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# ANALYSIS OF SQUIRREL CAGE MOTORS USING A FIELD PROGRAM

**SUMMARY** *The paper describes preparing and carrying out calculations of basic parameters of an induction motor using the FEM analysis. Computation of losses, currents induced in windings and torques were made on the basis of calculated values of magnetic induction in squirrel cage motors with 2 and 4 poles. Results of calculations obtained from the FEM analysis were compared with results of design calculations on the basis of a circuital schematic diagram which were then compared with results of laboratory measurements for these machines.*

**Keywords:** *induction motors, calculation of motor losses, electrotechnical metal sheets, analysis by the method of finite elements*

## 1. INTRODUCTION

Designing motors, using circuital methods has been conducted at the IEL Electrical Machine Department for many years [2]; several series of machines produced by leading producers in Poland were created on this basis. One of the programs developed at IEL is OSIN-ETA [8], it is an optimizing program which in the first phase of its action calculates an ideal motor and then it determines all dimensions and data of the winding of a real motor (a suboptimal solution). The program permits full optimizing calculations as well as calculations at assumed constant values of some parameters.

Development of computer technics and field programs based on finite elements allows for a deeper analysis of motors based on distribution of magnetic fields. Designing induction cage motors can be effectively supported using finite element methods which results in a more accurate analysis of these objects [3]. Full parametrization of motor structures, as objects of investigations also allows for fast changes in the geometry of the machine being designed as well as efficient identification of the values of magnitudes which characterize the machine.

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In conjunction with introduction of new methods for determining losses in induction motors, described in the PN-EN 60034-2-1:2010 and PN-EN 60034-30:2009 standards, laboratory measurements of losses of two induction motors were carried out and the results were compared with results of two different calculation methods basing on the circuitry and field model of the induction machine. The aim of the paper is to determine the degree of accuracy of calculation methods compared with of the measurement method according to the new requirements of standards.

Using field methods for analyzing the state of operation of induction motors is a procedure often used in testing machines. The field analysis permits for a fast verification of machine parameters, without measurements. Many examples of application of the FEM method for determining operation characteristics and parameters of different types of induction motors can be found in references. Characteristics of the idle operation and of the short circuit state of the 90 L-4 cage motor were determined using the FEM analysis for example in reference [1]. Efficiency of a cage motor and torques at low and high speeds were determined using the FEM analysis in reference [7].

Two numerical models were formulated for the FEM analysis of cage type 2- and 4-pole motors of 15 kW each. Laboratory measurements were made in addition for both the machines and also verifying calculations, using a program developed at IEL. Results of the two calculation methods, one based on the classical circuital model and another using a field model of the machine, were compared with results of laboratory measurements and included into the paper below.

Laboratory tests of motors were carried out according to the requirements of the PN-EN 60034-2-1:2010 standard. Temperature of the stator winding was determined applying the resistance method using PT 100 sensors. Losses and efficiencies of three-phase induction machines with powers of 1kW up to 150kW were determined using the method of particular losses with a load test, where the additional load losses $P_{LL}$ are determined from the residual losses (see p. 8.2.2.5.1 of the standards [5]). The results obtained by this method are characterized by low uncertainty.

## 2. OBJECTS OF ANALYSIS

Two cage type, 2- and 4-pole 15 kW induction motors were investigated. Models suitable for FEM calculations were developed for each one of them, where stationary and moving elements were distinguished. The later ones concern the motor together with air gap, designed in a rotating system of coordinates.

a) b)

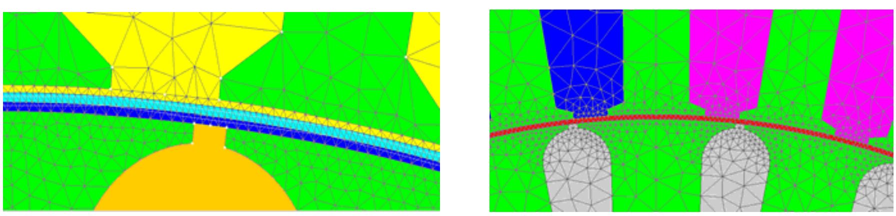

**Fig. 1. The mesh of the motor air gap:** a) of the 2-pole one, b) of the 4-pole one

Initial calculations of the auxiliary magnitude, “the magnetic torque”, as a function of angular shift, determine, as a result, the angular dislocation of the rotor versus the stator, which (the dislocation) is used for calculating the value of the remaining magnitudes, e.g. of torques and losses.

In the case of the 4-pole motor, the air gap was modelled by a single layer of finite elements, while in the 2-pole motor – as a triple layer of such elements.

The field calculations were carried out using the FLUX 2D/3D v.11.1 program. The field models take into consideration the frequency of the power supply voltage, the nonlinearity of magnetic materials and the effect of temperature on the resistivity of conducting elements. The primary winding was modelled as made of copper wire with a conductivity of $\gamma$ = 57000 S/mm and an aluminium cage of the rotor, with a conductivity of $\gamma$ = 35000 S/mm, on the basis of the calculations of the field model; the following basic parameters of the motors were identified: current of the primary winding, power taken from the grid, rotational speed and torques. These magnitudes were compared with data obtained from measurements made acc. to the latest requirements of standards [4, 5, 6].

## 2.1. The 2-pole motor

The first one of the analysed objects was the 2-pole motor with rated data: $P$ = 15 kW, $U$ = 400 V; $I$ = 26,1 A; $f$ = 50 Hz; $n$ = 2940 rpm; $\eta$ = 91,0%; cos$\varphi$ = 0,91; $2p$ = 2. Cage material – aluminium, material of the sheet metal – metal sheet M470-50A.

**TABLE 1**
List of dimensions and data of the winding of the 2-pole 15 kW motor

| | **Stator** | **Rotor** |
|---|---|---|
| **ext/int diameter [mm]** | 245/142 | 140,2/54 |
| **Air gap [mm]** | 0,9 | |
| **Lamination length [mm]** | 136 | 136 |
| **Slot number** | 36 | 28 |
| **Winding pitch** | 13 | |
| **Winding wire diameter [mm]** | 0,82/0,88 | |
| **Number of serial coils per phase** | 162 | |
| **Number of wires in slots** | 2x81 | |
| **Number of parallel branches** | 2 | |
| **Number of parallel wires** | 3 | |
| **Type of winding** | 2-layers | 2-layers |
| **Shorting ring of the cage [mm]** | | $a_{pń}$ = 25 |
| | | $b_{pń}$ = 35 |

The equivalent schematic diagram of the 2-pole motor winding, connected as a delta, introduced into the field program is shown in Figure 2.

The general symbols describing the schematic diagram are:

- (L) – elements representing the inductance of coil out hangs,
- (B) – elements of the winding – coils of copper wire to which the resistance of the whole winding is assigned,

- (U) – two linear power supply voltages, where the third one results from nulling the sum of complex values of voltages,
- (Q) – elements of the rotor cage containing resistances and inductances of bars and fragments of shorting rings.

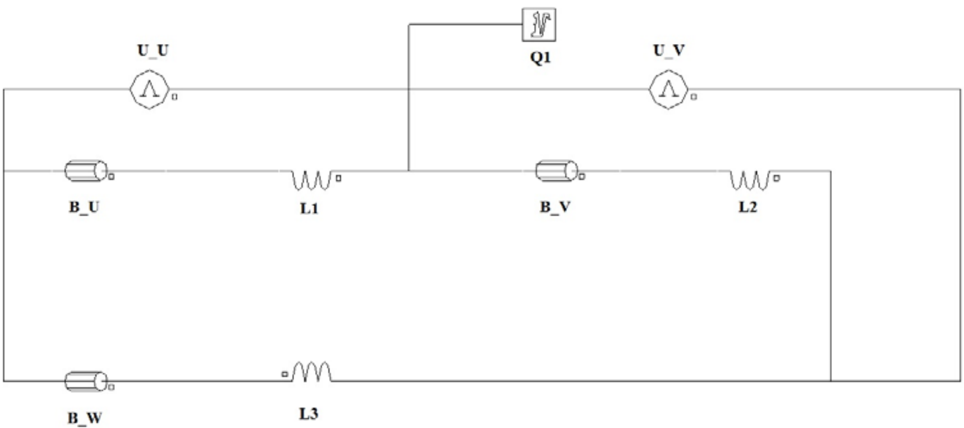


**Fig. 2. Equivalent schematic diagram of the 2-pole motor connected in delta together with an additional element representing the rotor cage**

Values of the particular elements of the equivalent schematic diagram:

B_U, B_V, B_W = 0,9895 Ω

L1, L2, L3 = 4,0484 mH

$U_u$ = 400 $e^{j0°}$ V; $U_v$ = 400 $e^{-j120°}$ V

Cage: number of bars = 28

- Resistance of a section of the shortening ring $R_{pn}$ = 56,3 μΩ
- Inductance of a section of the shortening ring $L_{pn}$ = 9,21 nH

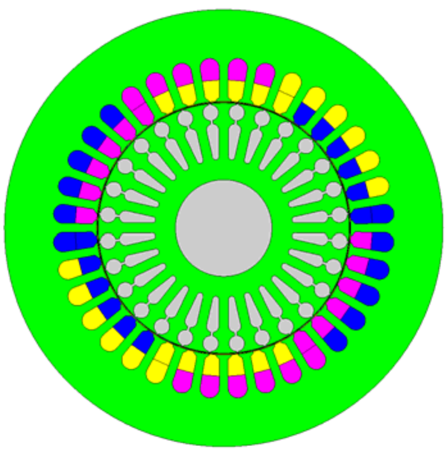

**Fig. 3. Geometry of rotor and stator metal sheets of the 2-pole motor with indicated regions of the particular winding coils**

Traces of the magnetic induction were determined: in yokes and teeth, both of the stator and rotor, as shown in Figure 4. In the diagrams regions of magnetic poles, as well the effect of teeth on the value of magnetic induction, can be clearly seen.

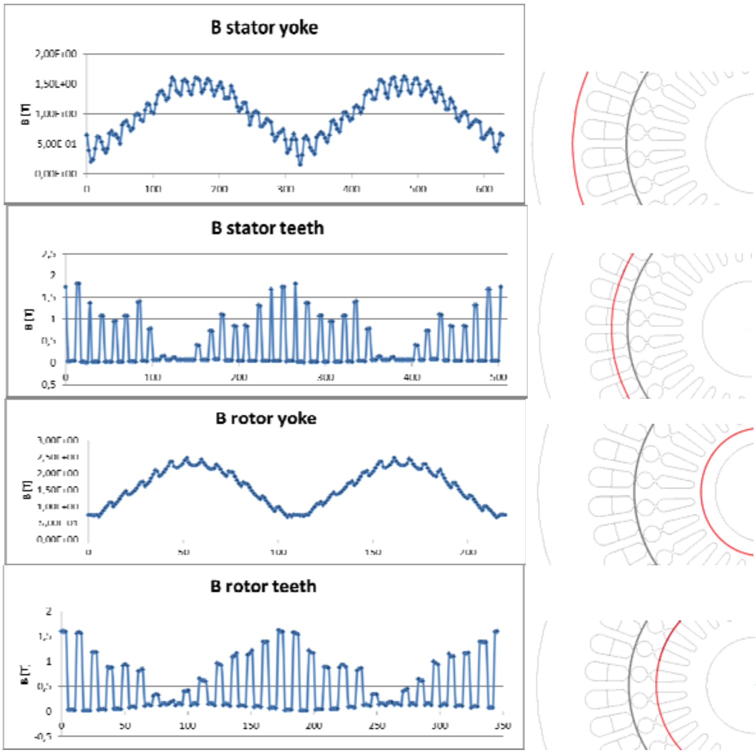


**Fig. 4. Traces of the magnetic modulus in the 2-pole motor at slip value 0,02**

Mean values of the magnetic induction were identified in every one of the motor elements:

- In the rotor yoke $B_{jw}$ = 1,59 T (s = 0,02)
- In the stator yoke $B_{js}$ = 1,02 T (s = 0,02)
- In stator teeth $B_{zs}$ = 1,11 T (s = 0,02)
- In rotor teeth $B_{zw}$ = 0,998 T (s = 0,02)

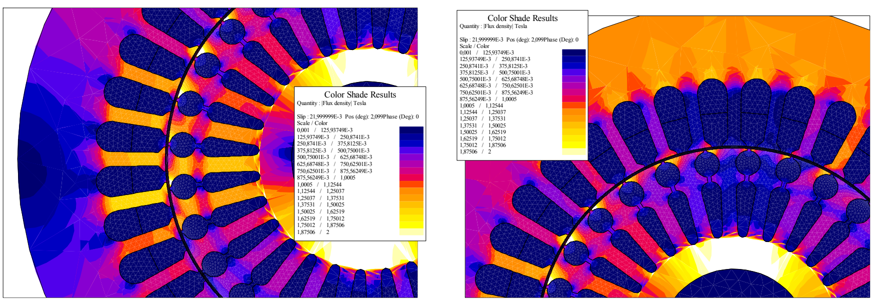


**Fig. 5. Distribution of the module of magnetic induction in the 2-pole motor**

**TABLE 2**
List of measurement and calculation results of the 2-pole, 15 kW induction motor; the present deviations are counted assuming the accurate value obtained from measurements

| Parameters | FEM | measurem ents | OSIN ETA | % FEM | % OSIN |
|---|---|---|---|---|---|
| **slip [-]** | 0,022 | 0,022 | 0,0202 | 0,00 | -8,18 |
| **losses in the core [W]** | 238 | 218 | 233,72 | 9,17 | 7,21 |
| **power taken form the grid [W]** | 16322 | 16600 | 16538 | -1,67 | -0,37 |
| **losses in the rotor winding [W]** | 343,8 | 335,8 | 315 | 2,38 | -6,19 |
| **losses in the stator winding [W]** | 692,4 | 677 | 698,1 | 2,27 | 3,12 |
| **additional losses [W]** | 81,6 | 151 | 151 | -45,95 | 0,00 |
| **phase current [A]** | 15,3 | 15,6 | 15,8 | -1,92 | 1,28 |
| **measured mechanical losses [W]** | 128 | 128 | 128 | 0,00 | 0,00 |
| **mechanical power [W]** | 15076 | 15689 | 15000 | -3,91 | -4,39 |
| **rotational speed [rpm]** | 2943 | 2935 | 2940 | 0,27 | 0,17 |
| **torque [Nm]** | 49,1 | 48,8 | 48,7 | 0,61 | -0,20 |
| **efficiency [%]** | 91 | 90,8 | 90,8 | 0,22 | 0,00 |

Calculations were carried out using two independent design programs and the results of these calculations were compared with results of laboratory measurements in order to determine the degree of likelihood (reliability) of the results of simulation calculations.

In Table 1 measured results are compared with calculation results carried out using accessible programs. The first one, based on the classical circuital method OSIN-ETA program was developed at the IEL Electric Machine Department. It serves for optimization calculations and for designing induction motors [2]. The other one is a program based on the finite element methods Flux 2D/3D. Results of laboratory measurements of the 15 kW motor made according to new requirements of standards, concerning tests of efficiency and losses in induction motors, were adopted as the point of reference. In the table, columns marked % FEM and % OSIN are the present deviations of the particular magnitudes obtained from calculations of the modelled motor with respect to those gained from laboratory measurements made on the real machine.

The field calculations show high consistency with results of laboratory measurements (consistency up to 2%) for the following magnitudes: slip, power taken from the grid, phase current, rotational speed, driving torque and motor efficiency. A lower consistency of results of field calculations with measurement results can be seen for the following parameters: losses in rotor and stator windings and the mechanical power of the motor (2-4%). A higher value of deviation (9,17%) was noted for losses in the core but this can be connected with nonuniformity of the material of electrotechnical sheet-metal. The value of mechanical losses was taken from measurements while the additional losses in the Flux programme are taken as equal to 0,5% of the power taken form the grid.

Calculations carried out using the OSIN-ETA program show good consistency (up to 2%) in the case of the parameters: power taken form the grid additional losses, phase current, rotational speed, torque and efficiency. Magnitudes with discrepancy of 2-5% are: losses in stator winding, mechanical power (here assumed 15 kW), discrepancies 6-9%: losses in rotor winding, losses in iron and slip obtained from calculations, lower by 8,18% than the measured ones.

## 2.2. Four pole motor

The other analysed object was a 4-pole motor with rated data: $P$ = 15 kW, $U$ = 400 V; $I$ = 27,8 A; $f$ = 50 Hz; $n$ = 1470 rpm; $\eta$ = 91,5 %; cos$\varphi$ = 0,85; 2$p$ = 4. Cage material – aluminium, material of the sheet metal – metal sheet M470-50A.

The equivalent schematic diagram of the 4-pole motor is identical with the diagram of the 2-pole motor shown in Figure 2. Values of the particular elements in the schematic diagram of the 4-pole motor:

B_U, B_V, B_W = 0,7241 Ω;
L1, L2, L3 =1,1048 mH;
$U_u = 400\ e^{j0°}$ V; $U_v = 400\ e^{-j120°}$ V
Cage: number of bars = 28

- Resistance of a section of the shortening ring $R_{pn}$ = 58,2 μΩ
- Inductance of a section of the shortening ring $L_{pn}$ = 8,15 nH

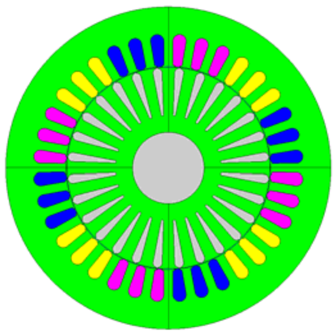

**Fig. 6. Geometry of rotor and stator metal sheets of the 4-pole motor with marked regions of the particular winding coils**

**TABLE 3**
List of dimensions and data of the winding of the 15 kW 4-pole motor

| | **Stator** | **Rotor** |
|---|---|---|
| **ext/int diameter [mm]** | 245/154 | 153,1/54 |
| **Air gap [mm]** | 0,45 | |
| **Lamination length [mm]** | 200 | 200 |
| **Slot number** | 36 | 28 |
| **Winding pitch** | 6,8,10 | |
| **Winding wire diameter [mm]** | 0,75/0,8 | |
| **Number of serial coils per phase** | 144 | |
| **Number of wires in slots** | 192 | |
| **Number of parallel branches** | 4 | |
| **Number of parallel wires** | 2 | |
| **Type of winding** | 1-layer | 1-cage |
| **Shortening ring of the cage [mm]** | | apń = 20 |
| | | bpń = 40 |

**TABLE 4**
List of measurement and calculation results of the 4-pole, 15 kW induction motor; the present deviations are counted assuming the accurate value obtained from measurements

| Parameters | FEM | measurem ents | OSIN ETA | %FEM | %OSIN |
|---|---|---|---|---|---|
| slip [-] | 0,0195 | 0,0220 | 0,0195 | -11,36 | -11,36 |
| losses in the core [W] | 309,6 | 315,8 | 354,3 | -1,96 | 12,19 |
| power taken from the grid [W] | 16684 | 16695 | 16538 | -0,07 | -0,94 |
| losses in the rotor winding [W] | 311,5 | 348,5 | 304,7 | -10,62 | -12,57 |
| losses in the stator winding [W] | 720,0 | 628,1 | 553,8 | 14,63 | -11,83 |
| additional losses [W] | 83,4 | 308,0 | 255,1 | -72,92 | -17,18 |
| phase current [A] | 18,1 | 17,2 | 16,5 | 5,23 | -4,07 |
| measured mechanical losses [W] | 63,0 | 63,0 | 63,0 | 0,00 | 0,00 |
| mechanical power [W] | 15515 | 15689 | 15000 | -1,11 | -4,39 |
| rotational speed [rpm] | 1470 | 1467 | 1470 | 0,20 | 0,20 |
| torque [Nm] | 100,7 | 97,7 | 97,3 | 3,07 | -0,41 |
| efficiency [%] | 91,3 | 89,9 | 90,7 | 1,56 | 0,89 |

In case of the 4-pole motor the values of mechanical losses were also taken from measurements while the additional losses are calculated identically as for the 2-pole motor.

The field calculations show good consistency with results of laboratory measurements (up to 2%) for the magnitudes: losses in core, power taken from grid, mechanical power, rotational speed and motor efficiency. A lower consistency (2-6%) have the parameters: torque and phase current. High differences occur in losses in rotor and stator windings, rotor winding losses lower by 10,6%; stator winding losses higher by 14,6%; slip determined by the field method is also lower by 11%.

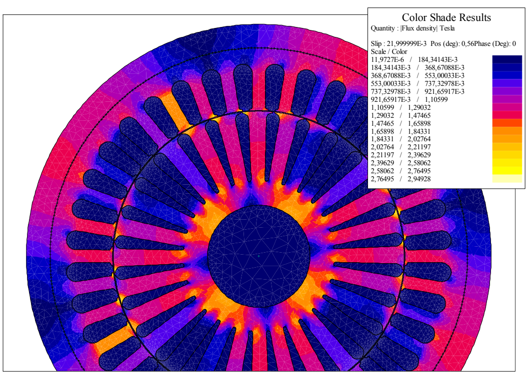


**Fig. 7. Distribution of the module of magnetic induction in the 4-pole motor**

Calculations carried out using the OSIN-ETA program show good consistency (up to 2%) in the case of parameters: power taken from grid, rotational speed , torque and efficiency. Magnitudes with discrepancies 2-5%: phase current, mechanical power (assumed here 15kW), discrepancies above 10%: losses in rotor and stator windings, losses in iron, slip and additional losses.

Calculations based on the analysis by the finite element method give a quite good agreement with laboratory measurement results of a 15 kW, 4-pole motor.

The only one parameter deviating from the values measured and calculated using the design program in both motors are the additional losses, which in the case of field calculations are being adopted at the level of 0,5% of the power taken form the grid. This assumption however, deviates significantly from the measured values and it finally increases the calculated efficiency of the motor.

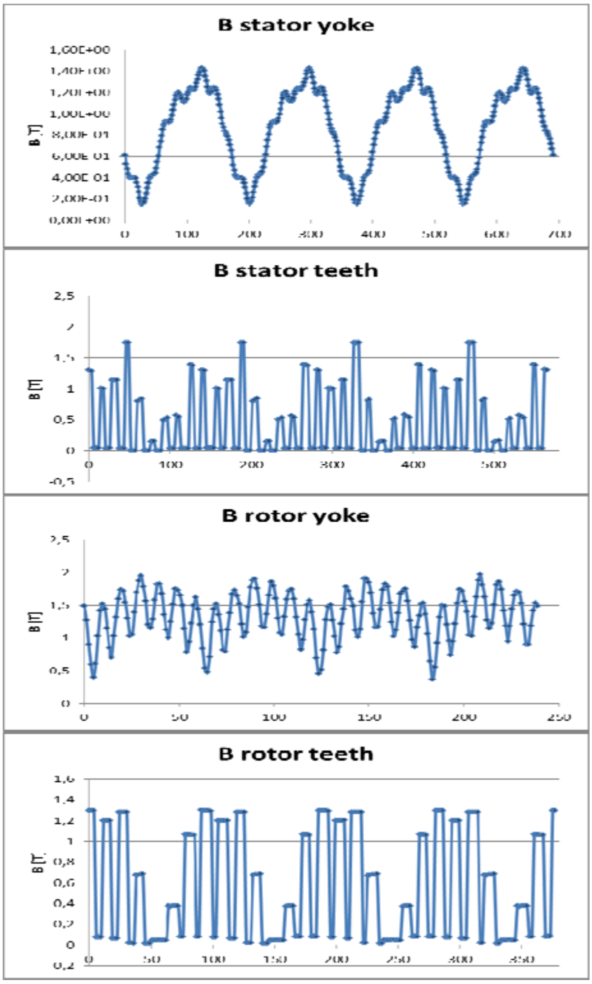


**Fig. 8. Traces of the magnetic induction module in the 4-pole motor at slip value 0,02**

Mean values of the magnetic induction were determined in every element of the motor:

- In the rotor yoke $B_{jw}$ = 1,34 T (s = 0,02)
- In the stator yoke $B_{js}$ = 1,06 T (s = 0,02)
- In stator teeth $B_{zs}$ = 1,30 T (s = 0,02)
- In rotor teeth $B_{zw}$ = 1,21 T (s = 0,02)

# 3. CONCLUSIONS

Scarcity of the compared material – only two investigated motors – does not give us the right to formulate generalizing conclusions, however they can be stated in relation to the two exemplary motors for which the comparison study described in this paper, was conducted.

The investigations conducted allow us to state prudently, that the design calculations for induction motors conducted using traditional programs based on circuital models can be supported by field calculations realized by a professional field program.

First of all, a field program provides visually trustworthy diagrams of the distributions of magnetic induction in stator and rotor yokes and teeth , which can help the designer, make easier a right choice of windings from the view point of elimination of damaging interactions resulting from a mutual interaction of two slot structures loaded moreover by the effect of shortening the windings.

The comparison of the results of design calculations with results of field calculations has shown, that the latter ones do not differ significantly from the design results and the divergences with respect to the values of basic parameters measured on the already carried out motors are, generally speaking, of the same order of magnitude. This concerns; first of all such magnitudes as: phase current of motor windings, losses of power in stator and rotor winding, losses in stator core, the rated torque, and so on.

As to the additional losses, concrete calculation results could be expected from the field program. As it is known, standards for testing induction motors admit evaluating values of this magnitudes with respect to the rated power and the field programs do not have anything new to offer in this respect.

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# ANALIZA SILNIKÓW KLATKOWYCH PROGRAMEM POLOWYM

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**STRESZCZENIE** *Analizowano wyniki pomiarów dwóch silników klatkowych (2 i 4 biegunowego) oraz wyniki obliczeń analitycznych wykonanych dwoma różnymi programami (jeden program projektowy wykonany w NME oparty o model obwodowy silnika, drugi program bazujący na metodzie elementów skończonych).*

*Uzyskane wyniki potwierdzają dość dobrą zgodność z wynikami pomiarów więc można obie metody wykorzystywać przy projektowaniu jak również w celach kontrolnych. Program bazujący na metodzie elementów skończonych do pełnej analizy potrzebuje dokładnego zestawu danych geometrycznych badanego obiektu jest także bardziej czasochłonny co przy projektowaniu jest pewnym mankamentem. Do wstępnych obliczeń projektowych bardziej nadają się programy bazujące na schemacie obwodowym maszyny są o wiele szybsze. Natomiast program oparty o metodę elementów skończonych bardziej nadaje się do weryfikacji uzyskanego projektu w drodze szybkich obliczeń na bazie metody obwodowej.*

*W wyniku przeprowadzonych analiz otrzymano dość dobrą zgodność obliczeń wykonanych metodą FEM z wynikami badań laboratoryjnych obu silników.*

**Słowa kluczowe:** *silnik indukcyjny, analiza polowa, metoda elementów skończonych, pomiary strat w silnikach indukcyjnych*