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Design Optimization of Interior Double-Radial Synthetic Magnetic Field Permanent Magnet Generator for Electric Vehicle

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Abstract. The Interior double-radial permanent magnent generator (IDRPMG) which composed by two groups of rectangular permanent magnets to provide parallel magnetic circuits of the rator and the sator core with less eddy current loss, low hormonic content and low cogging torque of the stator with fractional slot winding is developed. It has the advantages of remarkable magnetism gathering effect, strong magnetic field intensity and high space utilization.Combining Taguchi method and finite element method, the relevant parameters of the permanent magnet size and the angle between the first and second rectangle permanent magnets in rotor are optimized to get better the distortion rate of output voltage waveform, lower cogging torque and higer peak value of airgap flux density. Then finite element simulation is taken for the best optimization scheme through comparative analysis of the machine by before and after optimization.It showed that each performance index is improved after optimization. Finally, the prototype is manufactured, according to the optimization parameters and some experiments are conducted, which results verify the analys is preview well.

1 Introduction

Due to the permanent magnet generator has no excitation winding, carbon brush slip ring and brush compared to the silicon rectifying generator, it has the advantages of low loss, high efficiency and simple structure[1-2], So it's widely used in electric vehicle. However, the permanent magnet generator also has the inevitable defects such as the large cogging torque, high harmonic content and large magnetic flux leakage which will affect the output characteristics of permanent magnet generator[3-5]. In the literature[6], a new surface-Mounted permanent magnet generator is presented which the magnetic poles consists of a magnetic metal block and a permanent magnet. The generator uses the non-uniform air gap structure to reduce air gap flux density harmonics content and improve the output voltage waveform, but the disadvantage of this structure is that large magnetic flux leakage and low power generation efficiency. In the literature [7] by using the multi-layer permanent magnet instead of the traditional single layer permanent magnet as the magnetic pole of the generator to improve the air-gap magnetic waveform, but this structure requires more permanent magnet so that the cost is high. In the literature [8], by optimizing the shape of the permanent magnet with unequal thickness, the harmonic39 content and cogging torque are reduced, but at the same time, increasing machining difficulty of permanent magnet. It is necessary to develop a permanent magnet generator which has less power consumption, higher power generation efficiency, lower cogging torque and steady output voltage.

2 Multi-objective optimization design method of IDRPMG

2.1 Initial design parameters of IDRPMG

The initial design parameters of permanent magnet generator with double-radial synthetic magnetic field are obtained through the calculation of empirical formula. The results are shown in Table 1.

Table 1. Intial design parameters of IDRPMG.

Parameters	Values	Parameters	Values
The rated voltage(V)	14	Width of the first rectangular permanent magnet(mm)	11
The rated power(W)	1000	Width of the second rectangular permanent magnet(mm)	5
The pole pair number	4	Thickness of the first rectangle permanent magnet(mm)	3.5
Number of stator slots	36	Thickness of the second rectangle permanent magnet(mm)	2.5

Inner diameter of stator(mm)	91	The angle between the first and second permanent magnets(°)	46
Outer diameter of stator(mm)	126	The Outer diameter of rotor(mm)	90
The shape of the stator slot	Pyriform	The axial length(mm)	52

2.2 Design methods and objectives

In this paper, the multi-objective optimization design of permanent magnet generator is realized by Taguchi method to determine the experimental condition and calculate the target characteristics under specific test conditions by establishing orthogonal table,this method can obtain the best combination of parameters in the least number of experiments, thus realizing the optimization design of multi-objective characteristics[9-10]. In this study, the width of the first rectangular permanent magnet (b_1), magnetization direction thickness of the first rectangle permanent magnet (h_1), the width of the second rectangular permanent magnet(b_2), magnetization direction thickness of the second rectangle permanent magnet (h_2) and the angle between the first and second permanent magnets (θ) is selected as the optimization of parameters. As shown in Figure 1.

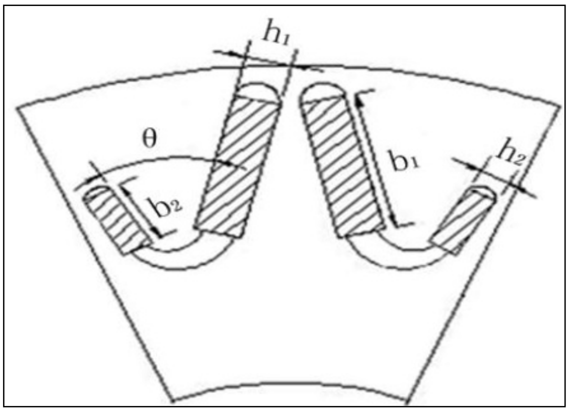

Figure 1. The schematic diagram of adjacent N and S poles

Each parameter selects 4 levels of influence factors,and the levels influence factors of parameters are selected near the initial design parameters.The cogging torque peak (T),the voltage waveform distortion rate (Kr) and the air gap flux density peak (G) are selected as the optimization objectives,the influence factor level shown in Table 2.

Table 2. The influence factors of structural parameters of permanent of permanent magnet generator

Level Factors	b_1(mm)	h_1(mm)	b_2(mm)	h_2(mm)	θ(°)
1	10	3.5	6	2	50
2	11	3	6.5	2.5	46
3	12	2.5	5.5	3.3	42
4	13	2	7	3	48

The calculation formula of output votage waveform distortion rate of permanent magnet generator:

$$K_\rho = \frac{\left(Y_2^2 + Y_3^2 \cdots\cdots + Y_N^2\right)^{\frac{1}{2}}}{Y_1} \times 100\% \qquad (1)$$

Where Y_N is the amplitude of Nth harmonic.

2.3 Optimization process

The orthogonal experiment selects 5 parameter variables, and each parameter has four level factor.Thus,the experimental matrix of expression $L_{16}(4^5)$ is established, If the traditional form of single variable and single objective optimization method are used, 4^5=1024 experiments are required. However, the Taguchi method can be used to optimize the multi-parameter and multi-objective design of the permanent magnet generator with only 16 times experiments.The experimental orthogonal table and simulation results are shown in Table 3.

Table 3. Experimental matrix and the results of finite element analysis

NO.	Experimental matrix					Test evalution index		
	b_1	h_1	b_2	h_2	θ	K_r (%)	T (N·m)	G (mT)
1	1	1	1	1	1	15.16	0.069	732
2	1	2	2	2	2	16.63	0.261	719
3	1	3	3	3	3	16.40	0.212	600
4	1	4	4	4	4	17.10	0.269	675
5	2	1	2	3	4	16.25	0.105	783
6	2	2	1	4	3	14.70	0.227	865
7	2	3	4	1	2	17.00	0.291	811
8	2	4	3	2	1	17.13	0.230	609
9	3	1	3	4	2	16.39	0.082	828
10	3	2	4	3	1	17.83	0.205	830
11	3	3	1	2	4	18.20	0.231	745
12	3	4	2	1	3	17.41	0.304	644
13	4	1	4	2	3	15.88	0.154	846
14	4	2	3	1	4	17.47	0.139	916
15	4	3	2	4	1	18.41	0.244	860
16	4	4	1	3	2	18.06	0.212	765

The average value is calculated in the solution of Table 3,the calculation formula as follows:

$$m = \frac{1}{n}\sum_{i}^{n} S_i \qquad (2)$$

Where n is experiment times. S_i is the value of the target performance of the ith experiment. The results are shown in Table 4.

Table 4. The average value of target performance indicators

Optimization	K_r(%)	T(N·m)	G(mT)
Index	16.88	0.202	764.5

Then the average value of each factor of the parameter is calculated for the specific target performance, the calculation formula as follows:

$$m_{xi} = \frac{1}{4}[m_x(j) + m_x(k) + m_l(l) + m_x(n)] \qquad (3)$$

Where m_{xi} is the average value of the performance index of the first influnce factor of perameter X; m_x is the performance index of parameter *X*. m_x is the performance index of parameter x in one experiment; *J, k, l, n* is Serial number of test.

In order to facilitate the comprehensive analysis, the index is represented by the line graph with the level change of factors,as shown in Figure 2.

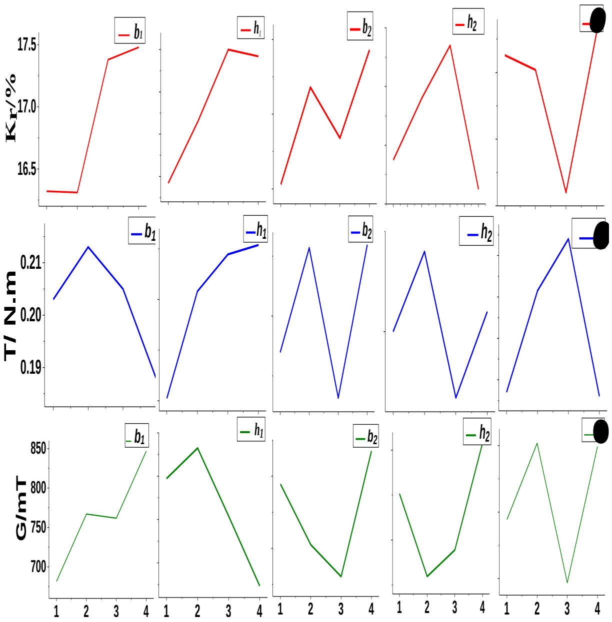

Figure 2. Infulence of various parameters for level factors on different performance

We can see from Figure 2, with the increase of the width of the first rectangle permanent magnet b_1, the decrease of the thickness of magnetization direction h1 and the decrease of angle θ, the distortion rate of the voltage waveform of the permanent magnet generator becomes larger.While with the decrease of the thickness of the first rectangular permanent magnet h_1, the opening angle between the first and second rectangular permanent magnent θ or the increase of the width the second rectangular permanent magnet, the peak value of the cogging torque is increased. In addition, when the width and thickness of the first rectangular permanent magnet are increased, the peak value of the air gap flux density of the permanent magnet generator is also increased. From the Figure 5,we can obtained the combination of the parameters which the smallest distortion rate of the voltage waveform is $b_1(2)h_1(1)b_2(1)h_2(1)\theta(3)$, the combination of the parameters which the minimum peak value of cogging torque is $b_1(4)h_1(1)b_2(3)h_2(3)\theta(1)$,the combination of the parameters which the maximum value of the peak value of air gap flux density is $b_1(1)h_1(2)b_2(4)h_2(4)\theta(2)$. Obviously, the three groups of level combinations are designed for the optimization of a single performance index, if considering the influence of three performance indexes on the permanent magnet generator, it is necessary to analyze the variance to further analyze the influence of the change of each parameter on the different performance indicators, and thus obtain the optimization results.

2.4 The analysis of proportion of each parameter to permance index

Analyze the variance of the average value of a performance index under different parameters at different levels for all the experimental performance indexes,We can determine which parameters had significant effect on the performance index, the results are shown in Table 5.The formula for calculation is as follows:

$$S_s = \frac{1}{Z}\sum_{i=1}^{z}(Q_{(i)} - Q)^2 \tag{4}$$

Where s is the influence factor, such as b_1,h_1,b_2,h_2,θ; Ss is the variance of a performance index under parameter,in this study, Z=4; $Q_{(i)}$ is the average value of the parameters in the level of factor i under certain performance index; Q is the total average value of permance index.

Table 5. The variance and proportion of performance index of each parameter.

Parameter	S_{kr}		S_T		S_G	
	Variance	Proportion(%)	Variance	Proportion(%)	Variance	Proportion(%)
b_1	0.340	37.32	9.2×10^{-5}	1.67	3427	43.14
h_1	0.410	45.02	3.7×10^{-3}	67.40	3558	44.79
b_2	0.055	6.03	7.6×10^{-4}	13.85	421	5.30
h_2	0.034	3.73	6.7×10^{-4}	12.22	236	2.97
θ	0.072	7.90	2.67×10^{-4}	4.86	302	3.80
Total	0.911	100	5.49×10^{-3}	100	7944	100

2.5 Determination of final optimizition scheme

From Table 5 we can found that the value of variance can directly reflect the influence of each optimization parameter on the performance index[11]. The thickness of the the first rectangular permanent magnet has the great influnce on three optimation indexes. Compared with other optimization indexs, the parameter b_1 has the significant influence on the peak value of air gap flux density.Among the three optimation indexes, the change of the opening angle between the first and the second rectangular permanent magnet has the largest influence on the voltage waveform distortion rate.

According to the above analysis, we selected the parameter b_1 and h_1, according to the optimization standards which the minimum distortion rate of the voltage waveform and the maximum peak value of the air gap flux density as the optimization standards, and the parameter θ is chosen as the optimization criterion of the minimum distortion rate of the voltage waveform.The final optimization result is $b_1(4)h_1(1)b_2(1)h_2(1)\theta(3)$.

3 Finite element analysis simulation analysis of IDRPM

According to the parameter values of the final scheme, the two-dimensional of double-radial synthetic magnetic field of permanent magnet generator is built, and the finite element simulation analysis is carried out.The simulation results are shown in Figures 3 and 4. In Figure 3,The main magnetic flux of permanent magnet generator is supplied by the first and second rectangular permanent magnets. The magnetic flux provided by the first rectangular permanent magnet is parallel with the magnetic flux provided by second rectangular permanent magnet ,the magnetic field distribution is uniform and the magnetic flux is less. In Figure4, the different colours represent different magnetic density in magnetic flux desity modulus maps,the magnetic density values of each part of permanent magnet generator can be obtained by the color distribution, the magnetic flux density distribution is uniform and the stator yoke flux density is 1.8 T,the simulation results meet the design requirements.

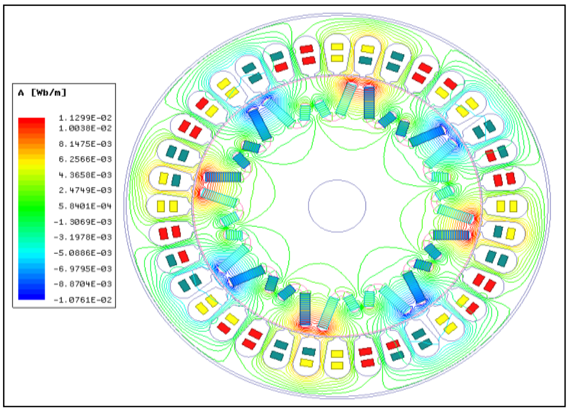

Figure3. The distribution of magnetic induction lines

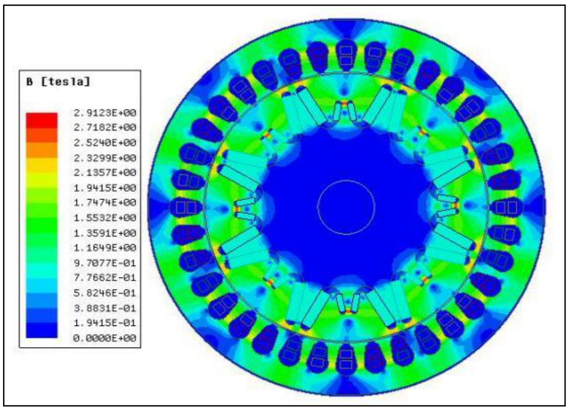

Figure4. The modulus values of magnetic flux density

In Figure 5 ,we can see that the peak value of cogging torque of permanent magnet is 0.23N·m before optimization, while the peak value of cogging torque reduced to 0.043N·m after optimization, the results of finite element simulation analysis shows that the cogging torque of the permanent magnet generator with double radial synthetic magnetic field is greatly weakened and the rationality of the design is verified.

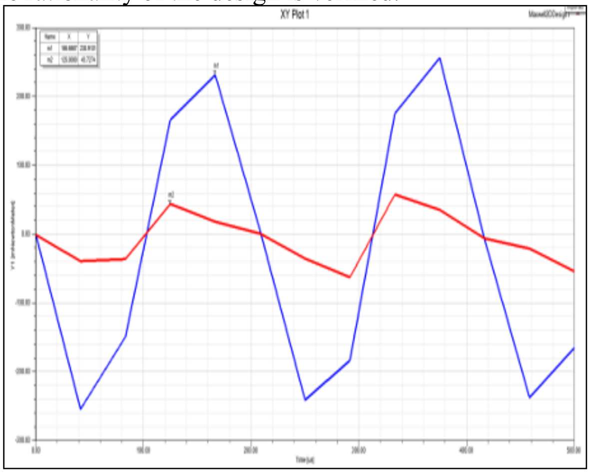

Figure 5. The comparison of cogging torque waveform before and after optimization

In Figure 6, we can see that the output voltage fluctuates greatly and the top of the voltage waveform shows obvious depression before optimization.In Figure7, the voltage waveform has a small fluctuation after optimization,but compared to before optimization more close to the sine wave.After optimization,the amplitude of the output voltage of the permanent magnet generator is reduced,the distortion rate of the voltage waveform is 15.6%,which is 1.6% lower than before optimization.In Figure 9, it can be seen that the peak value of air gap magnetic density is 705mT before optimization, after optimization the peak value of air gap magnetic density is 840mT, which is up about 20%.

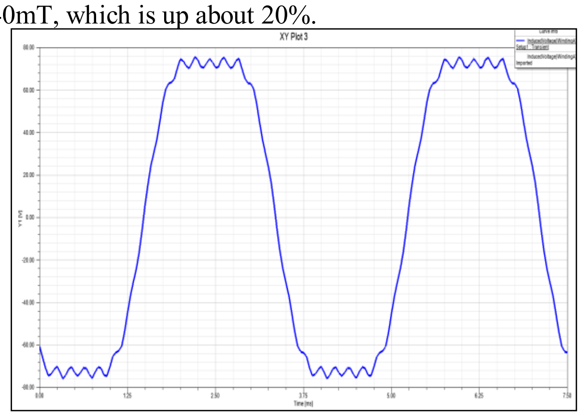

Figure 6. The Output voltage of permanent magnet generator before optimazition

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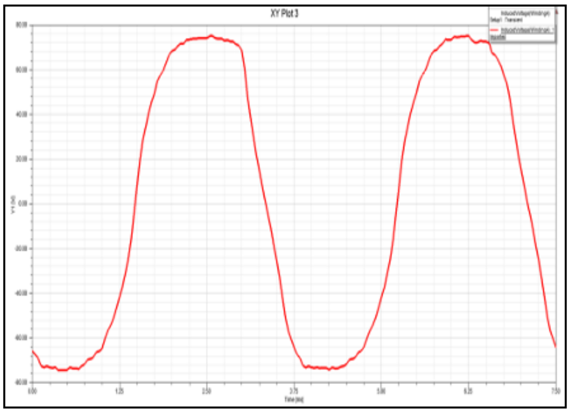

Figure 7. The Output voltage of permanent magnet generator after optimazition

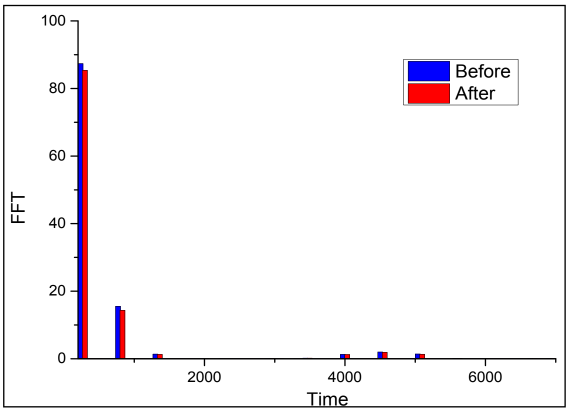

Figure 8. The harmonic amplitude of output voltage before and after optimization

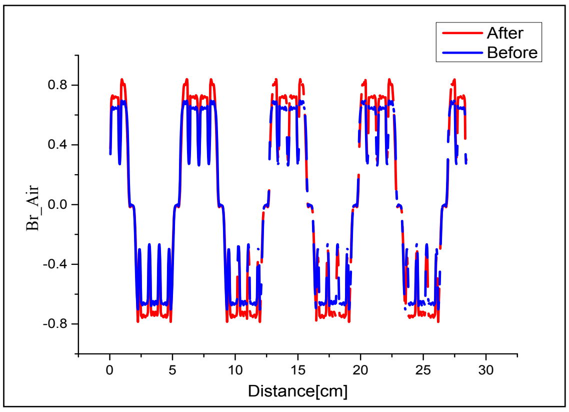

Figure 9. The peak value of air gap flux densitybefore and after optimization

4 Conclusion

(1) In this study, a new type of built in double radial synthetic magnetic field permanent magnet generator is developed, the generator is composed of two groups of rectangularpermanent magnets to produce parallel magnetic circuit, and the resulting magnetic fiedis synthesized in the air gap. The shunt circuit magnetic path can form a significant magnet magnet congregate effect, the air gap has large flux density and high efficiency.

(2) Compared Taguchi method and finite element method to optimize the design of permanent magnet generator, after optimized the output voltage distortion rate decreased 1.6%, the peak value of cogging torque is weakened by 81.3%, the air gap flux density peak is increased about 20%.

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