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COMMUNICATIONS

CORE LOSS ANALYSIS OF THE RELUCTANCE SYNCHRONOUS MOTOR WITH BARRIER ROTORS

Peter Hudák [*] — **Valeria Hrabovcová** [*] — **Pavol Rafajdus** [*] — **Jozef Mihok** [**]

This paper presents a numerical method for the core loss calculation based on the FEM. Magnitudes of the magnetic flux density in individual segments of the machine are gained by means of FEM. On the basis of Fourier analysis of the flux density waveform the core loss is calculated for a given value of voltage or current. This method is applied to a reluctance synchronous motor (RSM) with a barrier rotor. At the end, the core loss versus supplied voltage is calculated and compared with the measured values. The coincidence is very good.

Keywords: synchronous machines, reluctance synchronous motor, finite element method, core losses

1 INTRODUCTION

A part of each layout of electrical machines creates core loss and efficiency calculation. The core loss calculation is very complicated because it is based on the knowledge of the magnetic flux density in individual places of the magnetic material. The expressions given in the books dealing with electrical machine design are derived under some simplifications and give only approximate results.

The presented method for core loss calculation is based on FEM to be able to gain magnetic flux density waveforms in individual places of the cross-section area. These waveforms are subjected to Fourier analysis and then the core loss components are calculated for individual harmonics and places.

This method can be applied to any synchronous machine. In this case it was made for reluctance synchronous motor (RSM) with a barrier rotor. At the end the core loss versus supplied voltage is calculated and compared with the measured values.

2 SHORT DESCRIPTION OF THE INVESTIGATED RSM

The RSM works on the principle of reluctance torque development. The stator of such a motor is identical with that of the induction motor. The rotor can have various kinds of construction, but there is no excitation. The purpose is to get different magnetic reluctances in d and q axes to develop as high reluctance torque as possible. One kind of possible construction is the rotor with barriers that is investigated in this paper. A quarter of its cross-section area is in Fig. 1a. Its rating is as follows: 3 phase, 380/220 V, Y/Δ, 4 poles, 706 W, 50 Hz, 1500 rpm.

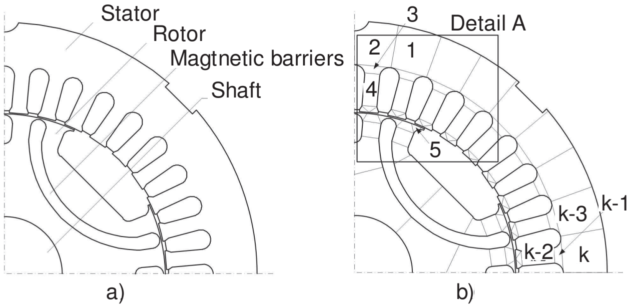

Fig. 1. a) A quarter of the cross-section area of investigated RSM, b) RSM cross-section area divided into segment

3 ANALYTICAL CORE LOSS CALCULATION

The approach used in this paper is based on the Finite Element Method (FEM) [5]. The simulation by FEM must be made for a certain current and rotor position, that means in a certain time instant. The cross-section area must be divided into some segments, the size of which depends on the rate of profile changing. As it is seen in the Fig. 1b, detailed dividing is made in the stator and rotor teeth, close to the air-gap, where the saturation influence can be very serious.

The flux density magnitude $B_{i,k}(t_j)$ of each segment is obtained by means of FEM analysis [5]. The x and y $B_{i,k}(t_j)$ components are investigated, where i is one of component (x or y), k is the figure of the segment, t_j is the time instant in which the investigation is made.

The simulation of the magnetic flux distribution by means of FEM is made for each step, when the rotor changes its positions. For each segment the profile of its magnetic flux density depending on the rotor position must be known. The rotor position depends on time. Then the Fourier analysis must be made for each magnetic flux

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[*] Faculty of Electrical Engineering, University of Žilina, Veľký Diel, 010 26 Žilina, Slovak Republic, Peter.Hudak@power-one.com, Valeria.Hrabovcova@fel.utc.sk [**] Technical University of Košice, Faculty of Mechanical Engineering, Letná 9, SK-04200 Košice

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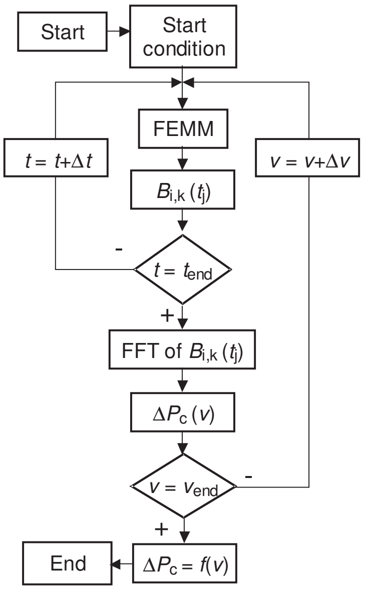

Fig. 2. Flow chart of analysis using FEM

waveform. The core losses in the mass unit Δp_{ck} in the k-segment are calculated as follows:

$$\Delta p_{c,i,k,n} = \Delta p_{ch} + \Delta p_{ce} = k_h f_n B_{i,k,n}^{\zeta} + k_e d^2 f_n^2 B_{i,k,n}^{\zeta} \quad (1)$$

where Δp_{ch} is hysteresis loss, Δp_{ce} is eddy current loss, f_n is $n-th$ harmonic component of frequency, $k_h = 1.85$ is the factor of hysteresis loss, according the used iron sheet material [2], $k_e = 1.26$ is the factor of eddy current loss, according the used iron sheet material [2], ζ is the exponent of magnetic flux density according its value, d is the thickness of the lamination, i is x or y component of the flux density, n is the order of harmonics. Then the total core loss in k-segment can be calculated:

$$\Delta P_{c,k} = V_k \rho \sum_{n=1}^{m} \big(\Delta p_{c,x,k,n} + \Delta p_{c,y,k,n}\big)$$

where V_k is the volume of the k-segment, ρ is the magnetic material density, x and y are directions in which the values of B are investigated. The total core loss will be got by the sum of individual segments:

$$\Delta P_c = \sum_k \Delta P_{c,k}$$

The approach used for core loss calculation in this paper is based on the detailed analysis of the x- and y-components of magnetic flux density in each segment of magnetic circuit. In such a way all influences, including slot- tooth pulsating components of magnetic flux density are involved and therefore pulsating losses in the stator teeth are also included in the gained results of core loss.

It is seen that the same approach has been used for hysteresis and eddy current loss calculation. Both components calculation is based on a sum of higher harmonic contributions.

As it is known, it is not recommended to calculate the hysteresis loss as a sum of its harmonic components. But it is true, that some authors, for example [5], [9] use this approach and the results are in good coincidence with the measured values. Therefore also in this paper such approach has been applied and the results and comparing with other methods are shown in Tab. 2.

On the other side also the other approach can be applied. It is based on the fact that the hysteresis loss depends on the supplied voltage waveform only. Therefore a parallel calculation has been made by means of the expression, in which the hysteresis loss is calculated on the base of the maximal value of the non-harmonic magnetic flux density waveform and eddy current loss in the same way as before, used in (1). Then the corrected expression (1) will be used in the form as follows:

$$\Delta p_{c,i,k,n} = k_h f_1 B_{i,k,non\_hrm}^{\zeta} + k_e d^2 f_n^2 B_{i,k,n}^{\zeta} \qquad (2)$$

where B_{knon_hrm} is the maximal value of non-harmonic magnetic flux density in k-segment. The results given in Tab. 2 show that they do not differ more then 10% from the other methods.

The further problem is the correct evaluation of the measured values to be able to verify the calculated values. Obviously it is recommended to make a no-load measurement and from no-load input power to subtract stator winding loss and mechanical loss. The rest should be an approximate value for core losses, including no- load stray (additional) losses, that means it is not value of the pure core loss.

Stray load losses are all miscellaneous losses not falling into one of the above categories. By convention, they are taken to be 1 % of the electrical output power of a machine (in the case of the RSM 1 % of the input power). Also this approach has been applied in this paper to get the core loss value. The measurement in full load range has been carried out and the core loss has been gained after the sum of the stator winding loss, mechanical loss, stray load loss (1 % of the actual input power) and shaft output power was subtracted from the input power. The results are shown in Tab. 2.

4 PROGRAM DESCRIPTION

To calculate core loss in the way mentioned above and to find out the values of the magnetic flux density in individual segments and in both x- and y- directions, a program FEMM v3.3 was used. To control the FEMM a program in MATLAB was developed. The flow chart of the whole program is shown in Fig. 2.

5 SIMULATION RESULTS

In Fig. 3 there is a detail of the magnetic flux distribution in the segments of stator yoke (segment number 1), stator tooth (number 4) and tip of the rotor tooth (number 5) in x and y directions, if the stator winding is supplied by 213.5 V (no-load current $I_0 = 3$ A), at time $t = 0$ s.

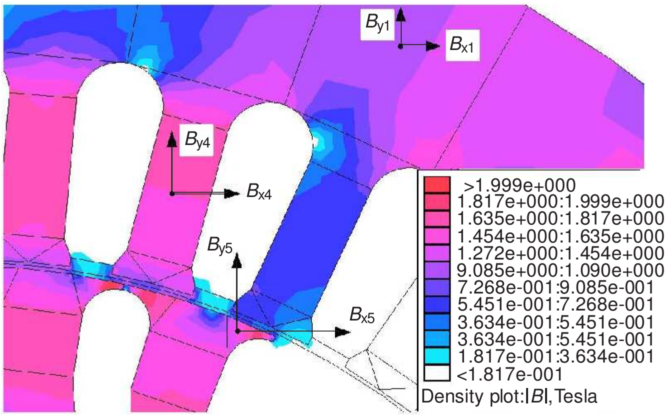

Fig. 3. Detail A (see Fig. 1b) of magnetic flux density distribution at 213.5 V and $t = 0$ s.

The waveforms of magnetic flux density in segments $1, 4, 5$ and their harmonic components in x and y directions are shown in Fig. 4.

The stator winding is fed by sinusoidal voltage. But the flux density waveforms in the stator yoke (segment number 1) and stator tooth (segment number 4) are not exactly sinusoidal, with a certain content of higher harmonic components, as it is seen in Fig. 4a,b,c,d. The fundamental frequency is identical with the supplied frequency.

In Fig. 4e,f there are flux density waveforms in the tip of rotor tooth (segment number 5) and their harmonic components. As it is seen there are considerable dc component because rotor is running at synchronous speed, that means in fact there should be dc magnetic flux density. But the waveform is distorted by stator slotting influence and there are seen considerable components mainly the 18th and 36th harmonics.

In Tab. 1 there are values of magnetic flux density in individual segments and the calculated core loss values for higher harmonic components for stator phase-voltage 213.5 V.

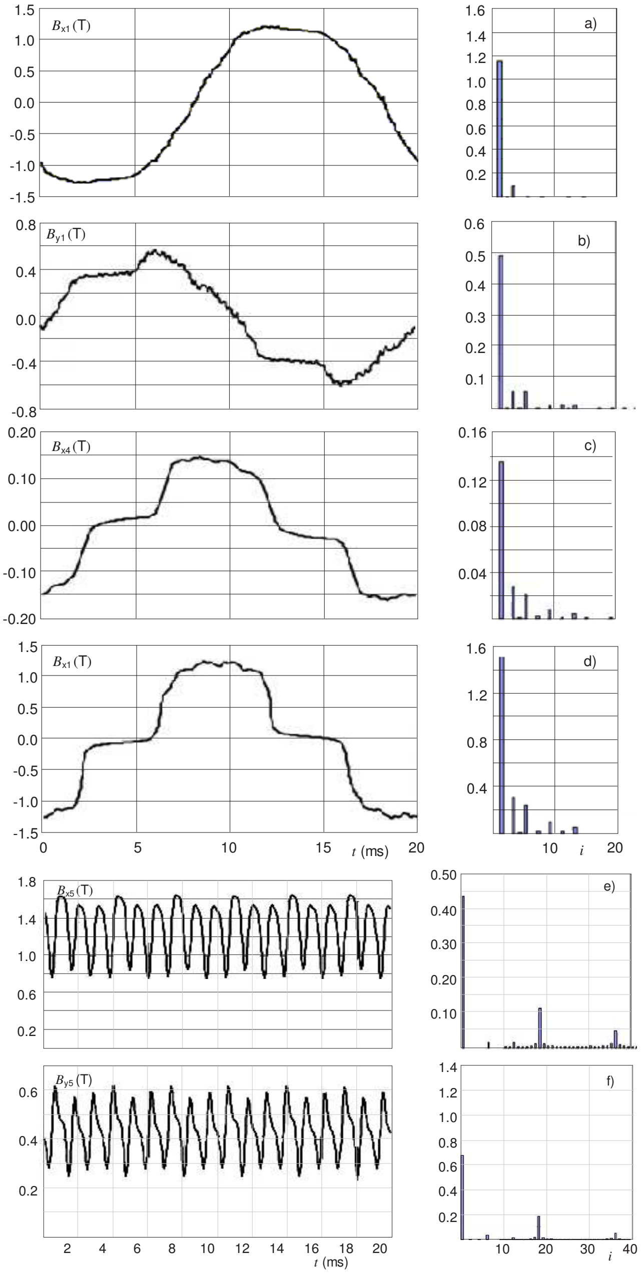

Fig. 4. The magnetic flux density waveforms and their harmonic components in a) segment 1, x-direction, b) segment 1, y-direction, c) segment 4, x-direction, d) segment 4, y-direction, e) segment 5, x-direction, f) segment 5, y-direction.

Table 1. The values of magnetic flux density in individual segments and calculated core loss for higher harmonic components for 213.5 V

segment	i	0	1	3	5	7	9	11	13
1	B_{x1} (mT)	2.55	1380	128	21.3	6.24	1.68	13.9	14.1
	B_{y1} (mT)	-0.724	506	56.9	56.0	4.86	12.4	13.3	9.50
	ΔP_{c1} (mW)	0	596	29.4	13.0	0.417	1.66	5.69	6.11
4	B_{x4} (mT)	0.394	137	27.7	21.1	2.84	8.79	1.79	4.54
	B_{y4} (mT)	4.47	1520	318	245	22.2	102	20.9	53.1
	ΔP_{c4} (mW)	0	176	415	593	0.906	300	1.83	162
segment	i	0	18	19	20	34	35	36	37
5	B_{x5} (mT)	1300	40.6	367	33.8	13.1	27.0	96.8	14.6
	B_{y5} (mT)	441	115	11.1	6.07	6.38	13.4	51.6	8.33
	ΔP_{c5} (mW)	0	129	1.23	0.407	0.635	2.88	40.4	0.997

Table 2. Measured and calculated values of core loss in dependence on supplied voltage or corresponding no-load current

Measured values				Calculated values	
V_{ph} (V)	I_0 (A)	ΔP_{c_0} (W)	ΔP_{c_load} (W)	P_{c_1} (W)	ΔP_{c_2} (W)
234.5	4.0	75.5	74	73.2	61.75
225	3.5	66	67	62.3	57.45
213.5	3.0	58	59	55.1	52.58
196	2.5	49	50	50.7	44.85
172	2.0	38.5	37.5	40	35.60
138	1.5	26.5	25	24.2	21.84
96	1.0	14	14	10.2	9.76
50	0.5	4	–	3.1	2.28

ΔP_{c_0} — measured value from no-load test
ΔP_{c_load} — measured value from load test
ΔP_{c_1} — calculated value according to formula (1)
ΔP_{c_4} — calculated value according to formula (2)

In Tab. 2 there are put measured and calculated core loss values in dependence on supplied phase-voltage, or corresponding no-load current. As it can be seen the coincidence is very good, with regard to the fact that only 2D FEM version was applied and that the measured values include also additional stray losses (see chapter 3). To demonstrate it, also a curve core loss versus supplied voltage is shown in Fig. 5.

6 CONCLUSION

The presented method uses quite complicated procedure to calculate core loss in RSM magnetic circuit. The time consumption depends on the quality of the computer but it is quite high because the analysis is made in great detail. However, the coincidence with the measurements is very good because it takes into account also influence of the slotting and saturation in tips of the tooth area.

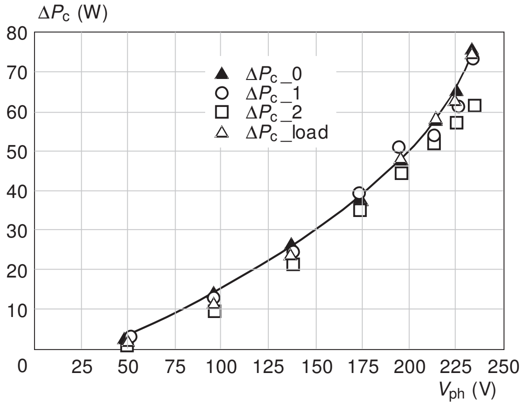

Fig. 5. Core loss versus supplied voltage.

Its further advantage is that it is universal for any kind of the electric machine and the procedure is fully automatic. It can be used also for non-harmonic fed electrical motors, what will be presented in future.

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Peter Hudák (MSc) received his MSc degree in electrical engineering from the University of Žilina (SK) in 2000. He was a PhD student at the University of Žilina, at present he is with the Power-One company, and his research activity is focused on electric machines, mainly on the reluctance synchronous motor.

Valeria Hrabovcová (Prof, MSc, PhD) graduated in electrical engineering from the University of Žilina in Žilina, gained her PhD in electrical engineering from the Slovak University of Technology in Bratislava in 1985. She is a professor of electric machines at the University of Žilina at undergraduate and postgraduate levels. Her professional area is electronically commutated electric machines.

Pavol Rafajdus (MSc, PhD) graduated in electrical engineering from University of Žilina in Žilina in 1995, gained his PhD in 2002. At present he is a senior assistant at the Faculty of Electrical Engineering, University of Žilina, in Žilina. His research is focused on the reluctance electrical machines.

Jozef Mihok (Assoc Prof, MSc, PhD) graduated in mechanical engineering from the Technical University in Košice in 1974, gained his PhD in mechanical engineering in 2001. He is associated professor at the Technical University of Košice since 2002. He deals with building of electrical machines, as well as industry management.