Some economic aspects of designing optimal energy-efficient and high-efficiency induction motors

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***Abstract* — In the paper high-efficiency (HEMs) and energy-efficient (EEMs) induction motor designs are defined separately as solutions of different optimisation problems. A result of a successful search for 1.5kW HEMs of Class Eff I according to CEMEP is presented. The economical superiority of the EEMs over HEMs is proved on an example. A new cost function is proposed to enable a time-invariant analysis of the EEMs designs. It is shown that a considerable improvement in motor efficiency can be expected if new materials and technology together with optimisation are applied.**

1. Introduction

An observation that in majority cases saving energy is a better strategy than producing it was a main reason that such concepts as an Integrated Resource Planning (IRP), Supply-Side Management (SSM) or Demand-Side Management (DSM) appeared after the energy crisis. Energy Efficient Motors (EEMs), called as well Higher Efficiency Motors (HEMs) or High Efficient Induction Motors (Hi-Motors), are a consequence of the DSM politics.

By now there is no commonly approved definition of Energy Efficient Motors. A few years ago severe requirements on Hi-Motors have been imposed by the MOTIVA, the Finnish Information Center for Energy Efficiency. For instance, for a 1.5kW four-pole induction motor a mandatory efficiency limit 85.9% (required 88.9%) has been established. Following this, a Hi-Motors Competition for 0.18 – 90 kW induction motors was set up by the International Energy Agency (IEA) to encourage designing such motors. This initiative was run by MOTIVA [1]. The competition time was June 1997 – August 1998, and the winner of this competition, ABB, was awarded for two motors, 5.5kW and 75kW.

CEMEP, the European Committee of Manufacturers of Electrical Machines and Power Electronics, and the European Commission (EC) agreed in 1999 in London to define three efficiency classes for 2 and 4 pole squirrel-cage induction motors of 1.1 to 90 kW: Class Eff I, Class Eff II and Class Eff III. The Class Eff I is for the highest efficiency motors. For instance, for a 1.5kW induction motor the minimum efficiency limits for Class Eff II and Class Eff I have been set to be 78.5% and 85.0% respectively. According to the above regulation, the efficiency values are determined on the basis of summation of losses method and some additional notes, among others that:

- the reference winding temperature may be used as the actual winding temperature rise + 15^0K
- the efficiency test should be done in a stabilized bearing lubrication condition and in case of motors with seals without installed seals.

Comparing it with IEC 34-2 direct method, applied for instance in the earlier mentioned IEA Competition, one can see that the efficiency value obtained in this way will be higher.

A chief aim of the paper is to show that distinguishing the meaning of the term EEMs from that of the HEMs (or Hi-Motors) is justified if a problem of energy wasting is considered in a broader sense than in the case of the motor itself. This is related to the reactive energy consumed by the motor.

The calculations are performed for a motor SEE90L-4 with the ratings: P_N=1.5kW, U_N=3x400V, 2p=4, f_N=50Hz.

2. Design calculation model and its identification

The synthesis program used in optimisation in this paper is a modification of its earlier versions [2]-[5]. It consists of two coupled algorithms describing steady-state electromagnetic and heating phenomena. The design calculation formulae arise from classical approach to designing induction motors, e.g. [6], [7]. Such phenomena as saturation, skin effect, are taken into account.

A reliable design calculation model is a condition of practical usefulness of optimisation results. In some cases an identification process relying on a simple reasoning can improve the model. If design requirements are difficult to satisfy than applying a formal approach based on type test data obtained for a similar motor, or for its earlier prototype, is desired. Such a situation appears often in the case of EEMs.

Results of the following tests were used when defining an error function of the model:

- no-load
- locked rotor
- heating for rated load

During identification winding temperatures have been assumed to be constant for each test and equal to the measured ones. Afterwards load characteristics have been used to verify the algorithm of electromagnetic calculations. Most important experimental coefficients of the heating model have been found with the help of sensitivity analysis results.

The identification procedure applied in this paper is a modification of that described in earlier papers [4], [8], [9].

3. An experiment with a Class Eff 1 induction motor.

Both the identification and optimisation calculations have been performed to find designs of a squirrel-cage induction motor SEE90L-4 satisfying the Class Eff I requirements [10].

Stator and rotor slot numbers and dimensions, stator winding parameters, rated temperature rise of stator winding, the stator/rotor stack length, and the electrical sheet type were optimisation variables.

Severe design restrictions have been imposed on the design to leave the old technology as much as possible.

Designs accepted by the producer were solutions of a problem:

$$\max_{\mathbf{x}} \eta_{NC} \Big| \mathbf{x} \in X \quad (1)$$

The quantity η_{NC} is the rated efficiency calculated according to EC/CEMEP agreement, $\mathbf{x}$ is an optimisation variable vector, and X is a feasible region representing the design requirements.

Two prototypes, designed for hand- (Prototype I) and machine winding (Prototype II), have been manufactured and measured. Obtained results denoted as AGH-INDUKTA are presented on Figure 1.

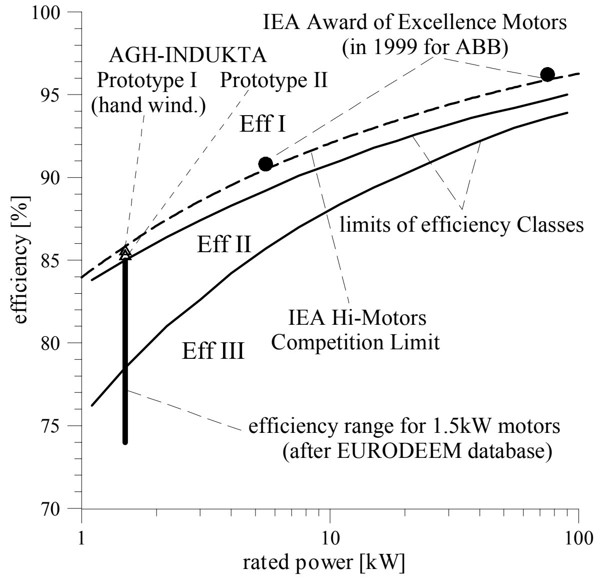

Fig.1. Results obtained for prototypes of the Class Eff I induction motor SEE90L-4 in comparison to the European Database of Efficient Electric Motors (EURODEEM)

A note concerning the motor efficiency definitions is necessary. As it was mentioned above, the values for the Prototypes I, II correspond to EC/CEMEP agreement, whilst the efficiency values of the ABB motors comply with Direct method according to IEC34-2.

An identification procedure mentioned earlier was a reason of achieving the result on Fig. 1 at a first attempt.

4. Optimum designed EEMs and HEMs

A research program has been performed to show a difference between the EEMs and HEMs, as well as to explore some possibilities offered by the optimisation method used in designing these motors.

A. Criterial functions

Among a variety of different criterial functions used when designing induction motors, a function of material (or production) cost, and efficiency (or active power losses cost) belong to the most important. According to this, in the paper the following criterial functions are used:

a) C_{ma} - a cost of active materials

$$C_{ma} = m_{Cu}c_{Cu} + m_{Al}c_{Al} + m_{Fe}c_{Fe} + m_{ins}c_{ins} \quad (2)$$

The quantity m denotes a mass, c – price, Cu – stator winding cooper, Al – rotor cage aluminium, Fe – electromagnetic sheet, and ins – insulation.

b) C_{oP} - a cost of active power loss reduced to the motor installation year

$$C_{oP} = \frac{\kappa\, h}{d} P_N \frac{1-\eta_l}{\eta_l} c_P \quad (3)$$

Additionally, in the paper a cost function C_{oQ} related to reactive energy is defined in the form:

$$C_{oQ} = C_{oQc} + C_{oQv} \quad (4)$$

where:

$$C_{oQc} = \frac{\kappa}{d}(1-a_q)d_c a_c c_c P_N \frac{\mathrm{tg}\,\varphi_l}{\eta_l} \quad (5)$$

and

$$C_{oQv} = c_Q a_q \frac{\kappa\, h}{d} P_N \frac{D(\varphi_l)}{\eta_l} \quad (6)$$

Coefficients c_P, c_Q denote the prices of 1kW.h and 1kVAr.h respectively, $D(\varphi_l)$ is a monotonically increasing function equal to zero for $\mathrm{tg}\,\varphi_l \le 0.4$. The meaning of other symbols is the same as in [3]. In calculations all prices are related to a price of 1 kW.h active energy.

B. Definitions of EEMs and HEMs

If optimisation is applied to find an energy efficient motor, it is possible to distinguish the meanings of the EEMs and HEMs.

In the paper a design of the HEMs is a solution of a problem:

$$\min_{\mathbf{x}} C_{ma} \Big| \ \eta_{NC} \ge \eta_{eff}\,,\ \mathbf{x} \in X \quad (7)$$

and a design of the EEMs:

$$\min_{\mathbf{x}} \left(C_{ma} + C_{oP} + C_{oQ}\right) \Big| \ \eta_{NC} \ge \eta_{eff}\,,\ \mathbf{x} \in X \quad (8)$$

where η_{eff} is an efficiency desired for a particular motor and its efficiency Class.

C. Superiority of the EEMs over HEMs

The problem (7) and (8) have been solved for the same optimisation variable vector $\mathbf{x}$ and feasible region X as in

(1) with two exceptions: the mechanical loss power has been assumed to be $\Delta P_m = 10\text{W}$ (a value close to the measured one), and stator bore diameter was an optimisation variable.
The results for cost functions C_{ma} and C_o are in Table I.

TABLE I
COST FUNCTION VALUES FOR HEMS AND EEMS

	$\min C_{ma}$ (for HEMs)	$\min\left(C_{ma} + C_{oP} + C_{oQ}\right)$ (for EEMs)
C_{ma} (kW.h)	234.2	254.7
C_o (kW.h)	2613.9	2403.6

The material cost C_{ma} of EEMs is 20.49kW.h higher than in the case of HEMs, but energy cost for 5 years work and 3200 hours/year is 210.3kW.h less. Similar qualitative results have been obtained for the others motors optimised earlier by the author. They show that a strategy of designing EEMs according to (8) is more profitable from a general point of view.

D. A new criterial function suitable for decision-maker analysis

A bikriterial problem:

$$\min_{\mathbf{x}} \left\{C_{ma}, C_o\right\}\Big|\ \mathbf{x} \in X \tag{9}$$

has been solved for two cases:
a) $C_o = C_{oP} + C_{oQ}$
b) $C_o = C_{oP} + C_{oQv}$
to analyse an influence of the definition of the operation cost C_o. It was assumed that 10% of reactive energy is not compensated.

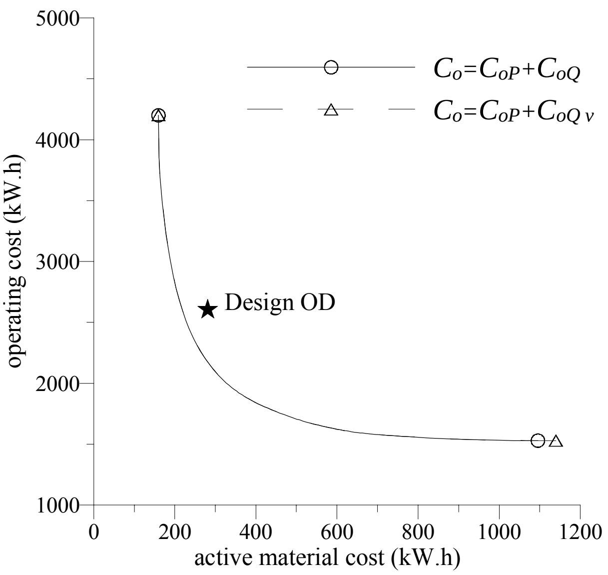

Fig.2 A comparison of cost functions for optimal designs for two cases (a) and (b) of the operation cost C_o in (9). Design OD is a design arising from (1) for Prototype II.

One can notice a very little influence of the component C_{oQc} of the operation cost function C_{oQ} on the result presented on Figure 2. It justifies a conclusion that in this case the function C_o can be simplified to a form:

$$C_o \cong C_{ov} = C_{oP} + C_{oQv} \tag{10}$$

without a noticeable loss of accuracy when solving the problem (9) to find an optimal design $\boldsymbol{x}^*$.

The function C_{ov} is a proposal of a new criterial function useful for a decision-maker when analysing compromise solutions of the problem (9) in the form:

$$\min_{\mathbf{x}} \left\{C_{ma}, C_{ov}\right\}\Big|\ \mathbf{x} \in X \tag{11}$$

E. Time-invariant property of the EEMs compromise design set.

Both the components C_{oP} and C_{oQv} of the energy cost function C_{ov} are time dependent. The problem (9) must be solved for any new motor amortisation time as well as operation time in a year. Fortunately, it is possible to get more general results if (10) is accepted.

It arises from Figure 2 that the problem (11) can be solved by means of so called multipiers method. It means a compromise solution set consists of solutions $\mathbf{x}^*(\alpha)$, $\alpha \in [0,1]$, of equivalent scalar problems:

$$\min_{\mathbf{x}} \left[\alpha\, C_{ma} + (1-\alpha)\, C_{ov}\right]\Big|\ \mathbf{x} \in X \tag{12}$$

From (3), (6), and (10) one can obtain that:

$$C_{ov} = \left[\frac{h}{d}\right] P_l \left[c_P \frac{1-\eta_l(P_l)}{\eta_l(P_l)} + c_Q a_q \frac{D(\varphi_l)}{\eta_l(P_l)}\right] \tag{13}$$

The quantity h is the yearly operating time, d – the amortisation rate, and the other coefficients have been mentioned earlier.

If calculations are performed for new values h' and d' of the above parameters h and d, than a new solution $\left(\mathbf{x}^*\right)'$ of the (12) is :

$$\left(\mathbf{x}^*\right)' = \mathbf{x}^*\left(\alpha'\right)$$

where:

$$\alpha' = \frac{\alpha}{\alpha + \dfrac{h'/h}{d'/d}\left(1-\alpha\right)} \tag{14}$$

It means that the compromise solution set of the (12) is time-independent, despite the components C_{oP} and C_{oQv} of the criterial function C_{ov} are functions of time.

If other design quantities are defined as functions of the parameter α, than the above property of the compromise design set enables a decision-maker to perform a full analysis for any combination of the h and d, without additional recalculations of the (12).

The above property is demonstrated on Fig. 3. The cost functions on Figures 2 and 3 are associated with the values h=3200 hours and d≅0.25, with the latter obtained for 5-years amortisation period and 8% discount rate. If these values are altered to another ones, say $\{h' = 8000\,\text{hours},\ d' \cong 0.1327\}$ corresponding to a 12-years amortisation period, than a design obtained for a value $\alpha = 0.5$ in the former case is exactly the same as that for $\alpha = \alpha' \cong 0.166$ in the latter one. It is enough to replace the axis α on Fig.3 with the α' (it is placed in the top of Figure

3 with spacing $\Delta\alpha' = 0.1$), and to scale the criterial function C_{ov} with a coefficient

$$\frac{h^{'}/h}{d^{'}/d} \cong 4.71$$

to obtain the altered compromise solution set.

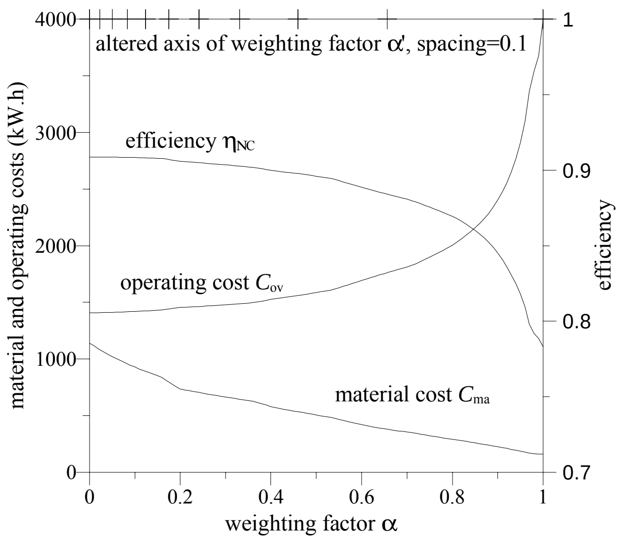

Fig.3 Cost functions, rated efficiency, and new α' axis. Explanations are in text.

It arises from optimisation theory that there is no problem to apply the above procedure if a constraint method [2], [3] is used to solve the bicriterial problem (11).

F. Searching for the best HEMs

The calculations of a motor described in point 3^0 have been performed with severe restrictions. In particular, the values of both the stator diameters and rotor cage ring dimensions have been imposed by a producer to be the same as those in prototypes of this motor manufactured earlier.

In this point the calculations are repeated for a few cases in order to verify a thesis that a better result can be expected if:

- the number of optimisation variables is higher
- the number of constraints is lower and/or the feasible region is greater
- the active materials of a motor with better physical properties are applied

The cases are:

Case I – represents the motor (Prototype II) in point 3^0, with ΔP_m=10W.

Case II – as *Case I* but the restrictions mentioned above are removed

Case III – as *Case II* but the stator slot fill factor is as large as possible theoretically for round conductors

Case IV – as *Case III* but the cage is made of copper

The following problem has been solved for each case:

$$\max_{\mathbf{x}} \eta_{NC} \left| C_{ma} \leq C_{ma}^{*}, \mathbf{x} \in X \right. \qquad (15)$$

The quantity C_{ma}^{*} is the material cost the same for all cases, equal to that of the Prototype II described in point 3. One can notice that the problem (15) is another form of the problem (7), it means the results are still HEMs.

The results of solving (15) for each case are in Table II.

TABLE II
DESIGN OPTIMISATION RESULTS

	η_{NC} (%)
Case I (*Prototype II, ΔP_m=10W*)	85.74
Case II *Case I+(D_{si}, D_{so}, a_{cr}, b_{cr} = var)*	87.53
Case III *Case II+(k_{slot}+0.1)*	87.74
Case IV *Case III+(Al→Cu)*	88.59

According to a change of properties of electrical sheet during a process of casting a copper cage the efficiency η_{NC} for Case IV is expected to be higher than that in Table II.

5. Conclusions.

1. The HEMs and EEMs should be considered as different meanings according to (7) and (8), (Table I).
2. The EEMs are more profitable than HEMs from the general energy saving point of view (Table I).
3. The new cost function C_{ov} proposed in (13) enables a decision-maker to perform a time-invariant analysis.
4. New materials and technology together with optimisation should be applied if a considerable improvement in motor efficiency is expected (Table II).

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