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Analysis of a Permanent - Magnet Brushless DC Motor with Fixed Dimensions

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Abstract. **The purpose of this paper is to describe the analysis of a permanent – magnet brushless DC motor with fixed outer diameter and active zone length. The influence of air gap, material of permanent magnets and their size on the magnetic flux density of the machine and magnetic flux is analyzed. The work presents the calculations of two programs, the comparison of the results and the most suitable combination of factors that has been found.**

Keywords: **brushless DC motors, flux density, magnetic flux, outer – rotor motor, permanent – magnet, synchronous machine.**

I. INTRODUCTION

Brushless DC (BLDC) motors are constantly getting wider application in adjustable electric drives especially in the cases of changing load. Their basic advantages in comparison with AC and DC collector motors are longer service life, higher level of safety and higher dimensioning and power indices [1] - [2].

Among BLDC motors widely used today the core place is occupied with the motors with permanent magnet excitation. In their embodiment these motors can have an inner as well as outer rotor [3] – [4].

Lack of high - quality and relatively cheap magnets resulted in delay of permanent – magnet brushless DC motors (PM BLDC) utilization during the last years. The situation started positive changes in 1950s when aluminium - nickel based permanent magnets were introduced into production with energy up to 60 kJ/m^3. Especially sharp development of the electric machines with permanent magnets has been considered in 1970s when the production of new materials on the basis of samarium cobalt and other rare elements was settled with energy about 360 kJ/m^3, residual flux density higher than 1.2 T and coercive force higher than 900 kA/m. Besides the magnets on the rare elements base in the construction of brushless DC motors the metal ceramic magnets on the basis of barium and strontium ferrites are applied. The main advantage of these magnets is in their simple production and relatively low expenses [5].

Scientists from many countries investigate the brushless DC motors by means of different approaches: considering them from the DC classic or automatic regulation theory point of view, using as a basis main principles of the theory of machines control, theory of synchronous machines control or describing the operation of brushless motor within uninterrupted transient process together with semiconductor switch with the help of system of differential equations. Each of these approaches has its advantages and disadvantages, however during the last time the brushless motors are being often considered as a synchronous machine operating in specific modes [6] - [7]. In this case the analysis is relatively simpler and more visual.

II. ANALYSIS OF THE OBJECT UNDER INVESTIGATION

This paper considers the calculations of outer – rotor PM BLDC motor for the case when the motor parameters indicated in the Table I are set.

TABLE I

FIXED PARAMETERS OF THE MOTOR UNDER INVESTIGATION

Number of poles	4
Outer diameter of the rotor yoke	61 mm
Inner diameter of the rotor yoke	53 mm
Length of the active zone	100 mm
Rotation frequency in the rated mode	13000 min^{-1}

The influence of some factors on the magnetic flux of the machine and flux density distribution in the parts of magnetic circuit is investigated. In this case the motor is considered from the theory of synchronous machines point of view.

The following parameters influencing the value of magnetic flux density and magnetic field are assumed as those initial variables:

- permanent – magnet angle α;
- permanent – magnet residual flux density B_r;
- permanent – magnet relative permeability μ_r;
- permanent – magnet thickness h;
- air gap length δ.

Thus there are 5 initial factors not dependent each on other.

Preliminary for the reviewing of the investigation range the values of the variables are limited as it is demonstrated in Table II.

TABLE II

LIMITS OF VARIABLES CHANGING

Variable factor	min. value	max. value
α, el. deg	108	158
B_r, T	0.4	1.2
μ_r	1.2	3.6
δ, mm	0.4	0.8
h, mm	2	3.6

Each of the mentioned factors is assigned with 5 fixed values (Table III).

TABLE III

FIXED VALUES OF THE FACTORS

	1	**2**	**3**	**4**	**5**
α, el. deg	158	146	133	121	108
$\mathbf{B_r}$, T	0.4	0.6	0.8	1	1.2
$\mathbf{\mu_r}$	1.2	1.8	2.4	3	3.6
δ, mm	0.4	0.5	0.6	0.7	0.8
h, mm	3.6	3.2	2.8	2.4	2

According to the methodology of the experiments rational planning [8] 25 possible experiments are investigated only, instead of $5^5 = 3125$. Table IV represents the combinations of factors and the results of these combinations examining as well.

Realization of the experiments within a wide range gives an opportunity to define preliminary results of the calculations.

A virtual training program for designing of the synchronous machines with permanent magnets is applied for the acceleration of the experiments examination process, Emetor [9].

The geometry of one of the virtual experiments is demonstrated in Fig.1.

Table IV represents the results of the calculated magnetic flux density in air gap, maximum magnetic flux density in teeth and in the yoke as well as magnetic flux density of the outer rotor yoke under the condition of no - load.

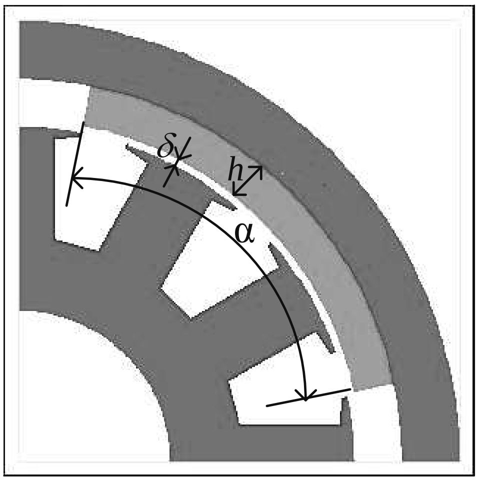

Fig. 1. The geometry of PM BLDC motor [9]

TABLE IV

RESULTS OF THE CALCULATION OF THE VARIANTS

	α, el.deg	$\mathbf{B_r}$, T	$\mathbf{\mu_r}$	**δ**, mm	**h**, mm	$\mathbf{B_\delta}$, T	$\mathbf{B_{a.t}}$, T	$\mathbf{B_{a.y}}$, T	$\mathbf{B_{r.y}}$, T	**D**, mm	**τ**, mm	**Φ**,Wb
1	158	0.4	3	0.6	2.8	0.319	0.85	0.875	1.05	47.8	37.54	0.000762
2	158	0.6	1.2	0.7	2.4	0.587	1.576	1.527	1.947	46.8	36.76	0.001374
3	158	0.8	3.6	0.4	2	0.6	1.682	1.433	2.077	48.2	37.86	0.001446
4	158	1	1.8	0.8	3.2	0.919	2.367	2.784	2.924	45	35.34	0.002068
5	158	1.2	2.4	0.5	3.6	1.201	3.121	3.761	3.855	44.8	35.19	0.00269
6	146	0.4	1.2	0.5	2	0.392	1.032	0.894	1.274	48	37.70	0.000941
7	146	0.6	3.6	0.6	3.6	0.482	1.181	1.459	1.459	44.6	35.03	0.001075
8	146	0.8	1.8	0.7	3.2	0.745	1.835	2.108	2.266	45.2	35.50	0.001684
9	146	1	2.4	0.4	2.4	0.465	0.987	1.875	1.218	47.4	37.23	0.001102
10	146	1.2	3	0.8	2.8	0.824	2.051	2.202	2.533	45.8	35.97	0.001887
11	133	0.4	3.6	0.8	2.4	0.22	0.53	0.523	0.654	46.6	36.60	0.000513
12	133	0.6	1.8	0.5	2.8	0.561	1.355	1.366	1.673	46.4	36.44	0.001302
13	133	0.8	2.4	0.6	3.6	0.712	1.652	2.041	2.041	44.6	35.03	0.001588
14	133	1	3	0.7	2.8	0.699	1.665	1.75	2.056	46	36.13	0.001608
15	133	1.2	1.2	0.4	3.2	1.305	3.123	3.353	3.856	45.8	35.97	0.002988
16	121	0.4	1.8	0.4	3.6	0.397	0.897	1.055	1.107	45	35.34	0.000893
17	121	0.6	2.4	0.8	3.2	0.44	0.98	1.153	1.211	45	35.34	0.00099
18	121	0.8	3	0.5	2.8	0.605	1.405	1.417	1.736	46.4	36.44	0.001404
19	121	1	1.2	0.6	2	0.854	2.029	1.79	2.506	47.8	37.54	0.002041
20	121	1.2	3.6	0.7	2.4	0.673	1.564	1.515	1.932	46.8	36.76	0.001575
21	108	0.4	2.4	0.7	3.2	0.286	0.617	0.709	0.762	45.2	35.50	0.000646
22	108	0.6	3	0.4	2.8	0.454	1.021	1.009	1.261	46.6	36.60	0.001058
23	108	0.8	1.2	0.8	2.4	0.623	1.375	1.359	1.699	46.6	36.60	0.001452
24	108	1	3.6	0.5	3.6	0.726	1.568	1.89	1.937	44.8	35.19	0.001626
25	108	1.2	1.8	0.6	2	0.837	1.911	1.686	2.360	47.8	37.54	0.002

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The magnetic flux within the air gap is calculated according to the expression:

$$\Phi = \frac{2}{\pi} \cdot B_\delta \tau L \ ,$$

where $\tau = \frac{\pi D}{4}$ - pole division, m; B_δ - magnetic flux density in the air gap, T; D – outer diameter of the yoke, m; L – length of the active zone of the motor, m.

The restrictions for the selection of factor combination are accepted like: magnetic flux density in the air gap should not exceed 1 T, magnetic flux density in teeth and yoke is $B \le 1.65$ T, in the yoke of outer rotor – $B \le 2$ T. The painted spaces in the Table IV are those values of the magnetic flux density that exceed the limitations indicated above. For the further testing, choose the most appropriate combination of factors that corresponds to the 23rd variant, where the magnetic flux of the first harmonic is $\Phi = 0.001452$Wb.

The repeated test is made for the results improvement varying the factors within the range values $\alpha = 108$ (el.deg.), $B_r = 0.8$ (T), $\mu_r = 1.2$, $\delta = 0.8$ (mm) and $h = 2.4$ (mm).

The more appropriate factor combination has been found after the repeated test: $\alpha = 123$ (el.deg.), $B_r = 0.7$ (T), $\mu_r = 1.1$, $\delta = 0.5$ (mm) and $h = 2.5$ (mm). The results of this combination examined with the help of program Emetor are given in Table V.

TABLE V

EMETOR RESULT

B$_\delta$, T	**B**$_{a.t}$, T	**B**$_{a.y}$, T	**B**$_{r.y}$, T	**D**, mm	**Φ**,Wb
0.679	1.605	1.525	1.983	47	0.001596

It should be mentioned that the program under consideration does not take into account saturation of the ferromagnetic material in the motor.

For the further examining of the selected variant with saturation of the material under no - load condition and with the load program QuickField is applied. It allows solution of plane and axis symmetric tasks with the use of final elements method.

First of all the calculation results of both programs Emetor and QuickField without saturation of the material under no - load condition are compared. The results are in Table VI.

TABLE VI

EMETOR RESULT IN COMPARISON WITH QUICKFIELD

Programs	**Bδ, T**	**Φ,Wb**
Emetor	0.679	0.001596
QuickField	0.597	0.001403

The results indicate that the magnetic flux of the first harmonic, received in QuickField, is 12% less than the value received in the Emetor.

The distribution of the magnetic field of brushless DC motor without saturation is given in Fig.2.

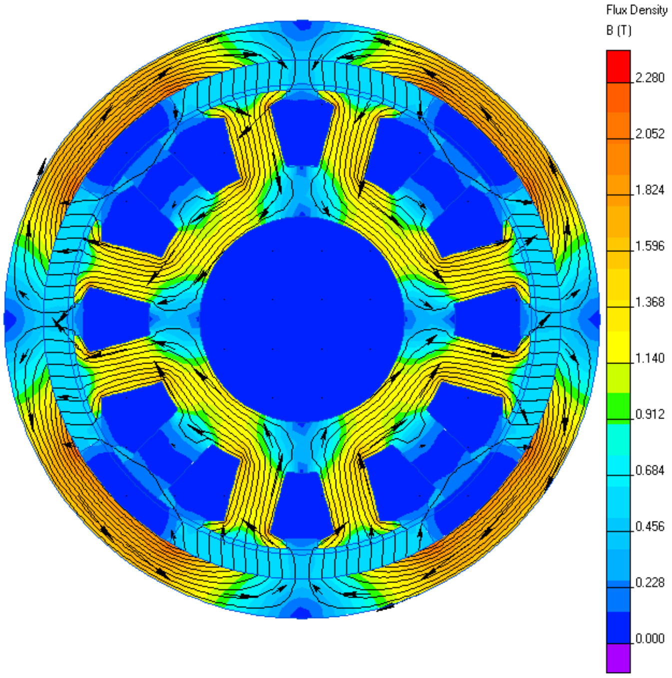

Fig. 2. Distribution of the magnetic field of brushless DC motor without saturation under no - load condition

For calculation of magnetic field taking into account the saturation of the material the saturation curve of 2411 grade steel is assigned.

Table VII represents the results of magnetic field calculation with material saturation under no - load condition. The distribution of the magnetic field of brushless DC motor with saturation is given in Fig.3.

TABLE VII

RESULT OBTAINED IN QUICKFIELD TAKING SATURATION INTO ACCOUNT

Program	**B**$_\delta$**, T**	**Φ, Wb**
QuickField	0.553	0.0013

The calculation results with saturation obtained in QuickField program differs from that obtained in Emetor for 19%.

Under the loaded condition calculated magnetic field (Table VIII), the magnetic flux of the first harmonic is practically unchanged. It could be concluded that the influence of armature reaction in the present construction is insignificant.

TABLE VIII

RESULT OBTAINED IN QUICKFIELD UNDER LOADED CONDITION

Program	**Bδ, T**	**Φ,Wb**
QuickField	0.554	0.001302

The distribution of the magnetic field of brushless DC motor under loaded condition is demonstrated in Fig. 4.

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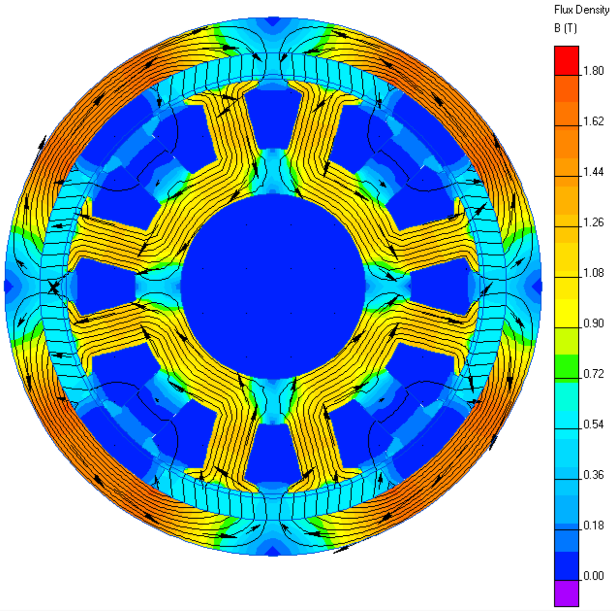

Fig. 3. Distribution of the magnetic field of brushless DC motor with saturation under no-load condition.

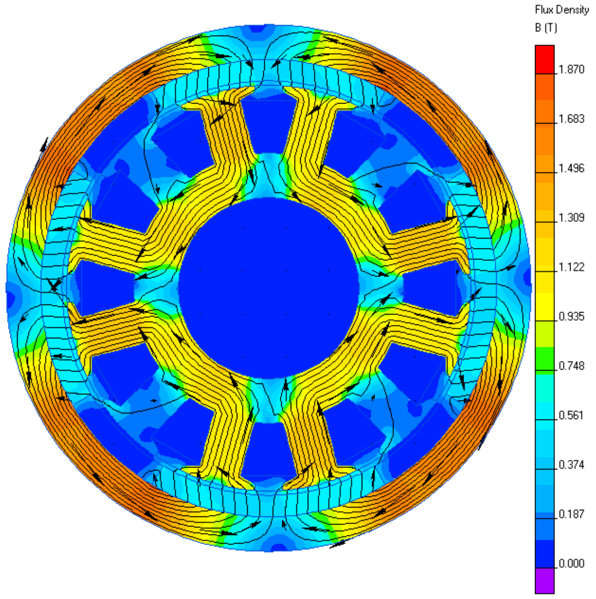

Fig. 4. Distribution of the magnetic field of brushless DC motor under loaded condition.

The applied methodology of the magnetic field calculation in program QuickField taking into account the saturation of the material could be used for the analysis of some factors influence on the magnetic flux of the first harmonic, for example that of the permanent magnet angle. As an example Fig. 5 represents magnetic flux changing according to the permanent magnet angle keeping values of other factors unchangeable.

It is obvious from graph $\Phi = f(\alpha)$, that the magnetic flux of the first harmonic achieves its peak value ($\Phi = 0.00131$ Wb) at $\alpha = 133$ el. deg.

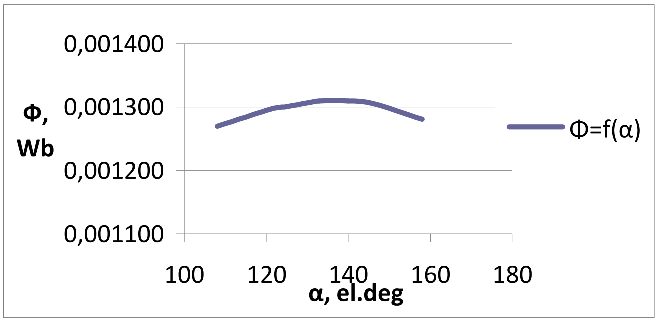

Fig. 5. Changing of magnetic flux according to the permanent magnet angle.

III. CONCLUSION

Program Emetor is convenient for the preliminary examining and selection of the correspondent variant, however, it should be taken into consideration that the values of flux density and the magnetic flux calculated by this program are considerably overstated.

To obtain more precise results of the analysis it is reasonable to apply the programs of magnetic field calculations that take into account saturation of magnetic circuit of the machine, for example QuickField.

During the planning of the calculation with the set outer rotor diameter, his inner diameter should not be fixed.

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