Optimal Design of Rotor Slot Geometry of Squirrel-Cage Type Induction Motors

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Abstract—**This paper deals with the optimal design of squirrel-cage rotor slots and copper bars of high power induction motors with respect to the values of starting torque, breakdown torque, rated values of efficiency and power factor as well as rotor heating. Three geometries of rotor slots and of bars cross-section, keeping the same cross-section area, are considered: rectangular shape, stepped shape and step-holed shape. This study is based on the finite element analysis of the induction motor where only the rotor slots and bars cross-section configurations change from an application to another. The comparison of simulation results proves that important increase of starting torque and high values of efficiency of copper squirrel-cage type induction motors can be obtained in case of step-holed shape of rotor bars cross-section, without significant decrease of the breakdown torque. Criteria for evaluation of optimal geometry of rotor bars and of optimal value of bars cross-section area are studied.**

I. Introduction

The optimal design of classical induction motors with respect to the electromagnetic torque must answer two contradictory requirements, respectively high value of starting torque and high value of breakdown torque. In case of squirrel-cage induction motors, these characteristics are very dependent on the rotor slot geometry [1], [3], [5].

This paper presents the results of a study related to the influence of the rotor slots geometry, respectively of the bars cross-section shape on the starting torque, breakdown torque, efficiency and power factor of a high power induction motor with copper squirrel-cage [2], [4].

II. Numerical Model

A 500 kW, 750 rpm, 6 kV, 50 Hz three-phase squirrel-cage induction motor and three shapes of the rotor bars cross-section are considered, Fig. 1. The area of rotor bars and end-ring cross-section, the radial dimension of the rotor magnetic yoke and the stator characteristics are the same for all numerical applications.

The study of the influence of various shapes of the rotor slots on the motor parameters is based on a 2D finite element analysis using a field-circuit coupling. The corresponding numerical model of the motor is able to take into account all the specific electromagnetic field related aspects, such as saturation of magnetic cores, skin effect in the rotor bars, etc.

III. Simulation Results Analysis

A. Rectangular shape bars

In case of rectangular shape of bars cross-section, Fig. 1a, the increase of ratio h_2/a_2 between height and thickness of rotor bars ensures the increase of per unit starting torque (M_p/M_n), Fig. 2, and the decrease of per unit starting current (I_p/I_n), Fig. 3. The very deep-bar configuration, characterized by the ratio h_2/a_2 = 55.94 mm / 4 mm = 13.98, ensures high values of starting torque and reduced values of starting current compared to the shapes characterized by values h_2/a_2 less than 2.

The increase of starting torque with ratio h_2/a_2, Fig. 2, is a positive effect, but with the "price" of an important decrease of per unit breakdown torque (M_{max}/M_n), Fig. 4.

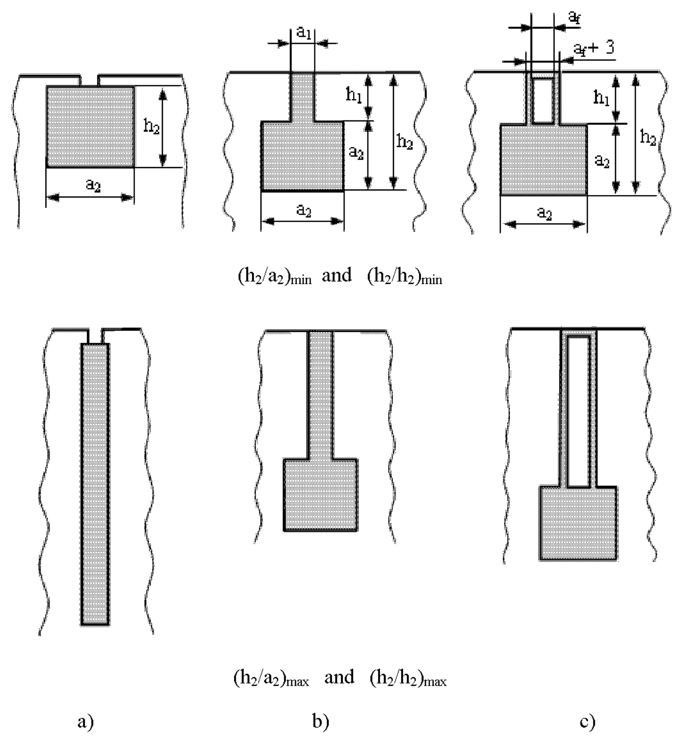

Figure 1. Slot geometries and limit shapes of rotor bars cross-section
a) rectangular shape; b) stepped shape; c) step-holed shape

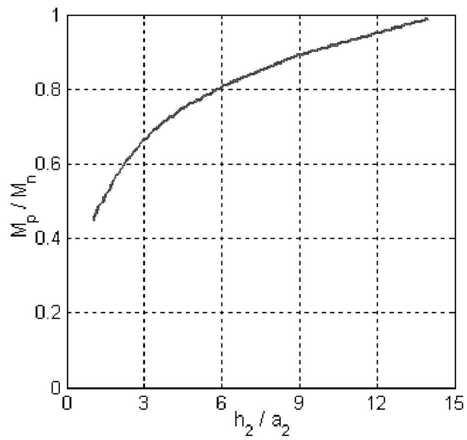

Figure 2. Per unit starting torque (M_p/M_n) versus ratio h_2/a_2 for rectangular shape bar cross-section

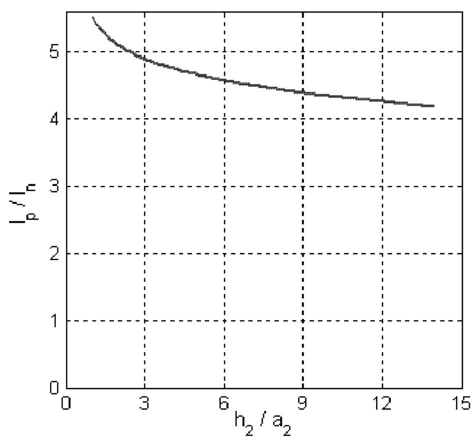

Figure 3. Per unit starting current (I_p/I_n) versus ratio h_2/a_2 for rectangular shape bar cross-section

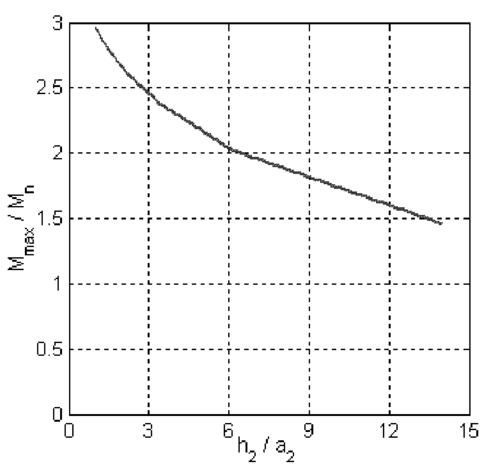

Figure 4. Per unit breakdown torque (M_{max}/M_n) versus ratio h_2/a_2

The two electromagnetic torque – slip characteristics (M-s) in Fig. 5, correspond to the lower $(h_2/a_2)_{min}$ and upper $(h_2/a_2)_{max}$ limits of rectangular bars cross-section geometry, Fig. 1a, considered in this study, i.e. an almost square bar, with a_2 = 15 mm and h_2 = 14.92 mm, solid line, respectively, a deep rectangular bar, with a_2 = 4 mm and h_2 = 55.93 mm, dashed line.

The increase of the ratio h_2/a_2 of bar cross-section significantly affects the current density distribution at motor start-up, Figs 6 - 9.

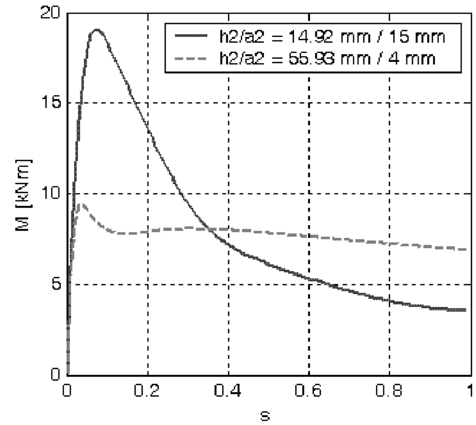

Figure 5. Electromagnetic torque versus slip for rectangular bars

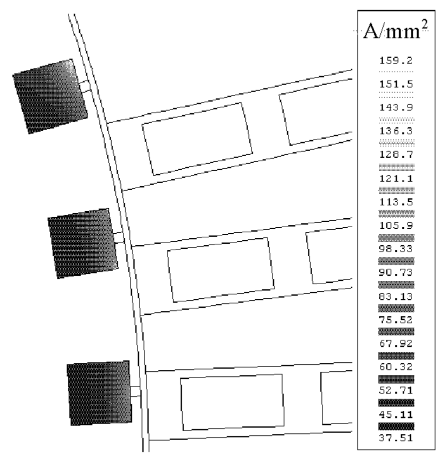

Figure 6. Current density chart in rectangular bars at motor start-up for $(h_2/a_2)_{min}$

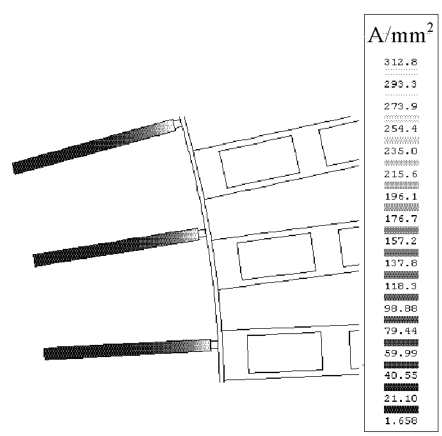

Figure 7. Current density chart in rectangular bars at motor start-up for $(h_2/a_2)_{max}$

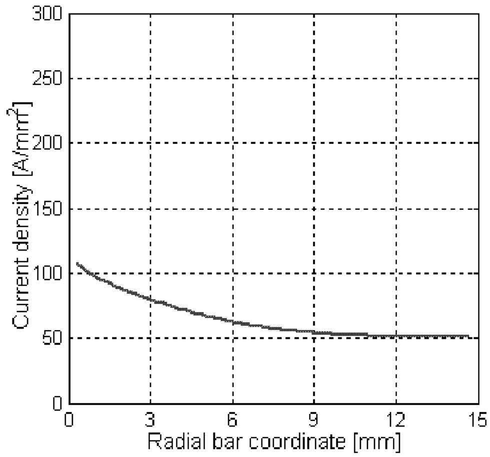

Figure 8. Radial variation of current density in the rotor bars for almost square shape bars

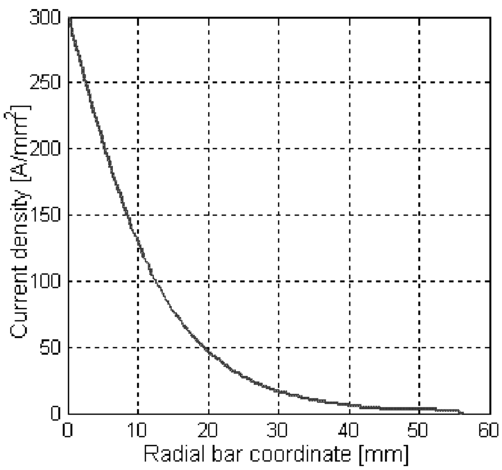

Figure 9. Radial variation of current density in the rotor bars for very deep bars

B. *Stepped shape bars*

In case of stepped shape of bars cross-section, Fig. 1b, the height h_1 of the upper bar step is the parameter of bar cross-section geometry and h_2 is the total height of the stepped bar. The thickness of the upper step has a constant value, a_1 = 3 mm. The lower step of the bar has square shape.

The chart of the current density in the rotor bars at motor start-up, Fig. 10, and the curve of radial variation of this current density, Fig. 11, for the bar characterized by the minimum value $(h_l/h_2)_{min}$ = 10/23.92 = 0.418, shows an increase of the maximum value of the current density in comparison with the rectangular shape bar geometry.

As presented in Figs 12 and 13, it is nonsense to increase the ratio h_l/h_2 over the optimal value $(h_l/h_2)_{opt}$ = 18/31.03 = 0.58, because after this limit both starting torque and breakdown torque decrease.

The electromagnetic torque - slip characteristics (M-s) in Fig. 14 correspond to the minimum value $(h_l/h_2)_{min}$ = 10/23.92 = 0.418 and to the optimal value $(h_l/h_2)_{opt}$ = 0.58. The comparison of these curves with those in Fig. 5 shows the following:

- if the almost square shape bars, with the ratio h_2/a_2 = 14.92/15 = 0.994 are replaced with bars of stepped shape cross-section with $(h_l/h_2)_{min}$ = 10/23.92 = 0.418, the starting torque increases with 58.4 % and to the breakdown torque diminishes with 41.3 %;

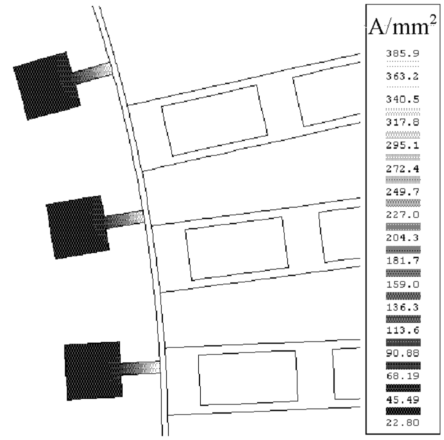

Figure 10. Current density chart in the rotor bars for stepped shape geometry

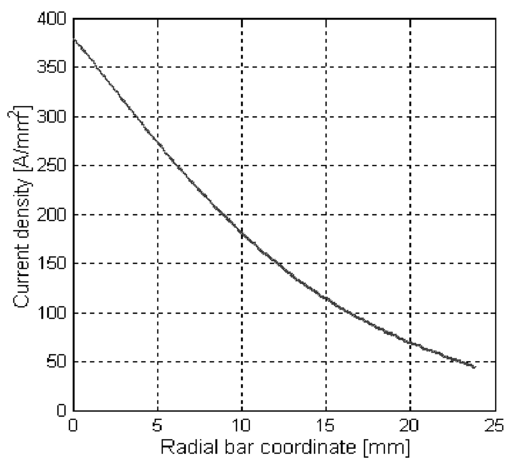

Figure 11. Radial variation of current density in the rotor bars for stepped shape geometry

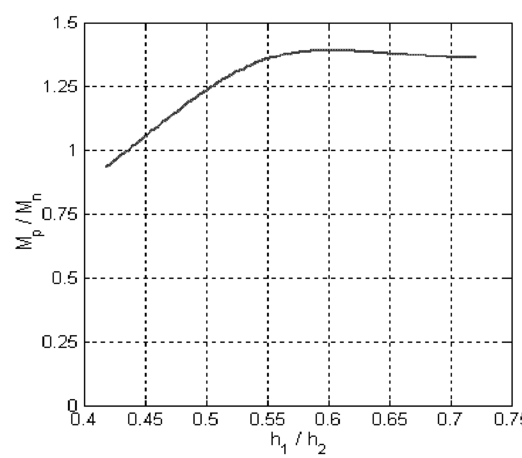

Figure 12. Per unit starting torque (M_p/M_n) versus (h_l/h_2) for stepped shape bars

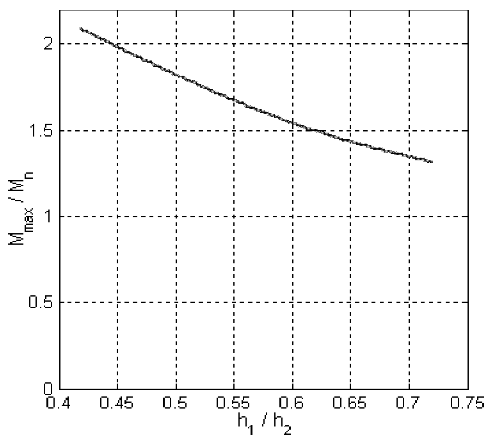

Figure 13. Per unit breakdown torque (M_{max}/M_n) versus (h_l/h_2) for stepped shape bars

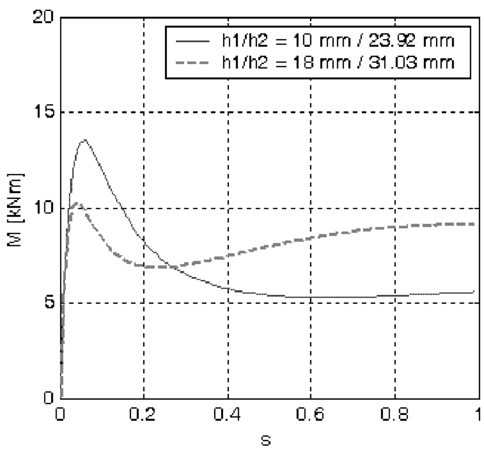

Figure 14. Electromagnetic torque versus slip for stepped shape bars

- if the deep rectangular bars with h_2/a_2 = 55.92/4 =13.98 are replaced with bars of stepped shape optimal cross-section, with $(h_l/h_2)_{opt}$ = 0.58, the starting torque increases with 32.6 % and the breakdown torque increases also with 9.2 %. Both starting torque and breakdown torque increase when changing the deep rectangular shape bars with optimal stepped shape bars.

C. Step-holed shape bars

In case of step-holed shape of bars cross-section, Fig. 1c, the total thickness of the two walls of the upper bar step is equal with the thickness a_l = 3 mm of the upper bar step in case stepped shape bars, Fig. 1b. The height h_l of the upper bar step is the parameter of bar cross-section geometry and h_2 is the total height of the bar. The lower step of the bar has square shape.

For step-holed shape bars, characterized by $(h_l/h_2)_{min}$ = 0.421, Fig. 15, the maximum value of the current density at motor start-up decreases in comparison with stepped shape bars, Fig. 10.

The presence of the bar hole is responsible for the increase of the thickness of the upper area of rotor slot in comparison with the case of stepped shape bars. As result, the value of the leakage reactance of the rotor electric circuit decreases and, as consequence, the value of the breakdown torque increases.

The increase of the parameter h_l/h_2 of step-holed bars over an optimal value has no sense, because both starting torque and the breakdown torque decrease, Figs 16 and 17. For the bar hole thickness a_f = 4 mm, this value is $(h_l/h_2)_{opt}$ = 0.687, and the corresponding value of starting torque is M_p/M_n = 1.294.

The increase of the hole thickness has as effect a slight decrease of the starting torque, Fig. 16, and a more important increase of the breakdown torque, Fig. 17.

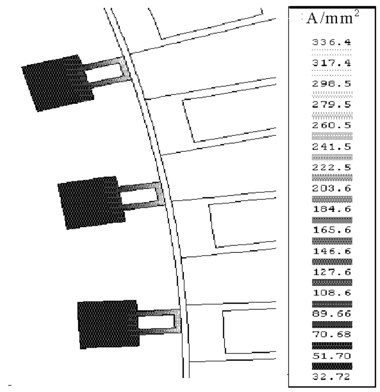

Figure 15. Current density chart in step-holed bars at motor start-up

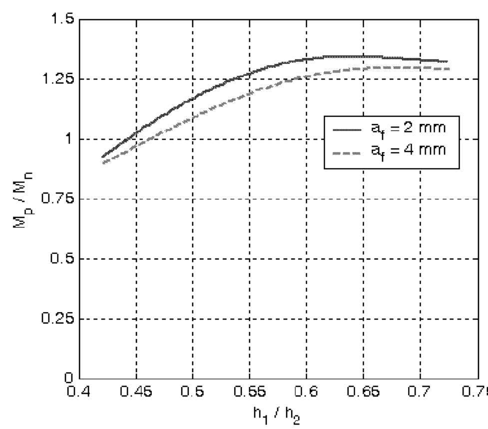

Figure 16. Per unit starting torque (M_p/M_n) versus (h_l/h_2) for step-holed bars

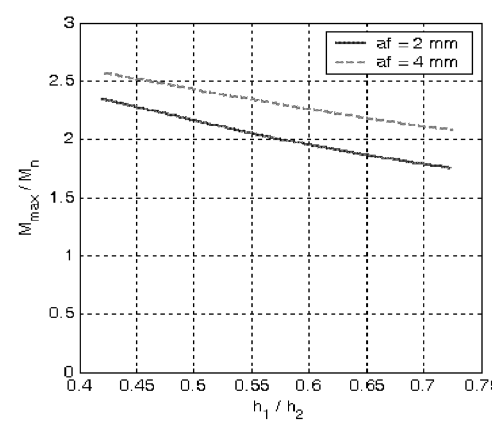

Figure 17. Per unit breakdown torque (M_{max}/M_n) versus (h_l/h_2) for step-holed bars

The electromagnetic torque – slip characteristics in Fig. 18 correspond to the minimum value $(h_l/h_2)_{min}$ = 10/23.7 = 0.421 and to the value h_l/h_2 = 18/30.8 = 0.584, close to the optimal value for stepped shape bars. The comparison with the results in Fig. 14 shows the following:

- if the stepped bars with $(h_l/h_2)_{min}$ = 0.418 are replaced with step-holed bars with practically the same value of the relative height, $(h_l/h_2)_{min}$ = 0.421, the starting torque does not change, but the breakdown torque has an important increase, of 22.8 %;

- if the bars of stepped shape optimal cross-section, with $(h_l/h_2)_{opt}$ = 0.58, are replaced with step-holed optimal bars with practically the same value of the relative height h_l/h_2 = 18/30.8 = 0.584, the increase of the breakdown torque is greater, 43.2 %, but the starting torque diminishes with 12.2 %.

The comparative analysis of the three cases shows that the step-holed shape, with values h_l/h_2 under, but no so far from an optimal value, represents the best solution for motors requiring high values of both starting torque and breakdown torque.

The numerical results related to the rated load motor characteristics in Table 1, show the following:

(a) If the rectangular shape bars change from almost square cross-section, with $(h_2/a_2)_{min}$ = 0.994, to very deep rectangular shape, with $(h_2/a_2)_{max}$ = 13.98, the results prove a very small decrease of motor efficiency, a slight decrease of power factor and a non-negligible increase of Joule losses in the rotor squirrel-cage, about 15 %. As established above, this change has as effects a two times higher starting torque and a two times smaller breaking torque, Fig. 5;

(b) In case of stepped shape bars, the increase of ratio h_l/h_2 up to the optimal value practically does not affect the motor efficiency. In comparison with the very deep rectangular bar, the optimal stepped bar configuration is characterized by almost the same values of the energetic efficiency parameters and by Joule losses in the rotor circuit reduced with 4.2 %;

(c) In case of step-holed shape bars, the values of the energetic parameters are the best and practically independent on the value of h_l/h_2 parameter.

Consequently, the step-holed shape of rotor bars cross-section, characterized by values of the ratio h_l/h_2 under, but no so far from the optimal value, represents also a suitable solution with respect to the energetic parameters of the motor.

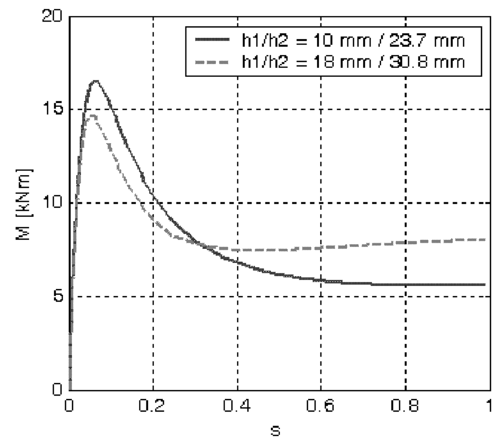

Figure 18. Electromagnetic torque versus slip for step-holed shape bars

D. Increase of bars cross-section area

The increase with 50 % of the cross-section area of the rotor step-holed bars with optimal values of the ratio h_l/h_2 leads to the decrease of the starting with only 1.85 %, to the increase of the breakdown torque with 2.96 %, and to a very small increase of 0.38 % for motor efficiency, and 0.06 % for power factor. Instead, the Joule losses in the rotor bars decreases with 30.2 %, from 5914 W to 4130 W. Therefore, the optimal value of the area of rotor bars cross-section is that for which the temperature of the rotor at rated load operation of the motor has the maximal accepted value.

IV. Conclusions

In case of rectangular shape of bars cross-section, if the ratio between bar height and bar thickness increases without changing the cross-section area, the starting torque increases and the starting current decreases. These positive effects are associated with the decrease of the breakdown torque and a slight decrease of motor energetic parameters.

In comparison with rectangular bars, higher values of the starting torque and practically the same values of motor energetic parameters are obtained with stepped shape bars. The decrease of the breakdown torque with the height of the bar is not as high in this case as in case of deep rectangular bars.

TABLE I.
Rated Load Motor Characteristics (P_2 = 500 kW)

	Rectangular shape bars, Fig. 1a		Stepped shape bars, Fig. 1b		Step-holed bars, Fig. 1c, a_f= 4 mm	
	$(h_2/a_2)_{min}$ = 0.994	$(h_2/a_2)_{max}$ = 13.98	$(h_l/h_2)_{min}$ = 0.418	$(h_l/h_2)_{opt}$ = 0.58	$(h_l/h_2)_{min}$ = 0.422	h_l/h_2 = 0.584
I_n [A]	58.40	64.10	60.40	62.60	58.50	58.90
n_n [rpm]	741.5	740.3	741.1	740.7	741.5	741.5
η_n [%]	95.40	95.10	95.30	95.20	95.40	95.40
$\cos\varphi_n$	0.860	0.790	0.830	0.800	0.860	0.850
M_n [kNm]	6.455	6.482	6.475	6.459	6.468	6.443
P_{J2n} [kW]	5.818	6.669	6.094	6.388	5.829	5.848

Due to the increase of bars resistance during the motor start-up, the step-holed bars ensure also high values of the starting torque. In addition, the rotor leakage reactance in this case being lower in comparison with stepped bars, the decrease of the breaking torque with the increase of the rotor bar height is not so important as in the cases of deep rectangular bars or stepped bars. The energetic parameters of the motor with step-holed bars are close to the maximal values, corresponding to the bars with almost square cross-section.

Since the influence of the area of bar cross-section on the rotor Joule losses is much more important than on the motor operation and energetic parameters, the optimal value of this area is that for which the rotor heating at motor rated load operation corresponds to the maximal accepted value of rotor temperature.

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