Optimum Designed Induction Motors with Die-Cast Aluminum and Copper Cages – – a Comparative Study.

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***Abstract*—A comparative analysis of optimal induction motor designs has been performed in the paper. A 5.5kW motor with die-cast aluminum as well as copper cages, for shaft heights of 112 mm and 132 mm, was under the scope of research All designs result from a solution of a bicriterial optimization problem with rated efficiency and active material cost as criterial functions. Other manufacturing cost components were taken into account as well. Some remarks related to design calculation models are given. Calculation results for two price levels of active materials, in 2003 and 2006 year, are presented in a graphical form. The superiority of motors with die-cast copper cages for both price levels has been shown. Some detailed conclusions related to presented results are drawn.**

***Index Terms*—bicriterial optimization, comparative analysis, designing, die-cast copper cage, induction motor.**

I. Introduction

Despite almost two times less resistivity of copper in comparison to aluminum, which suggests an obvious way to increase induction motor efficiency, there are important reasons slowing the progress in case of applying die-cast copper cage technology. The higher melting temperature of the copper and some phenomena reducing the quality of the rotor cage cast is not a serious obstacle in itself [1]. However, about two times higher price with over three times greater specific weight together with a higher copper cage technology cost are sufficient to discourage a vast majority of motor manufacturers. Advanced research works have proved that applying copper to die-cast rotor cages can be profitable [2]. Some manufacturers, e.g. SEW Eurodrives (2003) and SIEMENS (2005) in Europe, went into commercial production of induction motors with such rotor cages. Spectacular results in efficiency increasing at a cost of additional construction improvements were obtained, see http://www.copper-motor-rotor.org/pdf/SiemensNAMarketEntry.pdf.

Active material prices can influence the economical effectiveness of designed motors considerably. In the past 30 months a significant increase of material prices could be noticed, particularly for copper and aluminum, see Fig. 1. It can be interesting to look into its consequences.

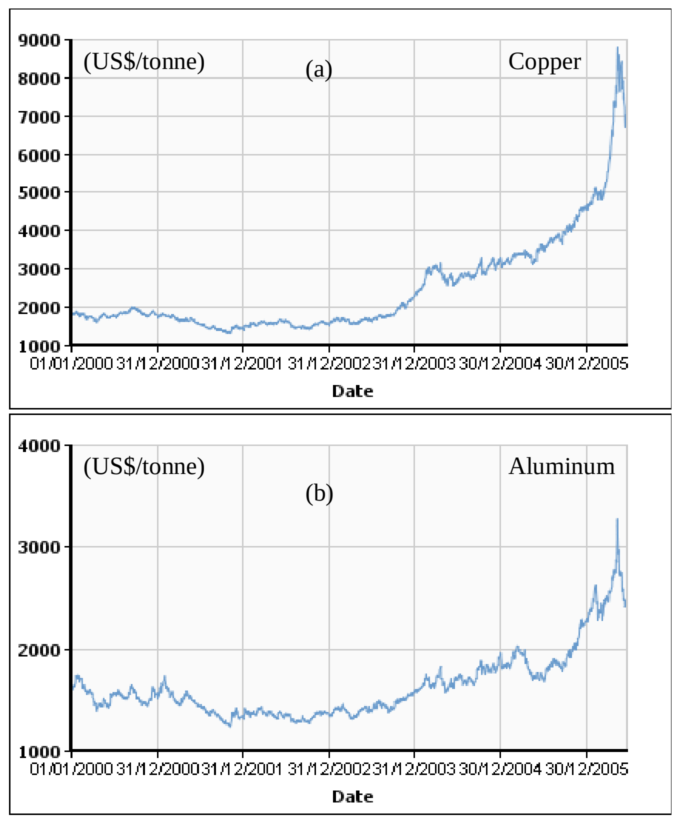

Fig. 1. A rapid change of copper and aluminum prices in the past 30 months. By courtesy of London Metal Exchange, http://www.lme.co.uk/.

Results of a comparative analysis of optimal designs of an induction motor P_N=5.5kW, U_N=3x400V, 2p=4, f_N=50Hz has been presented in the paper. Calculations were performed for active material price levels in 2003 and 2006, as well as for motor shaft heights 132 and 112. The paper is an extension of an earlier paper devoted to the subject of induction motors with die-cast copper cages [3].

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II. Design Calculation Model

In the paper an analytical model of design calculations has been used in the optimization procedure. Measurement data of a type test of a similar 7.5kW motor as well as related field calculation results have been used in model tuning and verification procedures. It was assumed that the models of a motor with copper and aluminum cages differ only in cage material parameters such as specific weight, specific resistivity, and price. Prices of the copper, aluminum and electrical sheet in 2006 have been assumed to be 4.0, 2.0 and 1.3 times higher than those in 2003 respectively.

A. *Analytical Model*

The analytical model used in the paper arises from a classical procedure of designing. For 20 years it has been successfully employed, after necessary modifications and improvements, in both research work and practical applications [4]-[6]. If a manufactured motor is optimized, measurement data are used to verify the model.

B. *Field Calculation Model*

According to common opinion, results obtained by means of a field calculation model are more credible than those arising from an analytical one. This opinion should be verified in practical applications, because analytical models of induction motors arise from a hundred-year-experience in designing and manufacturing. As an example, calculation and measurement data have been compared in the paper for no-load test, which supplies a designer with particularly useful information about machine construction. Fig. 2 presents the geometry of an existing 7.5 kW motor used in this example.

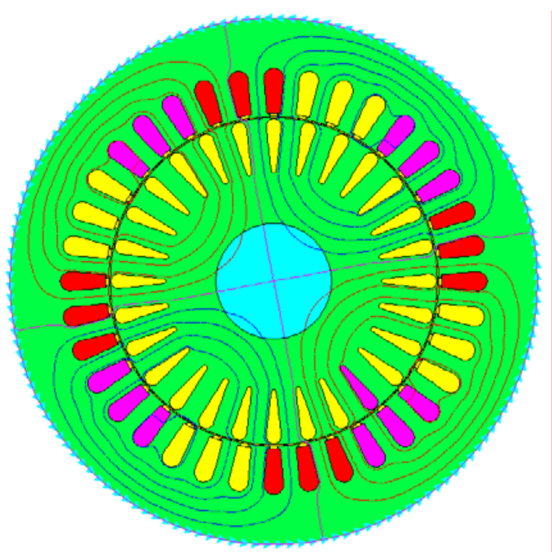

Fig. 2. Analyzed motor sheet geometry with equiflux lines at no-load.

Finite-element method for steady-state alternating current calculations is usually employed when determining machine properties. All quantities arise from a solution of a set of complex algebraic equations. In non-linear case it is a source of possible discrepancies between calculation and measurement data, and the results obtained this way should be considered with particular caution. Authors of the field calculation program strongly recommend it if iron losses are calculated [7].

Results of the analysis are presented in Fig. 3 and 4.

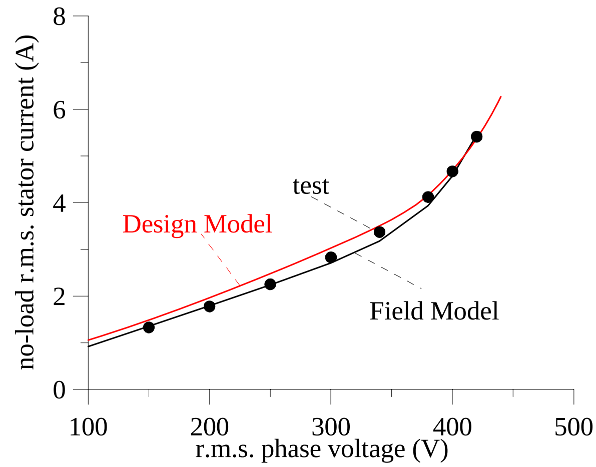

Fig. 3. No-load r.m.s. phase stator current from measurement (test), field calculations (Field Model), and analytical calculations (Design Model)

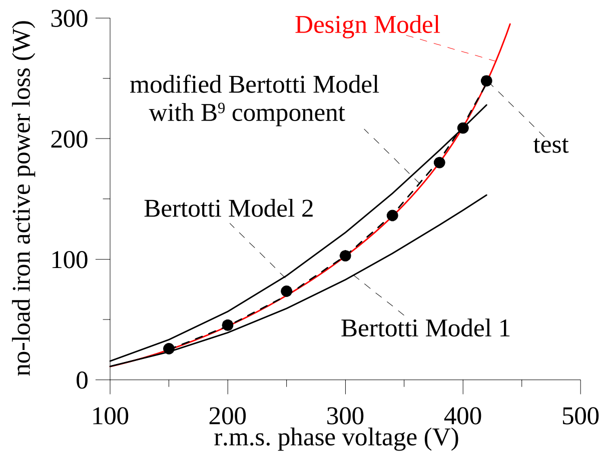

Fig. 4. No-load iron losses from measurement (test), field calculations (Bertotti Models), and analytical calculations (Design Model)

Characteristics in Fig. 3 for r.m.s. stator current, calculated by means of both the analytical and field models, are close to experimental data. Results in Fig. 4 are not so good. Iron loss calculation model available in the field program [7] is based on the theory of Bertotti [8]. Parameters of Bertotti Model 1 have been calculated to match experimental data related to specific losses of electrical sheet M-530-50A. Parameters in Bertotti Model 2 have been changed to meet a measurement point at rated voltage. Both models appeared to be a poor estimation of experimental data. Fig. 4 shows that an additional component in the iron loss formulae, which is proportional to the B_m^9, improves results considerably. The quantity B_m is the peak value of the magnetic flux density. A usefulness of similar extensions related to the B_m or supplying voltage is well known since a 50 years and was confirmed many times when matching models to no-load experimental data. The analytical design model represented in Fig. 4 by "Design Model" comprises the above mentioned additional component of the iron losses, and was used in optimization

III. Formulation of the Optimization Problem

Usually advanced improvements in motor construction accompany the die-cast copper cage in order to minimize losses as much as possible. In the majority of cases these improvements can be applied in motors with aluminum cages as well. It means it is justified to neglect their existence in a comparative analysis and this assumption has been accepted in the paper.

Motor cost components, such as labour and other structural materials (frame, shaft and bearings), are also taken into account in the end part of analysis, see Fig. 12. Data for defining corresponding cost functions have been supplied by a producer.

Another assumption was the same mechanical losses for all designs. The outer diameter of the stator stack as well as the shaft diameter was constant in optimization, although not the same for motors with different shaft heights. The same stator and rotor slot shapes and their numbers as in Fig. 2 have been accepted for all designs.

Optimal designs in the paper are results of solving the following bicriterial problem:

$$\min_{x} C_{ma}, \max_{x} \eta_N \,\middle|\, \boldsymbol{x} \in X \tag{1}$$

for the motors described in Table 1.

Table 1. Denotations of the analyzed motors

denotation(*)	cage material	shaft height [mm]
Al132	Al	132
Cu	Cu	112 and 132
112	Al and Cu	112

(*) Similar descriptions hold for motors denoted Al112, Cu112, Cu132, Al, and 132.

The cost C_{ma} of active materials comprises the cost of stator and rotor windings, stator and rotor cores, and stator winding insulation. The rated efficiency η_N is calculated according to the direct method in standards IEC 34-2. The vector $\boldsymbol{x}$ of 14 optimization variables represents dimensions of stator and rotor sheet punching, stator and rotor winding parameters and an auxiliary variable used in heating model. A set of 8 linear inequality constraints protects physical and technological reality of designs. A set of 9 non-linear inequality constraints are used to satisfy imposed motor operational requirements, for instance locked rotor minimum torque and maximum stator current. All constraints define the feasible set X in (1).

Compromise solution sets of the problem (1) have been determined by means of constraint methods, which require only directional convexity of the compromise set in the decision space. It can be seen in the next chapter, that the method of weighting factors could be employed as well. Both methods supply a decision-maker with the maximum amount of information and enable the selection of the best solution with the help of a'posteriori articulation of preferences technique. Auxiliary scalar problems have been solved with the help of successive quadratic approximation method. A method and related problem-oriented program implemented in FORTRAN [5] has been used for automated calculation of all the compromise sets.

IV. Calculations and Results

Results in Fig. 5 show that in general the motors "Cu" and "132" cost less than "Al" and "112" respectively. The difference between motors "112" and "132" increases as efficiency becomes higher. The construction "132" is liable to reach higher efficiency than "112".

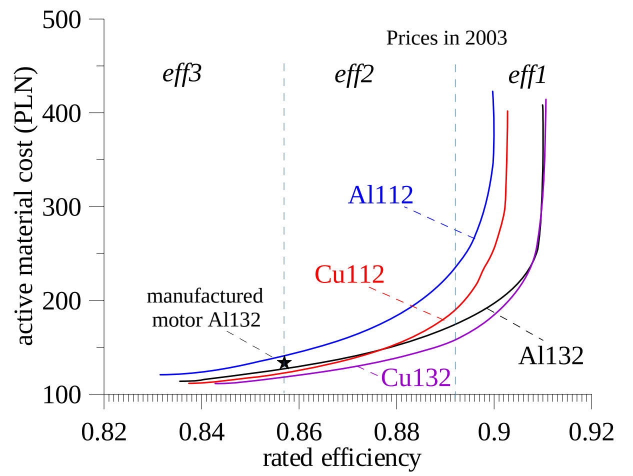

Fig. 5. Influence of rated efficiency on motor material cost. Price level in 2003 (1EUR≅4.1PLN, 1US$≅3.95PLN)

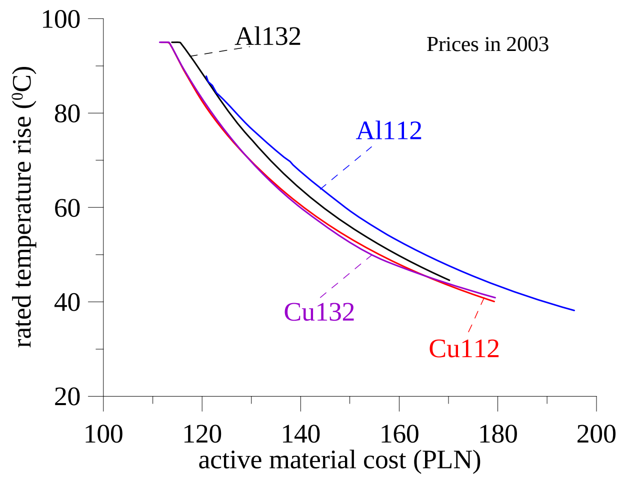

Fig. 6. Stator winding rated temperature rise as a function of active material cost for selected motor constructions.

A temperature rise of stator winding not only increases electrical losses, but also reduces the lifetime of its insulation. If this property is taken into account, the motors "Cu" appear to be more profitable, because they allow increasing amortization time. As it arises from Fig. 6, a few degrees less temperature can be expected in the case of "Cu" motors. Temperature differences between motors "Al" and "Cu" are more significant for "112" case than for "132".

In practical terms, meaning C_{ma}≤200PLN, the rated power factor rises in both "Al" and "Cu" constructions, see Fig. 7, but it is higher for "Al" because of a greater rotor winding resistance in this construction. Too low power factor can be a reason of the extra operation cost of the motor [4]-[6].

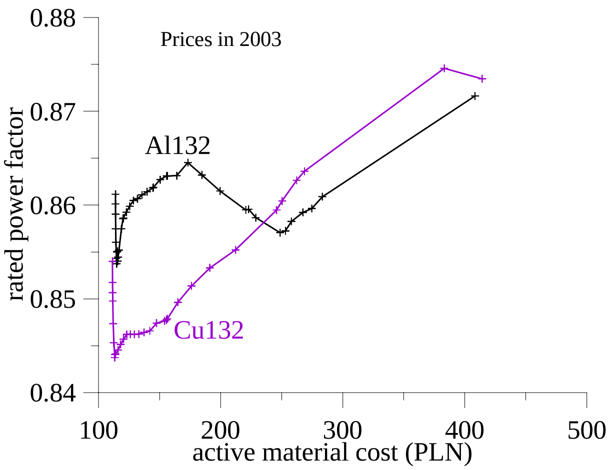

Fig. 7. A variation of rated power factor for "Al" and "Cu" motors as active material cost increases. Marked points denote solutions generated by solving algorithm.

Fig. 8 shows that a total winding cost in the *eff2* Class motors is almost the same for "Al" and "Cu" motors for a given efficiency value, with a remark that in the stator of the "Cu" motors it is lower, and in the rotor – higher. It is interesting to know that the rotor winding weight is almost independent of the rated efficiency for both the "Al" and "Cu" motors. In the *eff1* Class "Cu" motors the cost of stator winding rises faster than in the "Al" motors.

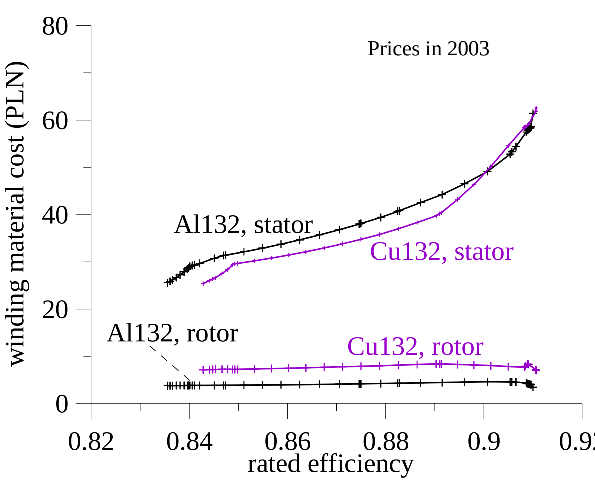

Fig. 8. A relationship between rated efficiency and cost components of "132" motor windings

Results in Fig. 9 correspond to those presented in Fig. 5 after a change of active material price level, as was mentioned in Chapter II. The relative relationships between motors are similar, although more distinct. The "Cu" motors of the *eff2* and *eff3* Class are cheaper than "Al" motors, and "132" motors appear to be cheaper for *eff1* Class. Approximately 4% material cost reduction of the "manufactured motor Al132" could be achieved through optimization in the case of the price level in year 2003. This figure increases to more than 10% for prices in 2006. Such motors should be redesigned because of serious losses associated with their production.

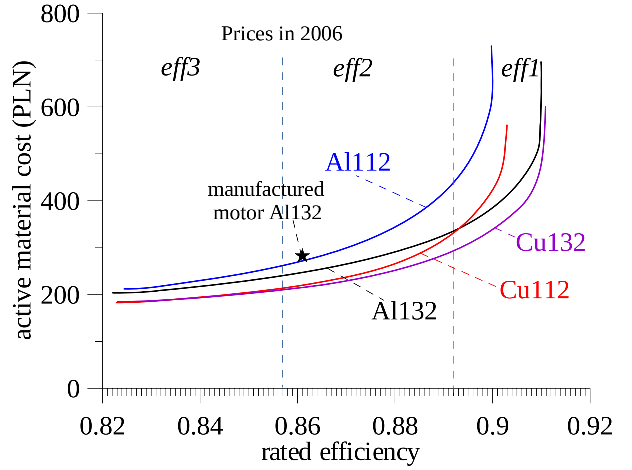

Fig. 9. Influence of rated efficiency on motor material cost. Price level in 2006 (1EUR≅4.1PLN, 1US$≅3.2PLN)

One can see in Fig. 10 that *eff1* Class motors used in variable load drives will be more profitable in the sense of operation cost [4-6], if the motor is designed for a maximum of efficiency η_Q associated with a load less than rated one, say P_Q=0.75P_N. For *eff3* and *eff2* Class motors the curve $\eta(P_{out})$ have a maximum for $\eta < \eta_N$, which is more distinct for motors with less value of the η_N. In the case of classical high-efficiency motors the function $\eta(P_{out})$ rises monotonically with a load, and its under loaded operation results in additional active power loss, which is higher than in the case of motors obtained from maximizing the η_Q.

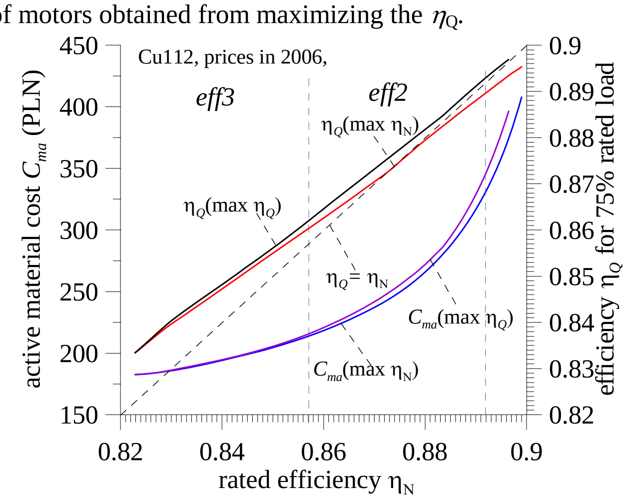

Fig. 10. A comparison of motors designed by a criterion $\max \eta_N(P_N)$), and $\max \eta_Q(P_Q = 0.75 P_N)$ for "Cu112" motors.

An almost linear relationship can be noticed between the motor core length and its active material cost in Fig. 11 in the area of practical meaning. Performed calculations show that it holds for both the 2003 and 2006 price levels. It is sufficient to find suboptimal solutions of a modified problem (1) without solving it. A criterial function in the modified problem is the production cost which comprises the C_{ma} and other components of the manufacturing cost. An assumption, usually satisfied in practice, is necessary that the function of other production cost components can be presented in the form of a piece-wise linear function of a class C^0 dependent on motor stack length. A related detailed algorithm and its proof can be found in [5]. This approach is of practical meaning because it allows splitting the work of a designer-analyst and a decision-maker. In particular it enables the latter to perform a multi-variant analysis without the need of solving (1).

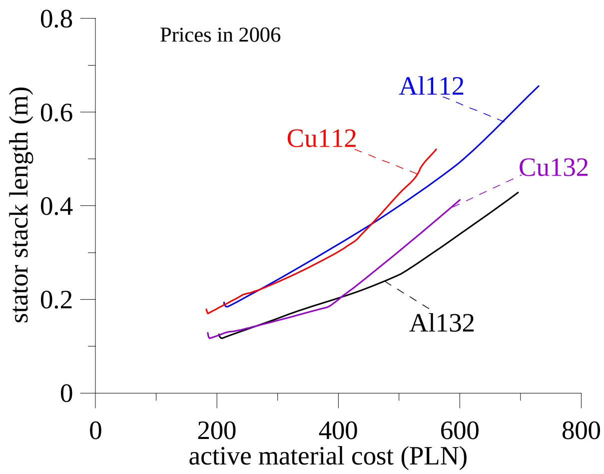

Fig. 11. Almost linear relationship between motor stack length and its active material cost for analyzed motors in an area of practical interest.

Some results of a simplified approach described briefly above are presented in Fig. 12. Results for motors "112" are the same in both Fig. 9 and Fig. 12. Functions representing the motors "132" in Fig. 12 are a sum of corresponding cost function in Fig. 9 and a difference between additional manufacture costs (without active materials) of the motors "132" and "112".

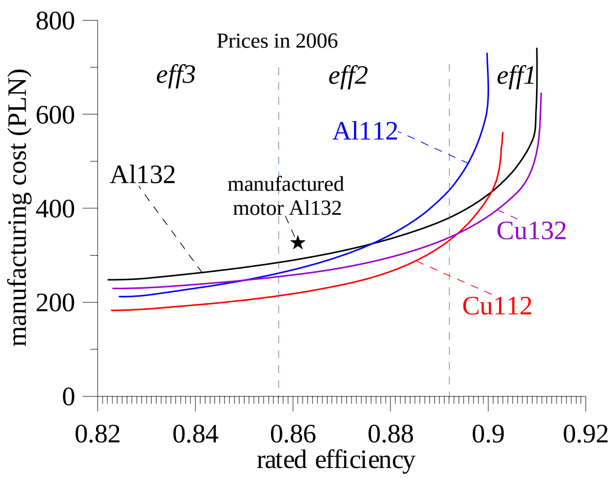

Fig. 12. Influence of other production cost components on relationship between manufacturing cost and rated efficiency.

The influence of a more expensive rotor copper technology has been neglected in this analysis. Now this assumption is certainly questionable, but after a time it can be accepted. In such a case a motor "Cu112" appears to be the best if *eff2* or *eff3* Class motors are designed, whilst the motor "Cu132" should be selected for the Class *eff1*.

V. Conclusion

For some time many papers devoted to the subject have appeared in professional literature. The analysis performed in this paper is based on results of bicriterial optimization and searching for a compromise between the two most important criteria – maximum of rated efficiency representing user interest, and minimum of manufacturing cost, which is of primary interest for producers. The described approach offers an increased credibility of conclusions, which is difficult to obtain by means of other approaches. The analysis confirms a superiority of induction motors with die-cast copper cages, even more at a price level in 2006 than in 2003. Additional costs not considered in the analysis, particularly those of more expensive technology related to copper cage manufacturing, should be taken into account to verify obtained results. It can be made after solving the optimization problem (1) to obtain suboptimal designs, which represent a compromise between the total manufacturing cost and rated efficiency.

The analysis of field calculation results should be performed with caution if *Steady AC magnetic* module of the program is employed. A warning related to validity limits [7] has been confirmed in the paper in the case of iron loss prediction. The proposed extension of the loss formulae could be helpful.

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