



## THREE-PHASE INDUCTION MOTOR EFFICIENCY IMPROVEMENTS WITH DIE-CAST COPPER ROTOR CAGE AND PREMIUM STEEL

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### Abstract

The paper presents the results of a research project whose aim was the efficiency improvement in industrial three-phase induction motors, making use die cast copper rotor cage and premium electrical steel. The study concerns with industrial low voltage three-phase induction motors, 4 pole, 50 Hz, 400 V, TEFC, in the 0.75÷22 kW power range. The results are related to the first step of the project, when a premium steel and copper rotor cage have been used instead of standard steel and aluminium cage.

### 1. - INTRODUCTION

The European Scheme to designate energy efficiency classes for low voltage AC motors has been in operation since 1999 as 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). It enables all OEMs (Original Equipment Manufacturers) and the other customers and users of induction motors to have a simple appreciation of the efficiency of this component. This agreement should stimulate the manufacturers in the development of new lines of high efficiency motors that require an accurate motor design, the adoption of new materials (e.g. premium steel) and innovative technologies (e.g. copper rotor cage die-casting).

### 2. – INNOVATIVE TECHNOLOGIES AND MATERIALS

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 loss. 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 lines 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 aluminium would result in attractive improvements in motor energy efficiency [3], [4].



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 aluminium the conductor of choice in all but the largest frame motors. High-pressure die-casting of aluminium squirrel-cage rotors is a mature process performed by most of motor manufacturers. The melting point for aluminium alloys is in the 670 °C range and the material used for the rotor's die-casting mould is not highly stressed at these temperatures. Die life can be in the hundreds of thousands of rotors depending on die complexity.

The most commonly used method to manufacture rotors with copper conductors is referred to as "welded assembly construction". Such fabrication involves intensive hand labour and therefore is expensive [5], [6]. Up today, only small numbers of very large motors utilize copper in the rotors by this mechanical fabrication.

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: it melts at 1083 °C. Although copper die-cast rotor construction is a much newer technology, current state of the art technology makes it possible to die cast similarly sized rotors in copper as can be cast in aluminium. The integrity and reliability of copper die-cast is just as good as in aluminium die-cast. The primary reason copper die-cast rotors are not commonplace yet is because it requires specialized equipment (investment) and know-how in this field.

### 3. – HIGH EFFICIENCY MOTOR RESEARCH

The authors have deeply investigated the use of copper rotor cage in combination of high quality electrical steels.

This activity falls in a research program partially supported by the Italian Ministry of Education, University and Research.

Together with the University of L'Aquila, three important Companies have been involved in the project:

- 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 Valmeu), 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 is 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 procedures and design strategies;
- to verify the actual efficiency improvements;
- to verify the arrangement of the motors respect to the European Classification Scheme (EC/CEMEP).

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.

The proposed research program has been subdivided in four steps, according to the design strategies used to study and made higher efficiency motors.

The cheapest strategy uses existing designs and tooling to produce more efficient motors and concerns the use of improved magnetic materials ("premium steel") and copper rotor cage: in this case the stator and rotor slots dimensions and the inner and outside stator diameter are unchanged.

The second strategy concerns the change of the stack length and the stator winding. More expensive strategy foresees also the change of lamination (stator and rotor slots dimensions) and this requires a renewal of the lamination tooling even if the inner and outside stator diameters are unchanged. The most expensive design strategy requires to change all motor dimensions, inner and outer stator diameters included. In this case a final option is the use of a larger frame size with modification of the existing housing and maintaining the shaft height.

The paper presents the results related to the first step of the project, when "premium steel" and copper rotor cage



have been used instead of standard steel and aluminium cage.

#### 4. – DEVELOPMENT OF THE PROJECT

Three power sizes have been considered in the range 0.75÷22 kW: 3, 7.5 and 15 kW, 4 pole, 50 Hz, 400 V, TEFC, single-cage rotor. The minimum nominal efficiencies for these motors according to the EC/CEMEP standard are show in Table 1.

Table 1- EC/CEMEP minimum efficiency standards for 4-pole motors

kW	Eff2	Eff1
3	82.6	87.4
7.5	87.0	90.1
15	89.4	91.8

Three standard motors have been chosen as “reference motors”: they are commercial motors with aluminium rotor cage and standard electrical steel; two motors (3 and 7.5 kW) belong to the low efficiency class Eff3, the third (15 kW) is in the Eff2 class .

#### 4.1 – Choice of the electrical steel

First of all, the most suitable electrical steel has been chosen. This choice has been done with reference to the material performance (loss/permeability) and hardness (HRB).

The standard electrical steel used in the reference motors construction is labelled 8050.

The following alternative electrical steels have been considered:

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

Their main characteristics are summarized in Fig. 1.

The influence of 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.

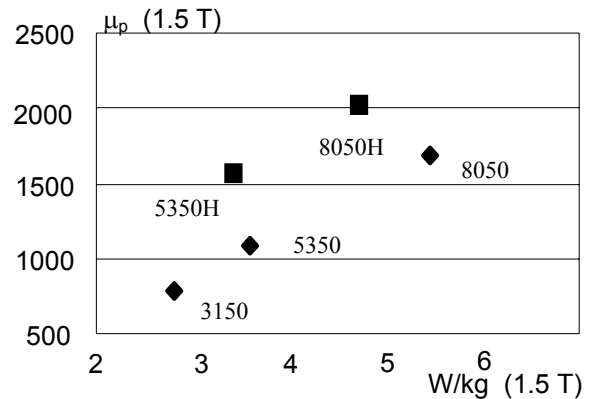


Fig. 1 - Permeability and loss at 1.5 T of the considered steels

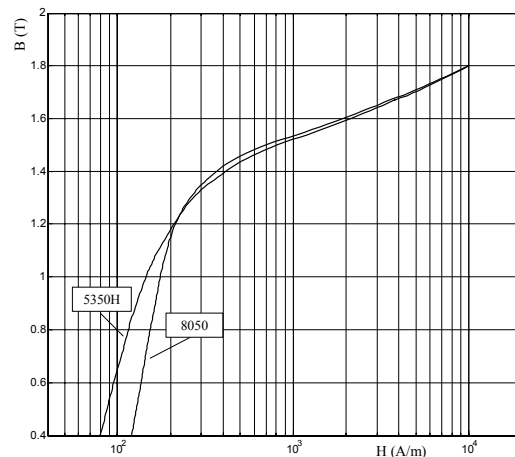


Fig. 2 – B-H curves of 8050 and 5350H

On the base of these preliminary analyses and the material hardness, the high permeability steel 5350H has been chosen. Electrical steel 5350H represents a very good compromise between specific loss and permeability. In fact, frequently better magnetic materials from the losses point of view have worse permeability (in Fig. 1 see electrical steels 3150 and 5350 in comparison with 8050). As a consequence, the increases 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 respect to 5.5 of the 8050) with high permeability (better than 8050 under 1.2 T, a little bit worse over, Fig. 2).

#### 4.2 –Tested motors

The results of this preliminary analysis have allowed to start the next step concerning the construction of the prototypes according to the following combinations, for each power size:

- a) standard steel 8050 and aluminium cage (“reference” commercial motor);
- b) standard steel 8050 and copper cage;
- c) premium steel 5350H and copper cage.

Comparisons between motors a) and b) allow to evaluate the improvements achievable with copper rotors only. Motors c) results show the effects of the premium steel respect to the standard steel (in comparison with motors b) and the improvements respect to the standard motor (in comparison with motors a)).

In order to obtain an accurate comparison between motors a) and b), the same wound stator with electrical steel 8050 was used for each size to test motors a) and b). Table 2 presents the main dimensions and weights of the tested motors (reference motors and new prototypes) while Fig. 3 shows a view of the copper rotors.

Table 2 - Tested motors main dimensions and weights

	3 kW	7.5 kW	15 kW
Stack length (mm)	130	160	220
Outer stator diameter (mm)	152	200	250
Inner stator diameter (mm)	90	127	160
Stator winding weight (kg)	2.45	5.40	14.5
Rotor cage weight (kg)			
Al	0.74	1.45	3.0
Cu	2.43	4.77	9.8
Gross iron (kg)	22.4	47.8	103



Fig. 3 – View of copper rotors for the considered motors

#### 5. – MOTOR PERFORMANCE TEST RESULTS

##### 5.1 – Standard test methods

Worldwide, there exist several standards for testing electric machinery. For induction motors, the three most important ones are:

- IEEE Standard 112, currently in use in USA and some parts of the world;
- JEC 37, in Japan;
- IEC 34-2, in use in most European countries.

In Canada, the Standard specified in the Energy Efficiency Regulations is : “Method for determining energy performance of three-phase induction motors” CSA C390-98. This Standard is equivalent to the well recognized Standard IEEE 112-1996, Method B: “Test Procedure for Polyphase Induction Motors and Generators”. IEEE and CSA 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.

In order to evaluate the copper rotor and premium steel effects on each loss category, a loss segregation method is required. Then, the experimental results presented in the paper refer to the Standard CSA C390-98.

##### 5.2 - Test results

Table 3 shows the CSA test results of the 3 kW tested motors.

The substitution of copper for aluminium directly achieved 75% of the total savings in rotor losses and was indirectly involved in saving the other 25% in stator resistance losses. Rotor  $I^2R$  losses were reduced by 46% and the efficiency resulted 2.1 percentage points higher; as expected, iron and F&W losses were constant.

Premium steel as magnetic material was involved in gaining about half point in efficiency. Saving in iron losses is partially compensated by the stator winding losses increasing, as a consequence of the magnetizing current increasing.

In case of 3 kW motor, copper rotor and premium steel adoptions have allowed to move motors in the Eff2 class.

Table 4 shows the other motors main performance.



Stator winding temperature rise  $\Delta T_{sw}$  was reduced by 4°C with copper cage and by 16°C with premium steel and copper cage compared with the commercial motor. That is a very important feature because temperature rise is significant in the life expectancy of the motor.

Table 3 – CSA C390-98 Efficiency and Loss Segregation Test Results. 3 kW motor.

3 kW	Al 8050	Cu 8050	Cu 5350H
$\eta$ %	82.0	84.1	84.5
$\Sigma$ losses (W)	655	563	545
Stator wind.	351	327	337
Rotor cage	153	83	83
Iron	117	124	94
SLL	13	13	8
F&W	21	16	23

Table 4 – 3 kW motors performance

3 kW	Al 8050	Cu 8050	Cu 5350H
I (A)	6.86	6.70	6.73
$\Delta T_{sw}$ (°C)	87	83	71
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

Power factor was constant while slip was significantly lower for both copper motors. In fact, due to the difference in conductivity between the two materials, copper motor generates a higher torque at same slip than the aluminium motor one: copper motor does not slow down much under load. This implies a very good response on variable frequency drives, but potential problems on variable torque loads like fans and pumps. Copper motors exhibited 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 aluminium. However, with further design adjustments (redesign of the stator and rotor laminations to take advantage of the increased conductivity of copper rotor bars) these negative torque factors could be corrected [3].

Tests of 7.5 kW motors (Table 5 and Table 6) confirm what found for the smaller motors. Rotor losses were 50% lower in the copper rotors and the overall losses were reduced by 23% and 26% (in case of copper rotor and premium steel adoption). Stator winding temperature rise  $\Delta T_{sw}$  was reduced by 18°C with copper cage and by

24°C with premium steel compared with the commercial motor. Lower temperatures mean that smaller cooling fans can be used and this has a significant effect in reducing the friction and windage losses on these motors with copper rotors and premium steel.

The efficiency improvements were 3.2 and 3.9 points respectively. Nevertheless, the motors do not move in the Eff1 class, stopping in Eff2.

Table 5 – CSA C390-98 Efficiency and Loss Segregation Test Results. 7.5 kW motor.

7.5 kW	Al 8050	Cu 8050	Cu 5350H
$\eta$ %	84.2	87.4	88.1
$\Sigma$ losses (W)	1401	1077	1035
Stator wind.	466	456	423
Rotor cage	284	141	138
Iron	361	349	338
SLL	237	92	88
F&W	53	39	48

Table 6 – 7.5 kW motors performance

7.5 kW	Al 8050	Cu 8050	Cu 5350H
I (A)	15.0	15.2	14.8
$\Delta T_{sw}$ (°C)	104	86	80
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

Table 7 – CSA C390-98 Efficiency and Loss Segregation Test Results. 15 kW motor.

15 kW	Al 8050	Cu 8050	Cu 5350H
$\eta$ %	90.1	91.0	91.9
$\Sigma$ losses (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

Table 8 – 15 kW motors performance

15 kW	Al 8050	Cu 8050	Cu 5350H
I (A)	28.3	28.3	28.6
$\Delta T_{sw}$ (°C)	62	58	58
Power Factor	0.84	0.83	0.81
Slip %	2.47	1.5	1.31





Tab. 7 and Tab. 8 show the 15 kW motors test results. In this case copper rotors yielded an average 44% reduction in measured rotor losses while the overall losses were reduced by 10%. With premium steel and copper rotor, 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.

**5.3 – Comparison with literature data**

Table 9 summarises the overall motor efficiencies and rotor losses reductions experimentally observed in motors fitted with copper rotors where comparisons with aluminium are reported in literature including the data of this study. The range 3÷18.8 kW, 4 poles motors is covered. The rotor loss reduction is in the range 40÷50%. The efficiency gain is between 1 and 3 points.

Table 9 - Overall motor efficiencies and rotor loss reductions via copper rotors. Data from this study and the literature

kW	Hz	Efficiency		Diff.	Rotor Loss Reduction %	Reference
		Al	Cu			
3	60	83.2	86.4	3.2	58	4
3	50	82.0	84.1	2.1	46	This study
7.5	50	84.2	87.4	3.2	50	This study
11.2	60	89.5	90.7	1.2	40	4
15	50	90.1	91.0	0.9	44	This study
18.8	60	90.9	92.5	1.6	40	4

**6. – 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. Three standard motors have been chosen as “reference motors”: two motors (3 and 7.5 kW) belong to the low efficiency class Eff3, the third (15 kW) is in the Eff2 class.

The substitution of copper for aluminium has allowed to move the 3 and 7.5 kW motors in the Eff2 class. The efficiency improvements are not uniform for all the sizes and vary from 0.9 points for the 15 kW to 3.2 points for the 7.5 kW. For the 15 kW it is interesting to remark that the tolerance on the new efficiency could classify this motor like as Eff1.

The use of 5350H electrical steel (premium steel) improves efficiencies of 0.4, 0.7 and 0.9 points from smaller to larger motors. However, premium steel and copper rotor do not give rise any further movement (from Eff2) for the 3 kW and 7.5 kW, while the 15 kW reaches the Eff1 class (without tolerance).

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