An Estimation Method of the Manufacturing Process' Effect on Iron Losses

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***Abstract*—More than 60% of industrial electricity consumption is made by electrical drives with induction motors. In 2008, by IEC 60034-30, the International Electrotechnical Commission defined the efficiency classes of induction motors namely: IE1, IE2 and IE3. The IE4 was defined in 2010 by IEC 60034-3. From 1 January 2015, the induction motors with a rated output of 7.5-375 kW shall not be less efficient than the IE3 class (Premium Efficiency Class). In order to obtain IE3 motors, manufacturers need to have a design method which takes into account the influence of the technological process on the properties of materials used; specially magnetic properties. This paper presents a new method to estimate the iron losses taking into account the effect of the mechanical cutting on the specific iron losses of the sheets. The method presented enables more accurate determination of the iron losses taking into account the effect of the punching process on the magnetic properties of sheets without a significant increase of the computational time. The case of M400 iron sheets was analyzed.**

***Index Terms*—Design engineering, Energy efficiency, Induction motors, Magnetic circuits, Magnetic losses.**

I. INTRODUCTION

More than 60 % of industrial electricity consumption is made by electrical drives with induction motors. Consequently, increasing the energy efficiency of the produced induction motors has a significant contribution to energy saving. In 2008, by IEC 60034-30, the International Electrotechnical Commission defined the efficiency classes of induction motors (low voltage, squirrel cage) namely: Standard Efficiency (IE1), High Efficiency (IE2) and Premium Efficiency (IE3). The IE4, Super Premium Efficiency, was defined in 2010 by IEC 60034-3.

According to the regulation no. 640/2009 of the European Commission, to implement Directive 2005/32/EC of the European Parliament and the Council, with effect from 1 January 2015, the induction motors with a rated output of 7.5-375 kW shall not be less efficient than the IE3, or should the IE2 efficiency level but be equipped with a variable-speed drive. As a result, induction electric motors manufacturers must adapt to these requirements.

In the design of induction motors [1-2], [18-20] the accurate modeling of motor characteristics is paramount. One of the critical points is to evaluate the iron losses. The magnetic circuit is subjected to working conditions difficult to model, namely: the presence of the phenomenon of saturation, non-sinusoidal form and variable frequency of the voltage applied. In these conditions, it is necessary to improve the design methods and to use materials with superior electrical and magnetic characteristics. On the other hand, knowledge of the manufacturing process influence on the magnetic properties of electrical sheet has a crucial role.

As is well known [4-10], manufacturing processes such as cutting, punching, drilling, pressing, welding, have the effect of damaging the magnetic properties of electrical sheet and therefore increase the iron losses.

Mechanical cutting causes local deterioration, near the cut edge, of the magnetic properties of the iron sheet [11-17]. This effect is also influenced by the contour shape of the cut. On the other hand, the mechanical cutting causes deformations of the iron sheets that amplify the effect in the magnetic circuit of the motor.

This paper presents a method to estimate the iron losses taking into account the effect of the mechanical cutting on the specific iron losses of the iron sheets. The method presented has the aim to allow manufacturers of induction motors a more accurate estimation of the iron losses without a significant increase of the computation time.

II. DETERMINATION OF THE CUTTING EFFECT ON THE SPECIFIC IRON LOSSES

The measurements were carried out of iron sheet M400-65 by using samples of 30mmx300mm. Samples were made using a special punch as to be obtained in a similar way as the induction motor's magnetic circuit.

To maximize the deformed area of the cut edges and by this the cutting effect, in addition, a total of 4 samples has been made with respective widths: 15, 10, 7.5 and 5 mm. The numbers of sections performed to obtain the width values are listed in Fig. 1.

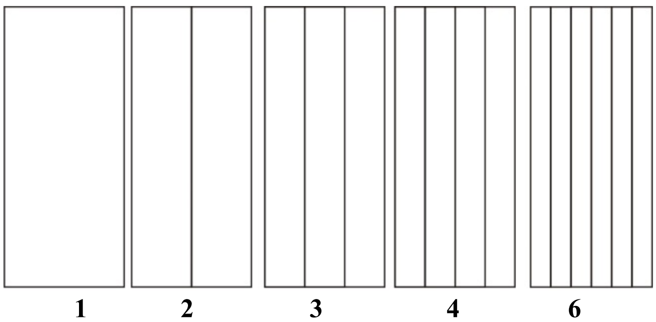


Figure 1. The number of sections

This work was supported by a grant of the Romanian Ministry of National Education, UEFISCDI, project number PN-II-PT-PCCA-2011-3.2-0373.

Digital Object Identifier 10.4316/AECE.2014.02008

Specific losses were determined for 14 values of magnetic polarization, between 50 and 2000 mT. The measurement results are presented in Table I.

TABLE I. THE MEASUREMENT RESULTS

sections	1	2	3	4	6
width [mm]	30	15	10	7.5	5
J [mT]	P_s [W/kg]	P_s [W/kg]	P_s [W/kg]	P_s [W/kg]	P_s [W/kg]
50	0.009	0.010	0.011	0.012	0.014
100	0.036	0.041	0.045	0.049	0.056
200	0.129	0.142	0.157	0.167	0.190
250	0.187	0.206	0.228	0.241	0.275
500	0.581	0.633	0.699	0.743	0.847
1000	1.888	2.021	2.184	2.301	2.520
1200	2.675	2.844	3.062	3.218	3.507
1500	4.574	4.791	5.060	5.221	5.532
1550	4.887	5.043	5.280	5.411	5.708
1600	5.215	5.361	5.599	5.737	6.029
1650	5.540	5.660	5.907	6.059	6.335
1700	5.878	5.956	6.216	6.368	6.697
1750	6.199	6.182	6.457	6.630	6.894
2000	6.356	6.530	6.789	7.020	7.291

Note that losses grow uniformly over the entire range of magnetic polarization.

This means that for induction motors that operate in saturation region, taking into account the cutting process (in the manufacturing of sheets) is necessary because it has direct influence on the losses.

III. Iron Losses Estimation and Experimental Validation

The measured data in Table I were integrated in the existing software [18-20] for designing induction motors. The software was produced by the first author and published for the first time in [18]. Fig. 2 shows the main menu of the program. In addition to the others existing software, in an innovative user-friendly interface, the program allows:

- Using a database including induction motors being currently manufactured and the characteristics of the materials used. It is presented in Fig. 3.
- Designing the induction motor (three- / single-phase) in five different computational variants: a) Imposed transversal and longitudinal geometry; b) Imposed transversal geometry; c) Imposed stator transversal geometry; d) Not imposed geometry; e) Re-computing (a motor is re-computed for different materials).

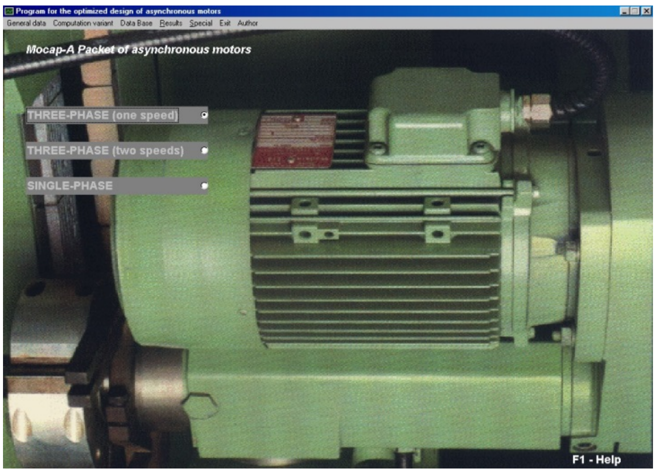


Figure 2. The main menu of the program

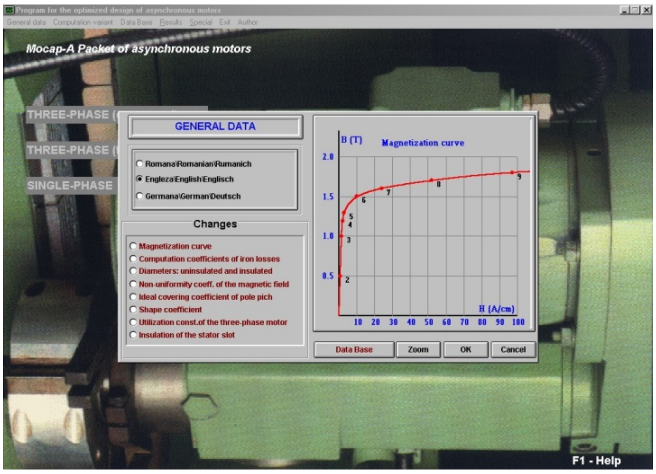


Figure 3. The data base

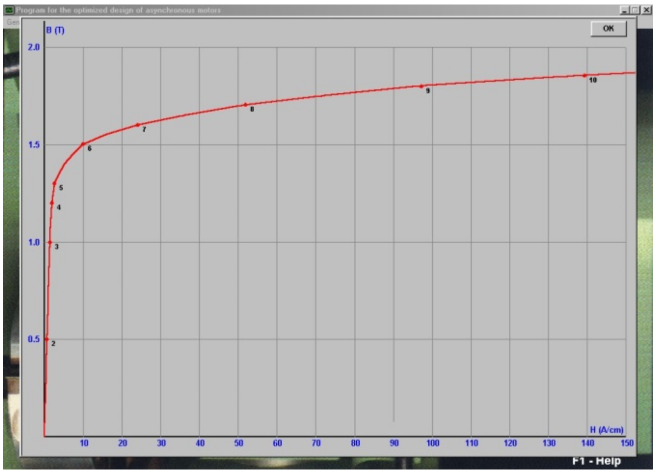


Figure 4. The magnetization curve of the M400 sheet

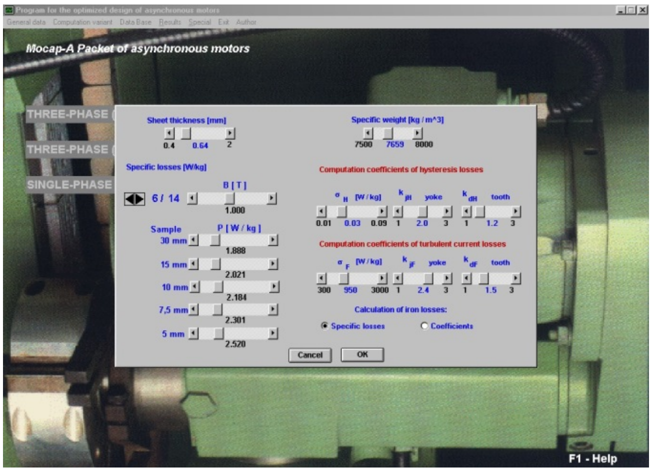


Figure 5. The specific losses

The magnetization curve of the M400 iron sheet was introduced in the database (Fig. 4) and the values of specific losses in Table I were introduced as well (Fig. 5).

A three-phase induction motor of 11 kW and 1000 rpm has been designed. For this motor, the IE3 efficiency is 90.3%, according to IEC 60034-30 and the minimum allowable efficiency is 88.8%, according to IEC 60034-1, Section 11.1 Tolerances. The stator and rotor transversal geometry is given in Fig. 6 and 7.

The values of iron losses were obtained by interpolation using the data contained in Table I (or Fig. 5). The Lagrange interpolation, using polynomials of second degree, has been used [21].

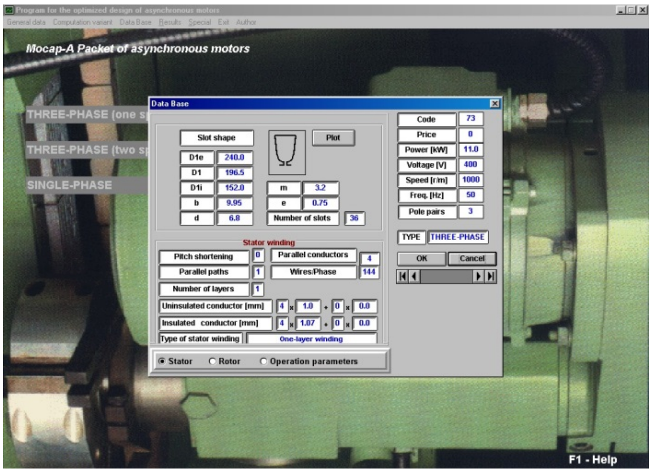


Figure 6. The stator transversal geometry

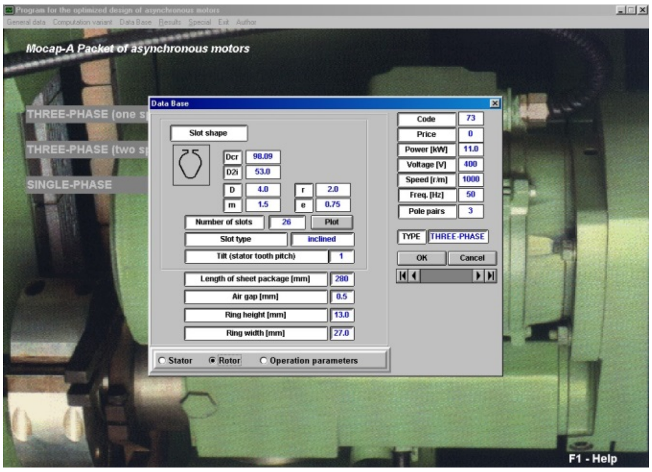


Figure 7. The rotor transversal geometry

The general corresponding relationship is:

$$P(x) = \sum_{i=1}^{3} y_i \cdot \prod_{\substack{j=1 \\ j \neq i}}^{3} \frac{x - x_j}{x_i - x_j} \tag{1}$$

In which:

$P(x)$: is the unknown function, in this case the iron losses in the yoke (or teeth);

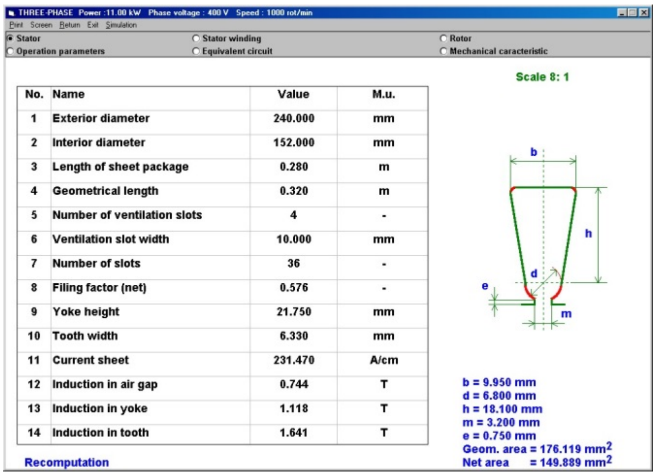
x: is the variable depending on the corresponding value of the unknown function is obtained, in this case the magnetic polarization in the yoke (or teeth);

(x_i, y_i): are three successive pairs of measurements (magnetic polarization, specific losses), selected from Table I, so that the value of x to be included in an interval determined by two successive values of x_i values.

Choosing one of the five curves determined by the values contained in Table I is achieved by linear interpolation using sample widths values specified in Table I in relation to the width of the yoke (ie tooth).

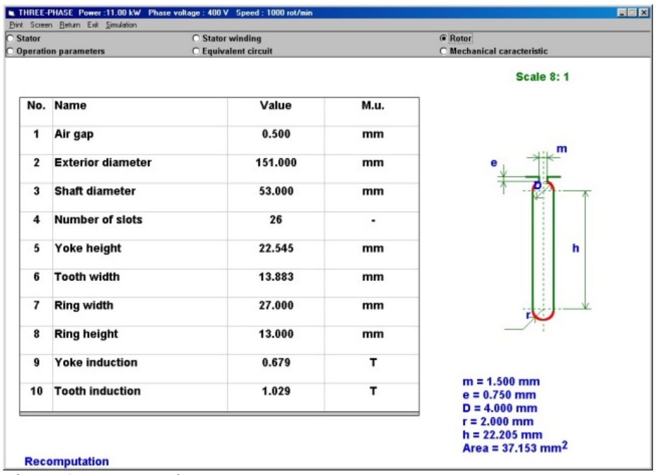
The results are presented in Fig. 8, 9 and 10. The calculated and measured values of the operating parameters are shown in Fig. 10.

It finds a good agreement between the calculated value of iron loss (180.072 W) and measured value (188 W). The measured efficiency is 88.91%, this value is included in the limits requested by the IE3 class, for the designed motor: 88.8% - 90.3%.



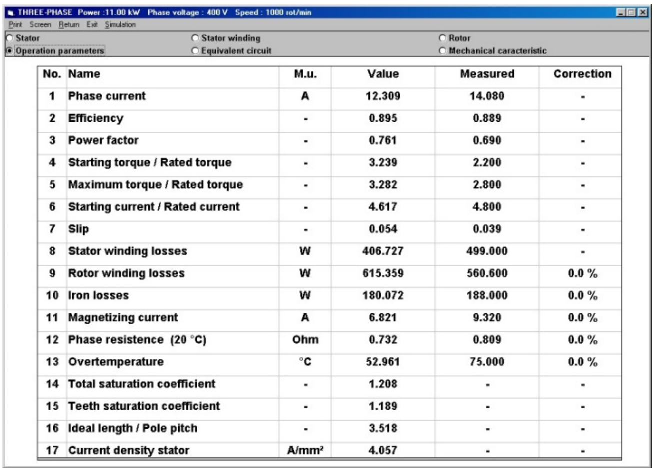
No.	Name	Value	M.u.
1	Exterior diameter	240.000	mm
2	Interior diameter	152.000	mm
3	Length of sheet package	0.280	m
4	Geometrical length	0.320	m
5	Number of ventilation slots	4	-
6	Ventilation slot width	10.000	mm
7	Number of slots	36	-
8	Filing factor (net)	0.576	-
9	Yoke height	21.750	mm
10	Tooth width	6.330	mm
11	Current sheet	231.470	A/cm
12	Induction in air gap	0.744	T
13	Induction in yoke	1.118	T
14	Induction in tooth	1.641	T

Figure 8. Stator results



No.	Name	Value	M.u.
1	Air gap	0.500	mm
2	Exterior diameter	151.000	mm
3	Shaft diameter	53.000	mm
4	Number of slots	26	-
5	Yoke height	22.545	mm
6	Tooth width	13.883	mm
7	Ring width	27.000	mm
8	Ring height	13.000	mm
9	Yoke induction	0.679	T
10	Tooth induction	1.029	T

Figure 9. Rotor results



No.	Name	M.u.	Value	Measured	Correction
1	Phase current	A	12.309	14.080	-
2	Efficiency	-	0.895	0.889	-
3	Power factor	-	0.761	0.690	-
4	Starting torque / Rated torque	-	3.239	2.200	-
5	Maximum torque / Rated torque	-	3.282	2.800	-
6	Starting current / Rated current	-	4.617	4.800	-
7	Slip	-	0.054	0.039	-
8	Stator winding losses	W	406.727	499.000	-
9	Rotor winding losses	W	615.359	560.600	0.0 %
10	Iron losses	W	180.072	188.000	0.0 %
11	Magnetizing current	A	6.821	9.320	0.0 %
12	Phase resistence (20 °C)	Ohm	0.732	0.809	0.0 %
13	Overtemperature	°C	52.961	75.000	0.0 %
14	Total saturation coefficient	-	1.208	-	-
15	Teeth saturation coefficient	-	1.189	-	-
16	Ideal length / Pole pitch	-	3.518	-	-
17	Current density stator	A/mm²	4.057	-	-

Figure 10. Operation parameters: calculated and measured values

IV. Conclusion

In order to obtain IE3 class motors, manufacturers need to have a design method which takes into account the influence of the technological process on the properties of materials used especially magnetic properties.

This paper focuses on the experimental validation of an estimation method of the iron losses taking into account the effect of the punching process on the magnetic properties of iron sheets. The new calculation method presented in this paper enables more accurate determination of the iron losses considering the mentioned effect and represents the main contribution of the paper.

The case of M400 iron sheets was analyzed. The results show a good agreement between calculated and measured values of the operating parameters. Also, the method presented does not significantly increase the duration of the design calculation. As a result, the motors manufacturers have a useful design program in order to obtain induction motors with increased efficiency.

ACKNOWLEDGMENT

This work was supported by a grant of the Romanian Ministry of National Education, UEFISCDI, project number PN-II-PT-PCCA-2011-3.2-0373.

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