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MODELING AND OPTIMIZATION OF AN IE4-CLASS HIGH-EFFICIENCY INDUCTION MOTOR PROTOTYPE.

Abstract: An approach to obtain a design of a high-efficiency induction motor prototype of an IE4-class is proposed in the paper. The motor is characterized by a minimal cost of manufacturing and maximal output. An identification procedure is described, which is necessary to obtain a credible analytical model in the synthesis program. Rated efficiency is determined from indirect measurement. Calculation results related to the method of summation of losses, with and without load test, are compared in the paper. A considerable improvement in accuracy of identification has been obtained through applying a model with variable parameters. The best design of the motor is searched for by means of a minimax problem, it means a simultaneous maximization of its rated output, and minimization of a distance between its rated efficiency and a predicted efficiency line representing the IE4 class.

1. Introduction

The world energetic crisis in 70th led to a considerable demand for energy-efficient machines, and it has an increasing trend. In a sense, the ability of these machines to save the electric energy is equivalent to an increase of the electric energy supply, which holds without producing it. In an obvious way this kind of human activity reduces pollution and saves environment. Another benefit is that energy-efficient constructions are characterized by a lower level of electro-magnetic and heating load, and this is a base for a higher life time period. The benefits arising from the energy-efficiency are obvious not only for end-users of electric energy. It has been noticed by the EU representatives. A result of it is corresponding regulations, which now are mandatory for producers of electric machines. According to these regulations they are obliged to withdraw gradually a production of less energy-efficiency, and replace it by a higher-efficiency one.

In the paper, an analysis is performed to check a possibility of increasing efficiency of an existing motor, with a constraint that the same technology and manufacturing implementation are applied. This constraint is a consequence of a requirement that the cost of a motor prototype should be minimal. In particular, the following assumptions have been accepted, when searching for the best electro-magnetic circuit of the motor:

- the frame and the shaft are the same,
- the inner stator diameter is not changed (due to a high cost of the rotor cage die-casting technology).

An influence of these limitations on the best designs will be investigated in the paper as well.

The goal of the paper can be reached by means of the following approach:

- applying a credible design procedure in the synthesis program,
- employing an optimization procedure, which satisfies convergence criteria in a reasonable computation time.

Since a time the models based on finite element method become more popular. They offer a relatively simple way of modeling and higher accuracy in a comparison to analytical ones. There is an obstacle in the form of a high calculation time, but now it is not as important as a time ago, due to a progress in computer equipment. This last remark is of a limited value in an optimization approach [1]. In this case the predicted very high calculation time imply a considerable simplification of a problem definition and a reduction of the performed research program, in a comparison to a similar approach based on an analytical model. A consequence of this is a reduction of a credibility of final optimization results.

In the paper an analytical model has been employed in designing, with some constant parameters and characteristics of active material properties arising from a suitable identification approach. In identification the experimental data concerning an existing 3-phase cage induction motor with ratings: P_N=0.75kW, U_N=400V, p=2, f_N=50Hz, have been applied.

Results of earlier research works of the author suggest that this identification approach together with a related technical documentation are sufficient to obtain credible optimization results for another motor of a similar construction.

A rated efficiency of a motor is a function of its rated output. Assuming that the requirements of corresponding standards [2],[3] are satisfied, an original approach has been proposed to develop the best motor construction, which formally is a solution of a minimax problem.

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2. Analytical model of the motor

Induction motor model employed in the synthesis program represents an analytical procedure of designing. It has been developed by the author for over 20 years [4]-[6], and a few times was verified experimentally, e.g. in [7]-[9]. Typical origins of uncertainty are nonlinear character of the physical phenomena, and a discrepancy of active material properties as well as technology. It is a reason that design calculations in practical applications should consider data of experiments performed on a similar motor manufactured by the same producer [9]. A specialized identification procedure has been worked out [7],[10] to determine the values of some constant parameters and core B-H characteristic used in design calculations. This procedure comprises a heating model in a form of a linear regression equation, which represents a rated temperature rise of the stator winding, with loss components as variables, and coefficients dependent on construction and active material quantities.

In a classical identification approach the relevance quantities describe motor properties such as rms. currents, active power, E-M torque. The non-linearity of the magnetic circuit and eddy-current phenomenon justify another approach. A more credible procedure seems to be to match function parameters defined by design algorithm to those arising from experiments performed for an existing motor. Such an approach has been applied in this paper, with measurement data related to the no-load and locked-rotor tests. Rated heating test was performed as well, to determine rated efficiency, and load test, to get proper characteristics. Results of both these tests were used when verifying the model represented by an equivalent circuit with variable parameters [10],[11]. Every point of the function parameters is a result of a solution of the equivalent circuit for an assumed steady state operation of the motor.

3. Description of the identification approach

The following assumptions have been accepted in the identification procedure:

1. the friction and windage losses represent a load in the no-load test.
2. Additional-load losses are $P_{\mathrm{LL}} = P_{\mathrm{LL,N}}(I_r^{'}/I_{rN}^{'})^2$, where $P_{\mathrm{LL,N}}$=14.1W (an information from a producer)
3. During the no-load and locked-rotor tests, the stator winding temperature θ_{s} and the rotor one θ_{r} are the same, but during the rated heating it holds $\theta_{\mathrm{r}}=\theta_{\mathrm{s}}+10$.
4. The resistance R_{s} of the stator winding is known (from a measurement) for every operation point of the motor

During the rated heating test, and when determining load characteristics, the investigated induction motor was loaded with a d.c. generator (with a load resistance in the armature circuit).

3.1. Experimental data for determining function parameters

Present standards [3] allow for a possibility of applying the equivalent circuit technique when determining rated efficiency and load characteristics. The experiments required for this purpose have been performed in the paper by means of a portable measurement system described in [12]. Two phase currents i_1 and i_3, two line voltages u_{12} and u_{32}, and the rotor revolution angle φ_{r} were recorded during a time of one second for every steady-state operation point, with a sample interval Δt=0.5ms. After applying a procedure of data processing, every motor operation point was characterized by a set of quantities $\{U, I_1, P, \omega, R_{\mathrm{s}}\}$, where: U – rms phase voltage, I_1 – rms phase current, $P=P_1/3$ – phase input power, ω - rotor angular velocity, and R_{s} – stator phase winding resistance.

3.2. No-load test

Identification results for the rms stator current and input power are presented on Fig.1. The marked points correspond to measurement data recorded during the test, and the continuous line – a model with variable parameters [3],[11] arising from this measurement. The dotted line concerns the analytical model defined by design calculations in the synthesis program.

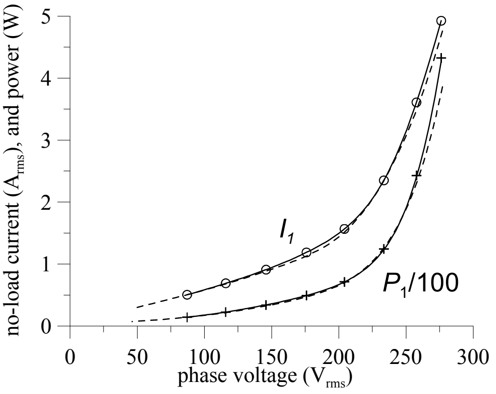

Fig.1. No-load test - identification results: marked points - measurement, continuous line - variable parameter model, and dotted line - design calculations.

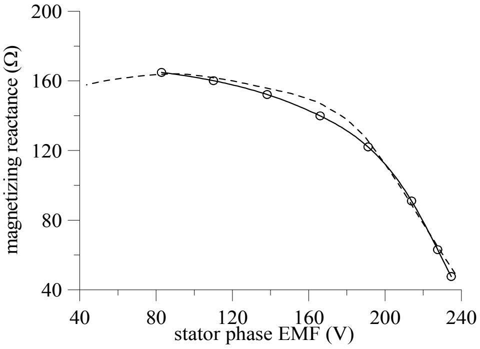

Fig.2. No-load test – magnetizing reactance after the identification: marked points - measurement, continuous line – variable parameter model, and dotted line – design calculations.

Perhaps more valuable information about machine properties arises from a magnetizing reactance X_{m}, which is presented on Fig. 2 as a function of the stator winding electromotive force E. One can notice a considerable influence of saturation effect on the reactance value. As a consequence, a fast increase of the magnetizing current and a drop of the power factor value can be expected.

The results on Fig.1 and 2 has been obtained by the following additional assumptions:

- the magnetizing reactance X_{m} and the resistance R_{fe} representing core losses in the equivalent circuit are functions of the stator winding EMF,
- the ratio X_{ls} / X'_{lr} of stator leakage to stator referred rotor leakage reactance is known from design calculations (the same assumption as in [3]),
- rated locked-rotor test measurement and all no-load experimental data are used in the identification process,
- identification variables are stator leakage reactance X_{ls} and stator referred rotor resistance R'_r.

Both the functions $X_{\mathrm{m}}(E)$ and $R_{\mathrm{fe}}(E)$ were relevance quantities for the same quantities arising from the design calculations analytical model in the synthesis program.

3.3. Locked-rotor test

The results presented on Fig.3 for locked-rotor test are not as good as for no-load.

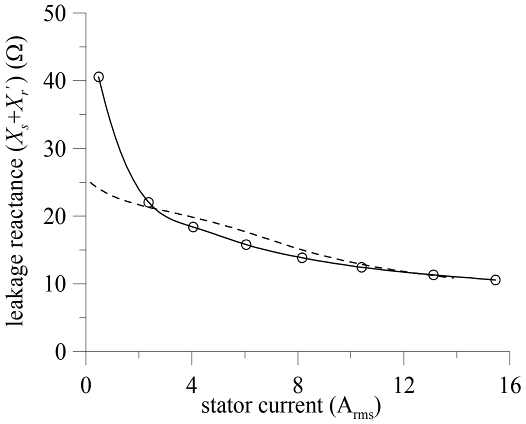

Fig.3. Motor leakage reactance function for locked-rotor test after identification: marked points – measurement, continuous line – variable parameter model, and dotted line – design calculations.

A main reason of discrepancy, particularly for low stator current values, seems to be a much stronger influence of rotor slots closing in the existing motor than it is represented in the design calculations. Unfortunately, this is difficult to predict and describe, mainly due to a high level of uncertainty concerning the dimensions of the closure in the existing motor.

The observed differences are substantial for stator current values less than rated one. It can be expected that this inaccuracy will not influence optimization results considerably.

3.4. Determination of motor efficiency

The most important quantity in the paper is motor efficiency. Some remarks concerning this quantity, in particular its determination by means of the method of summation of losses, with and without load test, is presented below, together with corresponding remarks related to the design calculation model.

According to the standards [3], the efficiency η and the total loss P_T components were determined from the formulae:

$$\eta = \frac{P_2}{P_1} \qquad P_2 = P_1 - P_T$$

$$P_T = P_s + P_r + P_{fe} + P_{fw} + P_{LL}$$

a) the method of summation of losses, without load test (equivalent circuit from rated no-load and locked-rotor tests):

$$P_s = 3R_{s,\theta} I_s^2 \qquad I_s = I_1 \qquad P_r = 3R'_{r,\theta} I'^2_r$$

$$P_{fe} = 3\frac{E_0^2}{R_{fe,0}} \qquad P_{LL} = P_{LL,N}\left(\frac{I'_r}{I'_{rN}}\right)^2$$

P_{fw} – the friction and windage losses, from no-load test, $R_{s,\theta}$ - from measurement, (it differs from [3]),

b) the method of summation of losses, with load test (no equivalent circuit, rated no-load and heating tests only):

$$P_s = 3R_s I_s^2 \qquad P_r = s(P_1 - P_s - P_{fe,0},)$$

$$P_{LL} = P_{LL,N}\left(\frac{I'_r}{I'_{rN}}\right)^2$$

$P_{fe,0}$ - the iron losses, from no-load test,

c) design calculations – an algorithm as in (b), with stator winding temperature rise $\Delta\theta_s$ from heating model.

Results obtained from the identification calculations, for the rated efficiency and other quantities, are presented in Table 1.

Both methods of summation of losses, with and without load test, offer results of a similar accuracy with a restriction that the results obtained from an equivalent circuit approach are derived for a correct stator winding temperature θ_s. It can be hard to predict this value in advance. Suggestions related to this problem in [3] gives overestimated values, particularly for energy-efficient motors. For this reason, producers are interested to perform the load test when determining rated efficiency. The design procedure in the synthesis program follows this approach as well.

Table 1. Results for rated load.

	measurement		model
quantity	equivalent circuit	with load test	design calculations
U_N [V]	400	401	400
P_N [W]	750	750.1	750
I_{1N} [A]	2.68	2.67	2.5
P_{1N} [W]	951.7	949.9	940
P_s [W]	103.8	104	93.5
P_r [W]	37.6	32.7	35.6
$P_{fe}+P_{fw}$[W]	46.1	49	44.8
P_{LL} [W]	14.1	14.1	14.1
cosφ	0.513	0.511	0.546
η_N [%]	78.81	78.97	79.01 (79.88)
θ_{1N} [^{0}C]	62	62.9	59.8

The heating model comprises a set of coefficients, including some experimental ones. Their values are modified according to the results of a local problem-oriented identification procedure with measurement data taken from an existing motor similar to that designed one. Despite this, an uncertainty level about the value of the rated stator winding temperature θ_s, estimated to be ±10^{0}C, has been assumed. A calculation experiment has been performed to fix an influence of this uncertainty on efficiency. Following the data in Table 1, it was assumed that the temperature θ_s varies in an interval [52,(62),72]^{0}C. An almost linear relationship has been obtained for the rated efficiency, with a corresponding interval $\eta_N \in$ [79.22, (78.81), 78.40] [%]. This interval can be considered as an uncertainty interval caused by the uncertainty in the heating model used in the paper.

Results presented in this paper, particularly those in Table 1, show that fitting the function parameters of the model to the experimental data (rated, no-load and locked-rotor ones) appears to be a credible approach when predicting motor operation properties.

4. Motor design optimization

4.1. The aim and description of the approach

The main goal of optimization was to find a design solution of an induction motor, which is characterized simultaneously by a maximum output and a minimum distance to a predicted line of a minimum efficiency of the IE4 class [2], with a minimum cost of the prototype as an additional requirement.

The optimization problem has been defined in the form:

$$\text{Problem1}: \max_{\mathbf{x}\in X} \mathrm{P_N}, \min_{\mathbf{x}\in X} \left|\eta_\mathrm{N} - \eta_\mathrm{IE4}\right| \qquad (1)$$

where: P_N, η_N – rated power and efficiency of the motor to be designed, η_{IE4} – a function of the minimum efficiency related to a class IE4, $\boldsymbol{x}$ – a vector of optimization variables, X – a feasible region.

The vector $\boldsymbol{x}$ was defined by means of 14 quantities defining the geometry of the motor and its windings. The feasible region has been represented by means of the following constraint set:

a) 10 linear inequalities,
b) one non-linear equality,
c) 8 non-linear inequalities.

Constraint functions ensure a physical realization of a design, standards requirements, and protect a possibility of applying the same manufacturing technology, as for an existing motor of similar ratings.

6.2. Results of optimization calculations

The most important result of solving Problem1 is presented on Fig.4. The whole curve “optimal designs” representing motors with maximum efficiency is under the line of minimum efficiency of the IE4 class (denoted as η_{IE4} in (1)). A part of this curve in the range $P_N \in [0.37, 0.75]$kW can be considered as a compromise solution set in the decision space of Problem (1). It means, each design belonging to this interval is a solution of Problem1. Unfortunately, there is no design satisfying the requirements of the IE4 efficiency class. An optimal design for P_N=0.55kW seems to be of practical meaning, it belongs to IE3 class with no changes. Very likely a motor with an output P_N=0.75kW can be improved to satisfy the same requirements as well, by applying active materials with better properties and/or a proper modification of the feasible region. As in a few similar cases in the past, applying an optimization procedure improves the existing construction. An increase of the rated efficiency of more than 2.5% can be expected, without substantial expenditure.

Discrete variables, like the number of stator slots and a number of parallel wires in a conductor of the stator winding, were taken in the optimization into account as well. An influence of the inner stator diameter selection on the maximum efficiency has been checked for three cases. Two values of this diameter were the same as those used by a producer in the factory, and in the third case the diameter was an optimization variable. Results of this experiment are presented on Fig.5.

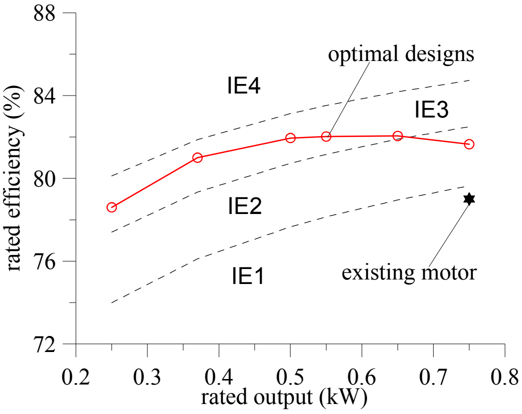

Fig.4. A solution of Problem1 in the objective space: the maximum efficiency of the motor as a function of its rated output, in a comparison with efficiency classes IE2-IE4 limits.

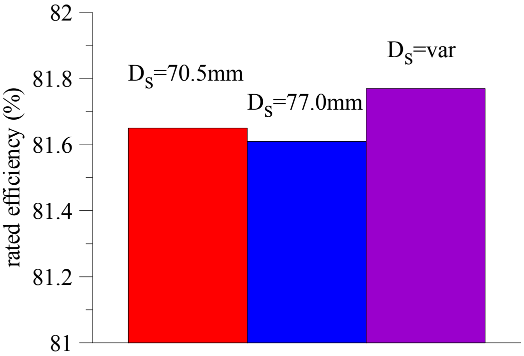

Fig.5. An influence of inner stator diameter on a maximal value of rated efficiency for a motor P_N=0.75 kW.

7. Conclusions

Some detailed remarks are presented in the paper. The following conclusions can be drawn from the performed research work:

a) Design calculation procedure employed in the synthesis program offers calculation results with a credibility corresponding to a method of summation of losses [3]. Applying an identification procedure is required to reach this conformity.
b) Without a modification of a feasible region in optimization it was not possible to obtain a motor with aluminum cage satisfying the IE4 efficiency class. Such a possibility exists for an IE3 class motor.

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