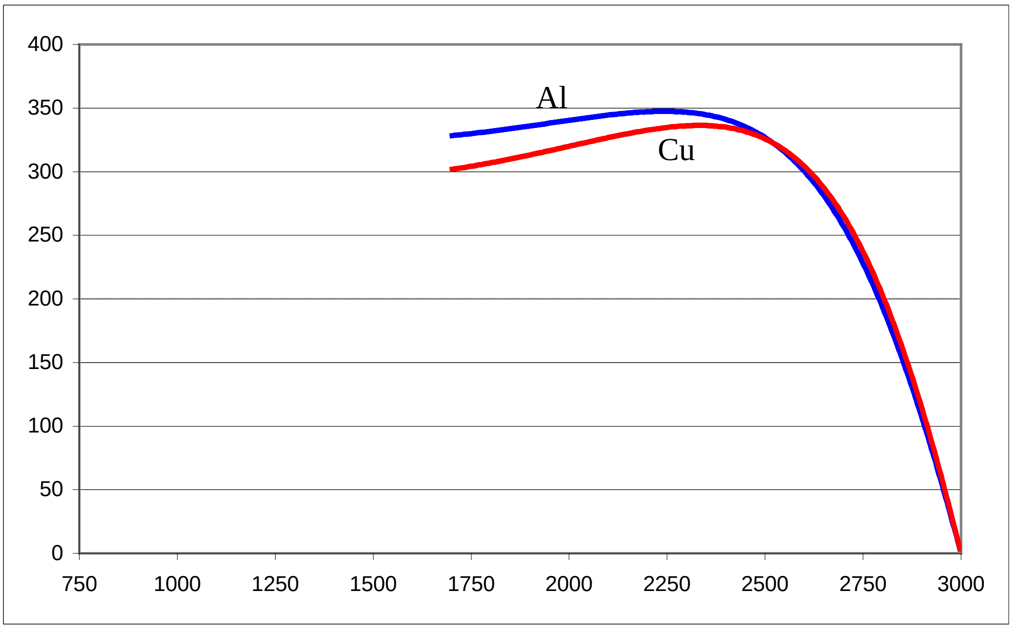
Δcost (€)
- **15.4**
- **15.5**
- **15.8**

**Comments**

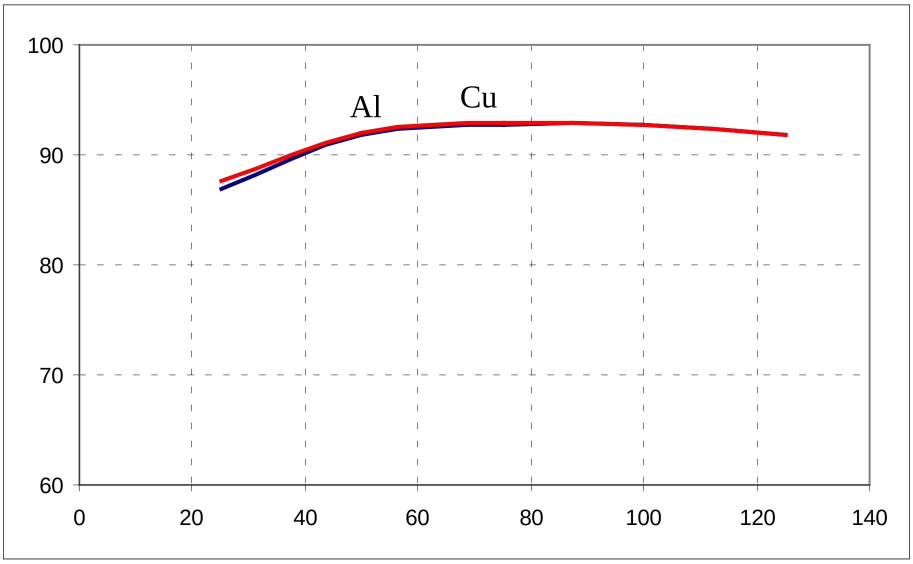
Both designs have the same rated efficiency (92.7%) and the performance are quite similar and consistent with typical performance of a commercial Al motor of the same size.
The outer stator diameters of both designs allow to use commercial housings produced by small and big company (see Annex I).
The 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):
The following figures show the “Torque-Speed” and “Efficiency-Load” curves. Both designs present good efficiencies also at partial load and a flat efficiency curves in the range 75%÷100%.

**22 kW, 2 pole**

Torque (Nm) – Speed (rpm)

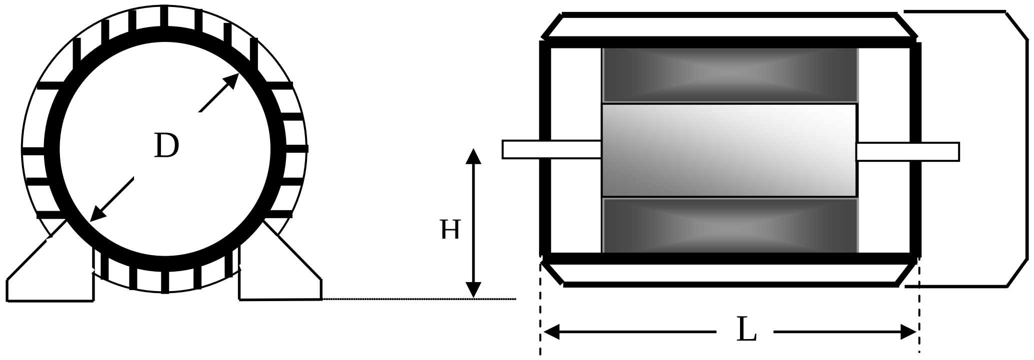



Efficiency % - Load %



# Annex 1

Dimensions of commercial housings (produced by Chinese small and big Companies)




Big Company

| Frame size H | 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 |

Small Company

| Frame size H | 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 |

# Annex II

Structure costs: Housing, Bearings, Shaft (in Euro)
(Chinese small and big Companies)

Big Company

| Frame size H | Housing | Bearings | Shaft |
|---|---|---|---|
| 90 L | 11 | 3.3 | 2.4 |
| 100 L | 16 | 4.0 | 3.3 |
| 112 M | 20 | 6.7 | 3.6 |
| 132 M | 32 | 9.5 | 6.0 |
| 160 M | 46 | 12 | 11 |
| 160 L | 54 | 12 | 12 |
| 180 M | 61 | 17 | 15 |
| 180 L | 70 | 17 | 17 |
| 200 L | 94 | 20 | 21 |

Small Company

| Frame size H | Housing | Bearings | Shaft |
|---|---|---|---|
| 90 L | 20 | 7.8 | 3.5 |
| 100 L | 24 | 8.2 | 5.7 |
| 112 M | 31 | 9.2 | 5.8 |
| 132 M | 49 | 18 | 9.0 |
| 160 M | 73 | 20 | 14 |
| 160 L | 76 | 20 | 16 |
| 180 M | 91 | 41 | 20 |
| 180 L | 98 | 41 | 23 |
| 200 L | 126 | 45 | 26 |

Notes:

- The housing price includes 2 end covers and outlet box.
- The Bearing price includes 2 bearings for each motor.

# Annex III

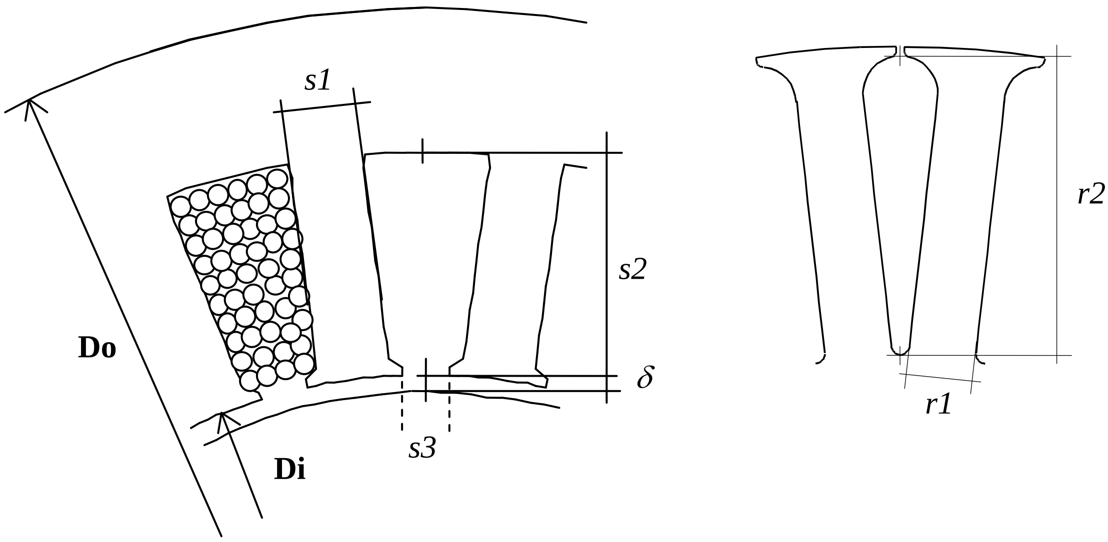
Magnetic characteristics of the "premium" steel 330-50AP (0.50 mm thickness)

50 Hz

| B (T) | H (A/m) | Losses (W/kg) |
|---|---|---|
| 0.5 | 67 | 0.42 |
| 0.6 | 75 | 0.56 |
| 0.7 | 83 | 0.73 |
| 0.8 | 93 | 0.90 |
| 0.9 | 105 | 1.10 |
| **1.0** | **121** | **1.31** |
| 1.1 | 143 | 1.55 |
| 1.2 | 178 | 1.80 |
| 1.3 | 242 | 2.09 |
| 1.4 | 402 | 2.45 |
| **1.5** | **946** | **2.86** |
| 1.6 | 2470 | 3.27 |
| 1.7 | 5281 | 3.71 |
| 1.8 | 9776 | 4.14 |

# Annex IV

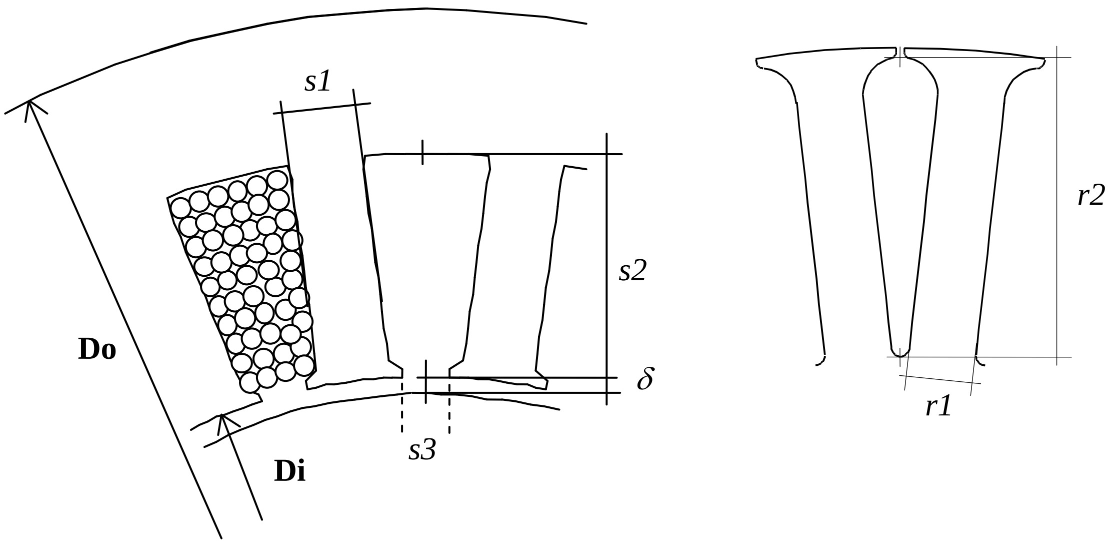
1.5 kW, 6 pole – Design data




(in mm)

| | Aluminum | Copper |
|---|---|---|
| N. stator slots | 54 | |
| N. rotor slots | 40 | |
| Stack length | 130 | 126 |
| Outer stator diameter Do | 160 | 152 |
| Inner stator diameter Di | 95 | 93 |
| Shaft diameter | 34 | |
| Air-gap length δ | 0.30 | |
| N. turns per phase | 342 | 342 |
| Wire size | 0.830 $mm^2$ | 0.688 $mm^2$ |
| Stator tooth width s1 | 2.80 | 2.98 |
| Stator slot heigh s2 | 21.2 | 19.7 |
| Stator slot opening s3 | 2.4 | |
| Rotor tooth width r1 | 3.28 | 3.67 |
| Rotor slot heigh r2 | 23.0 | 21.51 |
| Rotor skewing (in rotor slot pitch) | 1.8 | |
| Stator slor area | 81.9 $mm^2$ | 68.5 $mm^2$ |
| Rotor slor area | 50.2 $mm^2$ | 38.0 $mm^2$ |

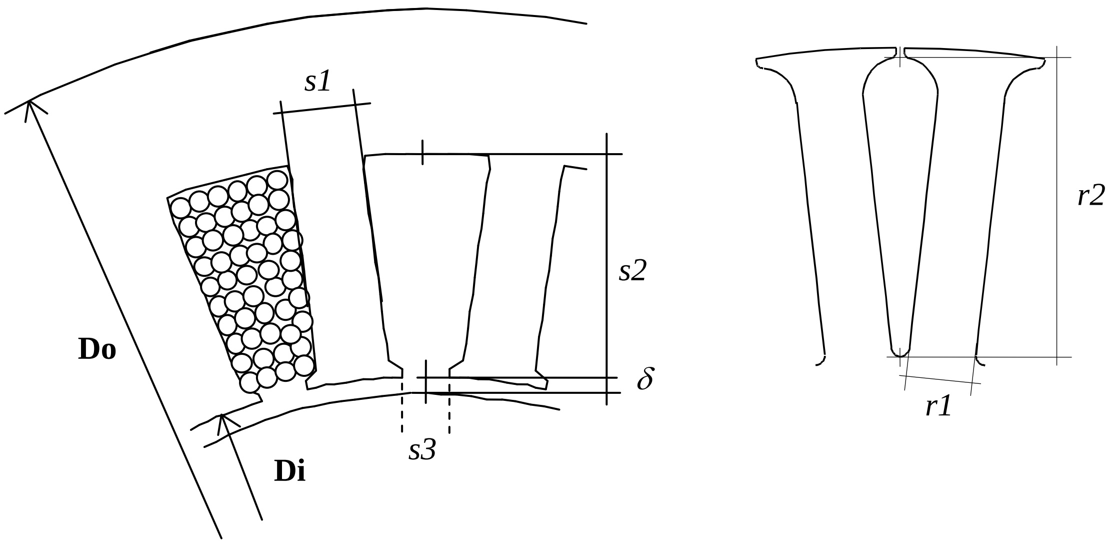
3 kW, 4 pole – Design data




(in mm)

| | Aluminum | Copper |
|---|---|---|
| N. stator slots | 36 | |
| N. rotor slots | 28 | |
| Stack length | 155 | 150 |
| Outer stator diameter Do | 165 | 160 |
| Inner stator diameter Di | 98 | 93 |
| Shaft diameter | 34 | |
| Air-gap length δ | 0.30 | |
| N. turns per phase | 186 | 186 |
| Wire size | 1.645 $mm^2$ | 1.311 $mm^2$ |
| Stator tooth width s1 | 3.60 | 3.85 |
| Stator slot heigh s2 | 19.7 | 18.2 |
| Stator slot opening s3 | 2.4 | |
| Rotor tooth width r1 | 3.65 | 4.60 |
| Rotor slot heigh r2 | 21.0 | 17.0 |
| Rotor skewing (in rotor slot pitch) | 1.8 | |
| Stator slor area | 125 $mm^2$ | 102 $mm^2$ |
| Rotor slor area | 93.8 $mm^2$ | 58.6 $mm^2$ |

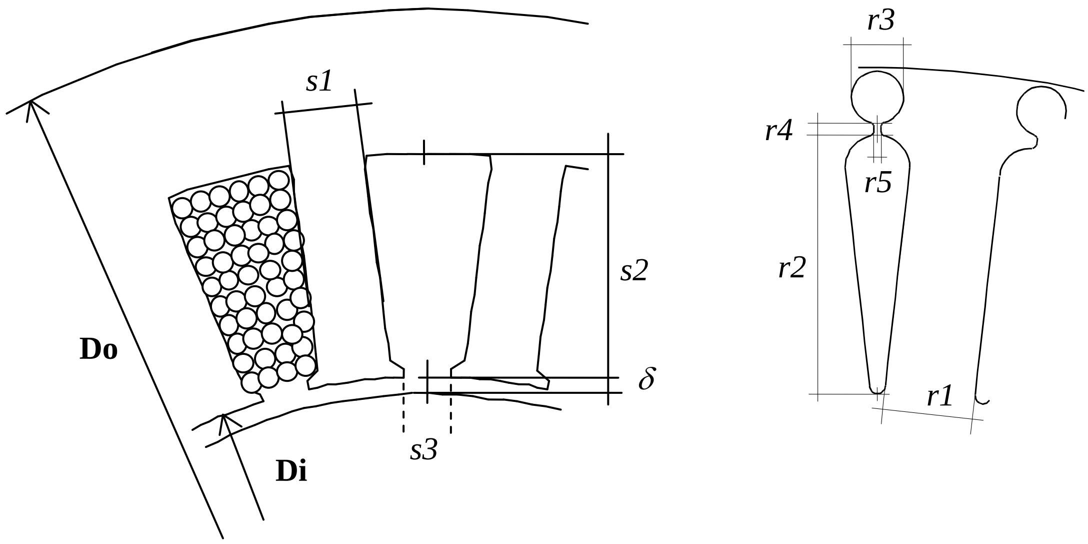
7.5 kW, 4 pole – Design data




(in mm)

| | Aluminum | Copper |
|---|---|---|
| N. stator slots | 36 | |
| N. rotor slots | 46 | |
| Stack length | 200 | 190 |
| Outer stator diameter Do | 215 | 210 |
| Inner stator diameter Di | 130 | 124 |
| Shaft diameter | 44 | |
| Air-gap length δ | 0.40 | |
| N. turns per phase | 114 | 108 |
| Wire size | 4.80 $mm^2$ | 4.15 $mm^2$ |
| Stator tooth width s1 | 4.50 | 4.90 |
| Stator slot heigh s2 | 23.9 | 22.2 |
| Stator slot opening s3 | 2.9 | |
| Rotor tooth width r1 | 2.80 | 4.0 |
| Rotor slot heigh r2 | 32.0 | 18.0 |
| Rotor skewing (in rotor slot pitch) | 2.2 | |
| Stator slor area | 205 $mm^2$ | 168 $mm^2$ |
| Rotor slor area | 115 $mm^2$ | 52.5 $mm^2$ |

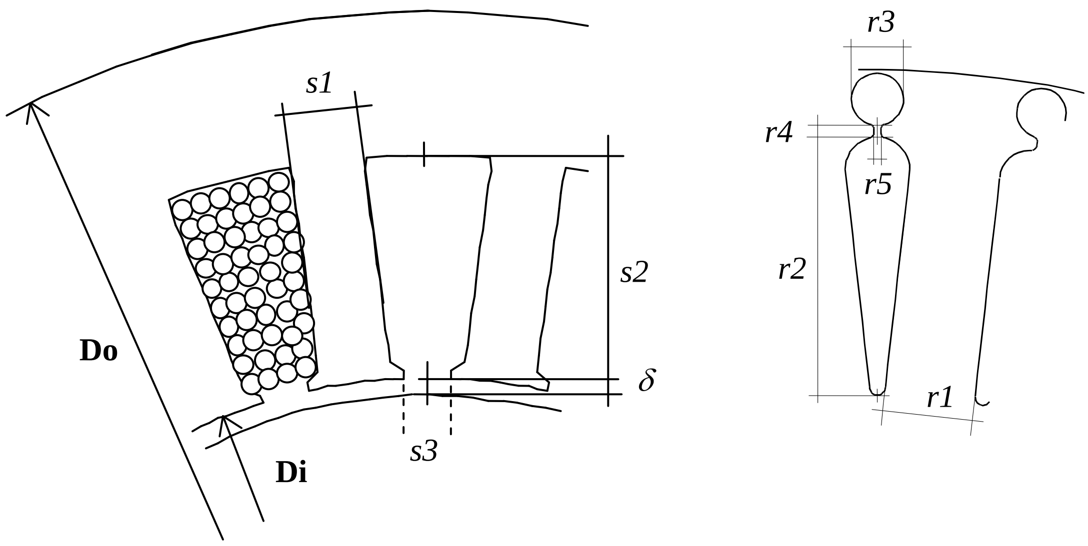
15 kW, 4 pole – Design data




(in mm)

| | Aluminum | Copper |
|---|---|---|
| N. stator slots | 36 | |
| N. rotor slots | 46 | |
| Stack length | 225 | 215 |
| Outer stator diameter Do | 255 | 245 |
| Inner stator diameter Di | 159 | 155 |
| Shaft diameter | 60 | |
| Air-gap length δ | 0.40 | |
| N. turns per phase | 78 | 78 |
| Wire size | 7.90 $mm^2$ | 5.60 $mm^2$ |
| Stator tooth width s1 | 6.50 | 6.70 |
| Stator slot heigh s2 | 25.94 | 22.80 |
| Stator slot opening s3 | 2.55 | |
| Inner rotor tooth width r1 | 5.40 | 5.40 |
| Inner rotor slot depth r2 | 16.38 | 10.0 |
| Outer rotor slot width r3 | 5.18 | 4.96 |
| Inner rotor slot opening depth r4 | 6.50 | 5.80 |
| Inner rotor slot opening width r5 | 1.60 | 1.60 |
| Rotor skewing (in rotor slot pitch) | 2.2 | |
| Stator slor area | 228 $mm^2$ | 182 $mm^2$ |
| Rotor slor area | 83 $mm^2$ | 65 $mm^2$ |

22 kW, 2 pole – Design data




(in mm)

| | Aluminum | Copper |
|---|---|---|
| N. stator slots | 36 | |
| N. rotor slots | 30 | |
| Stack length | 215 | 205 |
| Outer stator diameter Do | 290 | 285 |
| Inner stator diameter Di | 165 | 160 |
| Shaft diameter | 50 | |
| Air-gap length δ | 0.60 | |
| N. turns per phase | 84 | 84 |
| Wire size | 6.36 $mm^2$ | 4.80 $mm^2$ |
| Stator tooth width s1 | 6.5 | 6.0 |
| Stator slot heigh s2 | 22.5 | 19.2 |
| Stator slot opening s3 | 3.0 | |
| Inner rotor tooth width r1 | 8.0 | 7.8 |
| Inner rotor slot depth r2 | 17.70 | 10.0 |
| Outer rotor slot width r3 | 5.46 | 5.0 |
| Inner rotor slot opening depth r4 | 4.0 | 4.0 |
| Inner rotor slot opening width r5 | 1.6 | 1.6 |
| Rotor skewing (in rotor slot pitch) | 2.6 | |
| Stator slor area | 200 $mm^2$ | 164 $mm^2$ |
| Rotor slor area | 122 $mm^2$ | 83 $mm^2$ |

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