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DESIGNING AN OPTIMAL INDUCTION MOTOR WITH CENTRAL RING IN ROTOR CAGE

W.Jazdzynski
University of Mining and Metallurgy, Cracow, Poland.

Summary.

An approach to designing a squirrel-cage induction motor with skewed rotor bars and a central ring is presented in the paper. An equivalent circuit portraying this motor is proposed. Results of an identification procedure which confirm the validity of this model for the fundamental harmonic are presented. Design calculations are performed with the help of bicriterial optimisation. Criterial functions are active material, and operating costs of the motor. A method worked out for automatic detrmining the solutions of related optimisation problems is applied. Some optimisation results are presented. Described approach seems to be particularly useful for decision-makers.

1. Introduction.

Skewed bars as well as a central ring have a valuable feature of reducing the magnitude of parasitic torques. Usually solving a ladder-net circuit is required [1] to achieve an information how cage parameters influence motor properties. If the central ring exists, a number of complex linear equations greater than a double number of cage slots must be solved to reach the goal. Applying such an approach in a discrete multicriterial optimisation process based on gradient routines would lead to an extreme calculation time and cost. Simpler models which enable obtaining a compromise between the calculation cost and result accuracy are preferable. Usually an experimental verification of such models is necessary.

In the paper, an equivalent circuit and the results of an identification procedure for the motor Sg132M-4 with the data: P_N=7.5kW, U_N=3x380V_Δ, f_N=50Hz, 2p=4, are presented. The stator has a single-layer winding placed in 36 oval-shaped slots. Cores are made of a 0.5mm electrical sheet EB4 with a specific loss 2.5W/kg. The rotor has 28 skewed oval-shaped slots and a cage with a central ring.

Design optimisation calculations are performed by an assumption that the EB4 sheet is replaced with an Ei60 one which has the same thickness and specific loss. A design solution, which could be considered to be a compromise between the producer and user interests, is searched for. A bicriterial optimisation with criterial functions in the form of active material cost, and operating cost is applied.

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2. Equivalent circuit.

The motor in question is portrayed by an equivalent circuit obtained for the fundamental spatial harmonic. Rotor cage parameters of this circuit are derived by an assumption that the cage with skewed slots and a central ring is represented by an elementary electric circuit consisting of one bar and adjacent ring pieces. If the above assumption holds it is possible to replace the motor model by the equivalent one with an ordinary cage, it means a cage without the skew and central ring. Stator parameters R_1 and X_1, and magnetizing circuit ones R_{Fe} and X_μ, remain the same as in the primary model whereas the parameters R_2' and X_2' related to the stator quantities and representing the cage circuit in the equivalent model, can be presented in the form:

$$\mathrm{R}_2' = \frac{1}{k_s^2}\frac{Y_r}{Y_r^2+Y_i^2}\,\vartheta_u^{\,2} \qquad 1.$$

$$\mathrm{X}_2' = \frac{1}{k_s^2}\frac{1}{s}\frac{Y_i}{Y_r^2+Y_i^2}\,\vartheta_u^{\,2} \qquad 2.$$

where:

$Y_r = \mathrm{re}\underline{\mathrm{Y}}$, $Y_i = \mathrm{im}\underline{\mathrm{Y}}$

$\underline{\mathrm{Y}} = 1/\underline{\mathrm{Z}}_0 + \mathrm{tg}^2(\alpha_s/4)/\underline{\mathrm{Z}}_c$

$\underline{\mathrm{Z}}_0 = (\mathrm{R}_b + 2\mathrm{R}_r) + js(\mathrm{X}_b + 2\mathrm{X}_r)$

$\underline{\mathrm{Z}}_c = \underline{\mathrm{Z}}_0 + 4(\mathrm{R}_c + js\mathrm{X}_c)$

R_b, R_r, R_c = resistances of the bar, and adjacent pieces of the end-ring, and central ring, respectively

X_b, X_r, X_c = as above, but for leakage reactances

s = slip

ϑ_u = reduction factor from secondary to primary

$k_s = \sin(\alpha_s/2)/(\alpha_s/2)$

α_s = electrical phase angle between electric potentials at the opposite ends of a bar

3. Design calculation procedure.

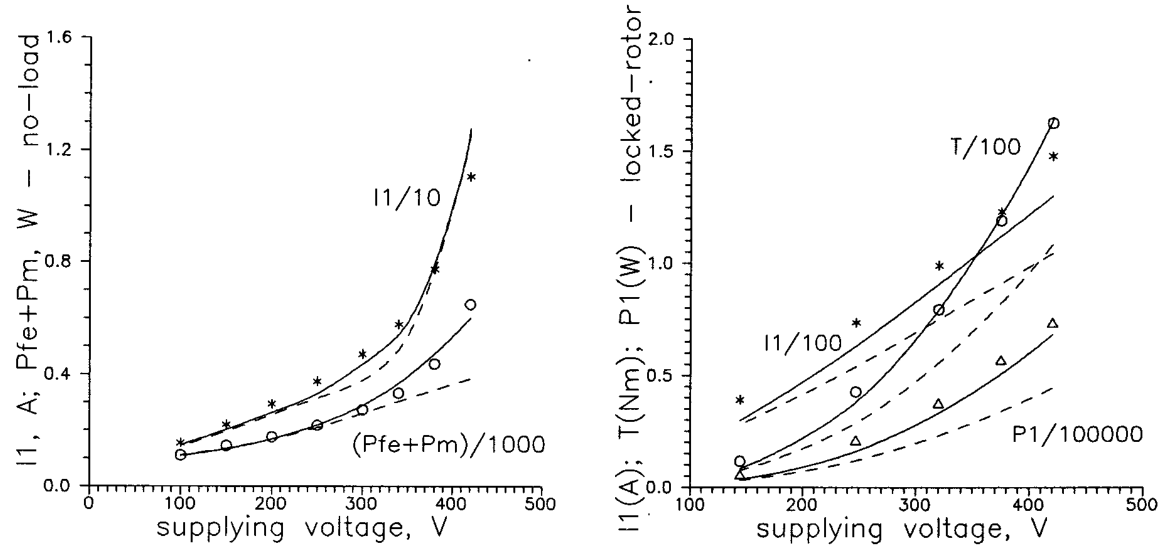
Only fundamental harmonic has been considered in design calculations. All quantities required in the synthesis program to evaluate both the criterial and constraint functions arose from the solution of the equivalent circuit described in the previous section. Similarly as in [2], a classical approach to designing is applied when determining the parameters of this circuit but design formulae have been revised [3,4], and altered if necessary, accordingly to the motor feature. Both the eddy-current and saturation phenomena are considered in the model. Magnetic calculations have been improved, particularly for core m.m.f., and are performed for any required load. A program--oriented multi-loop iterative procedure has been applied to solve the equivalent circuit at any analysed load of the motor.

Heating calculations are limited to the determination of the rated stator winding temperature rise. This quantity is represented by a linear function of loss components. Coefficients of this function depend on construction, as well as experimental parameters. Results of the temperature-rise test [5] and sensitivity coefficients of the heating model parameters were used to determine these experimental parameter values.

4. Model identification.

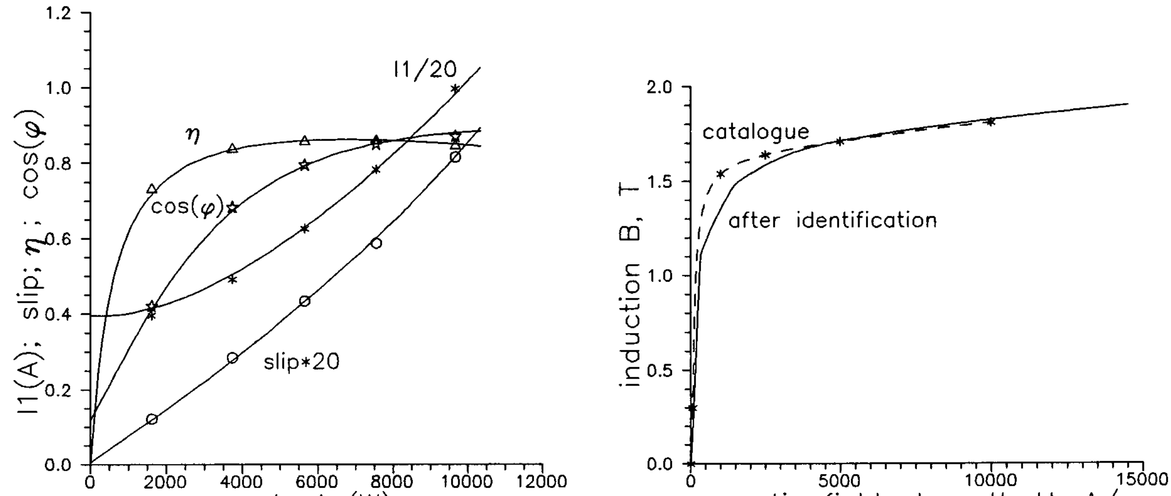
Design calculation results has been compared with the experimental data [5]. These results were not encouraging. After a careful analysis, 16 parameters has been chosen to adjust the model to the real machine at no-load, and locked-rotor operation. The task of the identification has been defined in the form of a scalar optimisation problem. In the case of no-load test, the reference quantities were the r.m.s. stator current I_1, and the sum of iron and mechanical losses $P_{Fe}+P_m$. The r.m.s. stator current I_1, input power P_1, and the shaft torque T were chosen for the locked-rotor test. Identification results are presented at Figures 1a, and 1b. It arise from these results that a considerably improvement has been achieved. Fig.2a compares experimental data with those obtained from the model after the identification, at load operation. This comparison shows that for this kind of operation the model produces acceptable results.

The considerably less conformability of both the experimental and calculation results presented at Fig.Fig. 1a,b in the comparison with those at Fig.2a can be explained as follows. The r.m.s. measured values are influenced by all harmonic components caused by the saturation of the main flux circuit at no-load operation as well as the leakage flux circuits at the locked-rotor operation, whereas the model represents the fundamental harmonic only. On the other hand, Fig.2a compares the results for such an operation condition when the fundamental harmonic components of the motor quantities are more dominant., and therefore the situation got to be much better.



(a) no-load (b) locked-rotor

Fig. 1. Identification results: marked points - experiment
dashed line - before identification
continuous line - after identification



(a) (b)

Fig.2. Identification results:
(a) - model verification for load operation
(b) - B-H characteristic from the catalogue (dashed), and after identification (continuous)

To obtain appropriate values of identification variables, a proper feasible region has been defined by means of 21 linear inequality constraints. All obtained alterations of theese variables have a reasonable explanation. For instance, Fig.2b shows the B-H characteristic of the EB4 magnetic sheet at two stages: based on catalogue data and used at the very beginning of the identification process, and after this process. An imporatant reason of the differences of the characteristic shapes can be an additional heat and chemical treatment applied to the sheet.

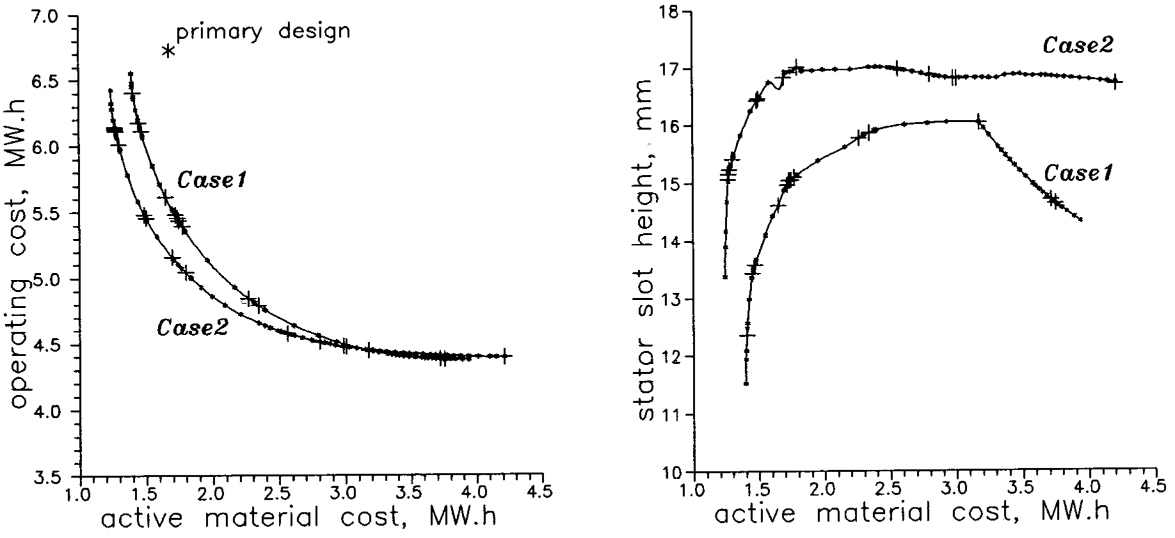
5. Design optimisation.

The aim of the work presented in this paper was to find an optimal design solution of the motor in question, on the assumption that the magnetic sheet EB4 is replaced by another one Ei60 with the same thickness and specific power loss. An multicriterial approach described earlier [2] has been applied to reach the goal. All constant data, particularly those concerning prices, were updated. For obvious reasons, only a limited portion of identification results could be used up in the optimised model. The compromise solution sets related to the defined optimisation problem were determined by means of 14 optimisation variables representing the motor construction. Imposed design requirements were considered through the definition of a feasible region in the form of nine nonlinear and 12 linear inequelity constraint functions. An effective procedure for automatic solving the bicriterial problem has been worked out and applied.

Fig.3 presents optimisation results for two cases:

Case1 - single-layer, single-path stator winding

Case2 - two-layer, two-path stator winding, chording=7/9



(a) (b)

Fig.3. Bicriterial optimisation results, see text below for explanations.

Little points marked on the curves are related to the subsequent solutions of corresponding scalar optimisation problems [6], and are produced by the above mentioned automatic solving procedure. Greater (+) signs inform, where an alteration of the feasible region structure occurs. The great (*) sign beyond the curves at Fig.3a concerns the design solution relevant to the existing motor after replacing the magnetic sheet. The benefit of applying optimisation seems to be obvious at this stage of designing procedure.

Presenting these and other design quantities in the form proposed at Fig.Fig. 3a,b can be helpful when taking the final decision of the choice of the best design. In the case of inverter-fed induction motors applied in traction drives, such quantities as rated slip, efficiency, and the amplitudes of pulsating torques [7] can be used for this purpose.

6. Conclusions.

A great virtue of the equivalent circuit proposed in the paper, and portraying the motor in question, seems to be its simplicity, but an analysis of the relationships (1) and (2) as well as identification results suggest that one can expect correct results of optimisation calculations. A further research work is required to check the validity of the model, although it arise from Fig.Fig. 1a, 1b, and 2a, that such a validity for the fundamental harmonic occurs.

In the applied identification procedure, a particular attention should be given to the relationships and formulae describing the B-H characteristic, core losses, the saturation of leakage reactancies, and the winding temperature, particularly that of the rotor cage.

Fig.3a confirms the advantage of applying proposed bicriterial approach over a scalar optimisation. The decisions are more reliable. The relationship given at Fig.3b for the stator height shows that some alterations of the feasible region structure can involve a rapid change of design quantities. It should be a warning for designers who are trying to estimate compromise solution sets by means of a small number of its elements.

At Figures 2a and 2b, the solution for *Case2* seems to be better but this conclusion may be opposite if additional production costs other than active material ones will be taken into consideration.

Presented approach to designing seems to be particularly useful for a decision-maker and can be considered by producers of induction motors as a standard at a stage of designing.

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