eemods '11 conference

energy efficiency in motor driven systems

Technical-economical analysis of the use of die-cast copper rotor in normalized induction motors

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Summary

- Introduction
- Aluminum x Copper Melting - Physical Aspects
- Aluminum x Copper Die Casting - Technological Aspects
- Technical-Economical Analysis of Squirrel Cage Motors
- Conclusions

Introduction

- Aluminum cage → Historically used in induction motors below 500 kW

- Increasing energy savings + CO_2 emission reduction concerns → More efficient products

- Copper cage
  - 10-15% reduction in motor losses
  - Raw material total cost reduction
  - Greater complexity of die casting

Introduction

- Aluminum cage → Historically used in induction motors below 500 kW

- Increasing energy savings + CO_2 emission reduction concerns → More efficient products

- Copper cage
  - 10-15% reduction in motor losses
  - Raw material total cost reduction (?)
  - Greater complexity of die casting (⇧$)

Copper cage x Aluminum cage

Asserted advantage	Verification
▪ Reduction in motor losses around 10-15% ▪ Reduction in rotor Joule losses up to 40% ▪ Motor efficiency increase	Simple replacement of die cast Al for molten Cu in a standard induction motor design, without any further changes in the original design parameters
▪ Reduction in the total cost of raw materials for motors presenting same efficiency levels	New specifically optimized motor designs for the use of the material in question (Cu x Al) in the rotor cage in each case

Evaluation method

- **Analytical calculations of industrial 3Φ induction motors**
    - 0.75 kW – 4 p – 400 V – 50 Hz – 80 frame size
    - 4 kW – 4 p – 400 V – 50 Hz – 112M frame size
    - 15 kW – 4 p – 400 V – 50 Hz – 160L frame size
- **Efficiency classes from IE-code**
- **Purely sinusoidal supply**

Melting physical aspects

Metal	Melting temperature	Injection temperature *
Aluminum	≈ 660 °C	≈ 800 °C
Copper	≈ 1083 °C	≈ 1300 °C

* Slightly higher than the melting temperature, in order to guarantee the good quality of the injection (adequate filling of the rotor bars and short circuit rings)

Copper handling difficulties

- **Higher temperatures than for Al die casting**
  - Higher stresses in the whole injection tooling set
  - Special materials required for the production machinery
- **High oxidation rate**
  - No formation of external oxide skin film
  - Susceptibility to external contamination
  - Copper oxide reduces electrical conductivity
  - Cold champers (liquid-state storage) cannot be used

Copper handling difficulties

- **Higher temperatures than for Al die casting**
  - Higher stresses in the whole injection tooling set
  - Special materials required for the production machinery
- **High oxidation rate** **(=Al)**
  - No formation of external oxide skin film **(≠ Al)**
  - Susceptibility to external contamination **(≠ Al)**
  - Copper oxide reduces electrical conductivity **(= Al)**
  - Cold champers (liquid-state storage) cannot be used **(≠ Al)**

Die casting technological aspects

Metal	Number of shots *	Mold lifetime *
Aluminum	≈ 50 000	100%
Copper	≈ 600	≈ 1%

* For conventional tooling materials (H13 quality steel)

Copper die casting difficulties

- **Prevention methods against molten copper oxidation**
  - Addition of O_2 absorbers reduces Cu purity grade (⇧ Ω.m)
- **Mold preheating necessary to avoid thermal shock**
  - Without preheating machinery cracks may appear after 20 shots
  - Uniform preheating required to avoid tooling deformation
- **Intense investigations currently going on worldwide**
  - FEA, process experiences, new materials (thermal steels), etc.
- **Straightest possible short circuit rings**
  - Longer mold lifetime

Technical-economical motor analysis

- **Evaluation of the feasibility of substituting Al for Cu as rotor cage base material in series production of IM**
  - Consideration of both technical and economical aspects
- **0.75 kW – 4 kW – 15 kW (4 poles)**
  - Sinusoidal 400 V – 50 Hz
  - IE1 – IE2 – IE3 as per IEC 60034-30
- **Two situations/analyses:**
  - Current standard motor designs
  - Specially optimized motor designs

First analysis

- **Simple replacement of Al for Cu in the rotor cages of current standard motors (originally designed for Al cage)**
  - All other parameters* of the original electromagnetic designs of the motors are kept unchanged

- **Evaluation of the reduction levels achieved in motor losses**
  - Published figures:

    10-15% reduction in global losses

    40% reduction in rotor Joule losses

* Slot geometry, airgap, stack length, stator windings, short circuit rings dimensions, etc.

1st analysis - Standard motor designs

- **IE1**
  - Losses in Watts

	0.75 kW - 80			4 kW - 112M			15 kW - 160L		
	W_Al	W_Cu	Var.	W_Al	W_Cu	Var.	W_Al	W_Cu	Var.
pj1	142	132	-7.1%	362	341	-5.7%	862	824	-4.4%
pj2	51	29	-43.7%	163	93	-42.8%	320	187	-41.7%
pt	**251**	**219**	**-12.7%**	**746**	**656**	**-12.2%**	**1 718**	**1 548**	**-9.9%**

where: pj1 = stator Joule losses
pj2 = rotor Joule losses
pt = total motor losses

1st analysis - Standard motor designs

- **IE2**
  - Losses in Watts

	0.75 kW - 80			4 kW - 112M			15 kW - 160L		
	W_Al	W_Cu	Var.	W_Al	W_Cu	Var.	W_Al	W_Cu	Var.
pj1	94	88	-6.6%	340	322	-5.4%	862	823	-4.5%
pj2	39	22	-43.8%	144	84	-41.7%	326	193	-40.9%
pt	**177**	**154**	**-13.0%**	**619**	**548**	**-11.5%**	**1 556**	**1 400**	**-10.0%**

where: pj1 = stator Joule losses
pj2 = rotor Joule losses
pt = total motor losses

1st analysis - Standard motor designs

- **IE3**
  - Losses in Watts

	0.75 kW - 80			4 kW - 112M			15 kW - 160L		
	W_Al	W_Cu	Var.	W_Al	W_Cu	Var.	W_Al	W_Cu	Var.
pj1	76	73	-4.5%	249	240	-3.4%	613	597	-2.7%
pj2	34	20	-41.3%	116	68	-41.3%	247	147	-40.6%
pt	**155**	**138**	**-11.4%**	**508**	**452**	**-11.1%**	**1 209**	**1 092**	-9.7%

where: pj1 = stator Joule losses
pj2 = rotor Joule losses
pt = total motor losses

1st analysis - Standard motor designs

- **Efficiency (%)**
  - Rated conditions of voltage, speed and load

	0.75 kW - 80		4 kW - 112M		15 kW - 160L	
	Al	Cu	Al	Cu	Al	Cu
IE1	74.9	77.4	84.3	85.9	89.7	90.6
IE2	80.9	82.9	86.6	87.9	90.6	91.5
IE3	82.8	84.5	88.7	89.8	92.5	93.2

1st analysis - Standard motor designs

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	0.75 kW - 80		4 kW - 112M		15 kW - 160L	
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1st analysis - Standard motor designs

- **Active material cost (%)**
  - London Metal Exchange quotation
  - $\$_{Cu}$ / $\$_{Al}$ = 3.5 (Nov 2010 average) *

	0.75 kW - 80		4 kW - 112M		15 kW - 160L	
	Al	Cu	Al	Cu	Al	Cu
IE1	100	137	100	132	100	135
IE2	100	134	100	132	100	132
IE3	100	133	100	131	100	130

* This ratio tend to increase, since copper is a rarer element in nature than aluminum!

Second analysis

- **Specifically optimized motor designs**
  - New motor designs specially developed to attend the original efficiency levels of the previous analysis at the lowest active material costs in each case (Al cage x Cu cage)
- **Evaluation of the relative active material costs of the differentiated motor designs (Al cage x Cu cage)**
  - Published info: the use of molten copper in the rotor cage, replacing the classical die cast aluminum, enables an overall reduction in the raw material costs.

2nd analysis - Optimized motor designs

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  - Rated conditions of voltage, speed and load

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2nd analysis - Optimized motor designs

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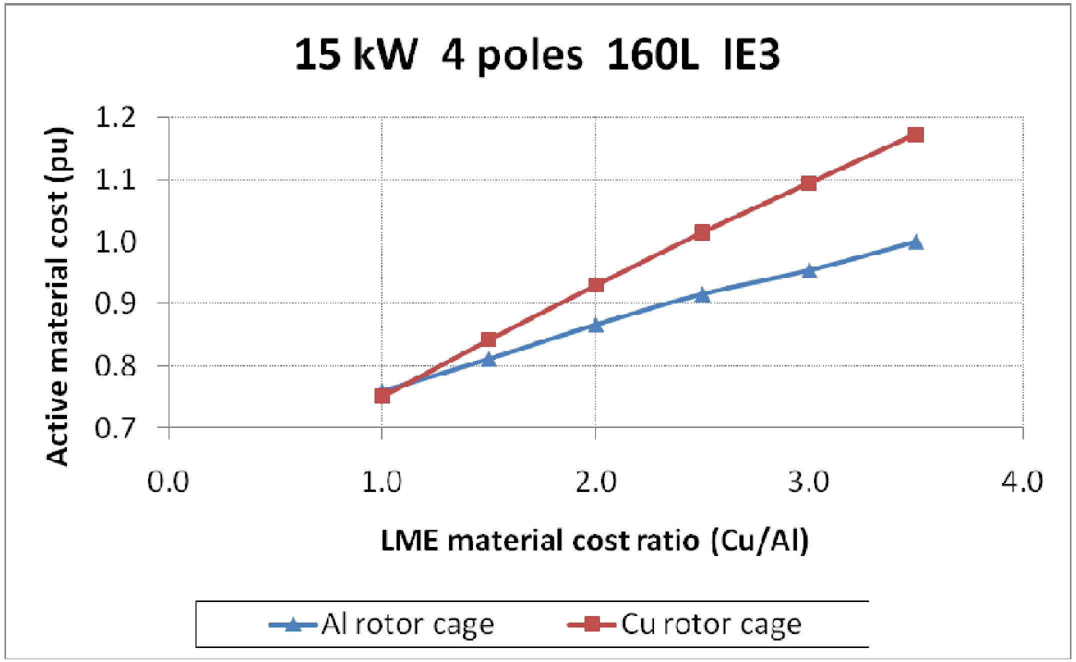
	0.75 kW - 80		4 kW - 112M		15 kW - 160L	
	Al	Cu	Al	Cu	Al	Cu
IE1	100	118	100	116	100	118
IE2	100	114	100	114	100	118
IE3	100	111	100	117	100	117

* This ratio tend to increase, since copper is a rarer element in nature than aluminum!

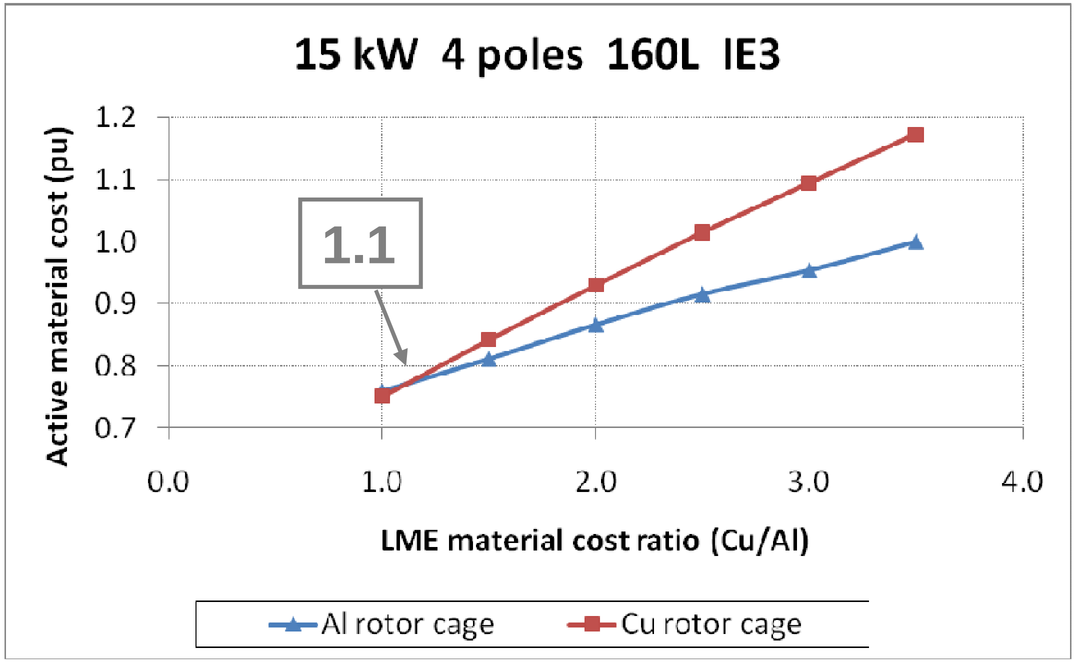
2nd analysis - Optimized motor designs

- **Economic viability study**
  - Hypothetical relative quotations for Al and Cu



2nd analysis - Optimized motor designs

- Manufacturing process issues not considered!
- Motor components other than the active materials not considered!



Conclusions

- The use of molten Cu instead of die cast Al in induction motors rotor cage has been investigated both from the technical and the economical points of view;
- With current standard (originally thought for Al cage) motor designs, the simple substitution of Al for Cu in the rotor cage may result in loss reductions up to 13% at an active material cost increase around 30%;
- With especially optimized motor designs for Cu cage presenting the same efficiency levels of current standard Al cage motors, the active material cost increase results 10 to 20% higher;
- For the use of molten Cu to become economically advantageous in the production of industrial motors, the Cu/Al quotation (price/kg) ratio in the international market should be no greater than 1.1.

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THANK YOU!

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