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Design and Optimization of Electromagnetic Parameters in a Linear Magnetic-Geared Generator Based on Orthogonal Statistical Method

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Abstract—The magnetic-geared generator integrates a magnetic gear and a generator by using the magnetic field modulation technology. It has the characteristics of high power density, high material utilization, and has a wide application prospect. However, compared with the general generator, its structure is relatively complex which makes its design and optimization become more complex. Therefore, a new structure and an optimization method based on orthogonal regression statistics are proposed. The experimental results fully prove the effectiveness of the proposed structure and optimization method.

1. INTRODUCTION

With the progress and development of modern technology, many electromechanical systems put forward higher requirements for motor performance. Therefore, the research of high power density motor has become a hot spot. Magnetic-geared composite motor has attracted extensive attention of researchers, which has the characteristics of high power density, high material utilization, safety, and reliability. This kind of motor integrates a magnetic field modulation gear and a motor organically, and has the dual advantages of magnetic gear and motor [1]. It has compact structure, high transmission efficiency, and good reliability, and can realize the direct drive of low speed and high torque. It has broad development prospects in industrial transmission [2], automobile traction [3], wind power [4], aviation, and other fields. At present, there are more researches on rotary magnetic gear compound motor and less on linear magnetic gear compound motor. Many systems, such as power locomotive traction, wave power generation, and dish Stirling solar thermal power generation, are linear drive systems, which need linear motors or generators. At the same time, in order to improve the energy conversion efficiency of the system, these systems have higher requirements on the power density of the motor or generator. Therefore, linear magnetic-geared motor or generator with high power density can effectively provide system energy conversion efficiency.

However, like a rotary magnetic-geared generator, a linear magnetic-geared generator has more design parameters than the ordinary generator due to the integration of the magnetic gear part, which makes the design and optimization of the generator more difficult. Therefore, a simple and feasible parameter optimization method for magnetic-geared generator can simplify its design process. Traditional optimization is based on long-term experience accumulation, and there is no mature formula for reference, which has great blindness and dependence on personnel. With the development of computer technology, an optimization method using iterative algorithm has been proposed, but it cannot be used because of the large amount of computation and CPU occupation. In recent years, with the rapid development of computer technology, the optimization theory of modern mathematics has been widely used in motor optimization, and many optimization algorithms have been produced [5–12].

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These algorithms can help designers quickly find the optimal solution of the objective function and open up a new field for motor optimization. However, these methods generally have the disadvantages of slow convergence speed and long time consuming, and the optimization effect is not ideal [13–18].

In this paper, an optimization method based on orthogonal statistical analysis is used to design and optimize a linear magnetic-geared generator. Section 2 provides the structure, working principle, and preliminary design parameters of the generator. Section 3 introduces the mechanism of orthogonal statistical optimization method and optimization process of the generator. Section 4 presents the optimization results and comparative analysis. Section 5 presents test results of the prototype. Section 6 presents the conclusions.

2. PRELIMINARY DESIGN OF A LINEAR MAGNETIC-GEARED GENERATOR

The magnetic-geared generator belongs to linear generator, which has the commonality of linear generator, and the working mechanism follows the basic principle of motor. According to the different coupling modes of magnetic circuit, there are two kinds of magnetic-geared generator: series type and parallel type. The power density of parallel coupling type is the highest, but it has three air gaps and the most complex structure. The structure of series coupling type is simpler than that of parallel type, but its power density is lower than that of parallel type. Considering the process conditions, the series type has more practical application value. Therefore, a series coupled hybrid generator is discussed in this paper. The following is the preliminary design.

2.1. Structure of the Generator

Series coupling is to connect the high-speed mover of the magnetic gear directly with the generator's secondary. Although this coupling mode makes the motor larger, the permanent magnet on the high-speed mover is divided into two parts, so that the magnetic circuit of the magnetic gear and the generator is completely separated, and the electromagnetic design becomes simple. The designs of permanent magnet in high-speed mover and secondary of traditional series coupled generator are different, so it is necessary to separate them by guide angle. Due to the existence of the guide angle, the stroke of the linear generator is limited, so it is not convenient to use in the actual system. Therefore, a magnetic-geared generator without guide angle is designed in this paper which is shown in Fig. 1. PM is the permanent magnet.

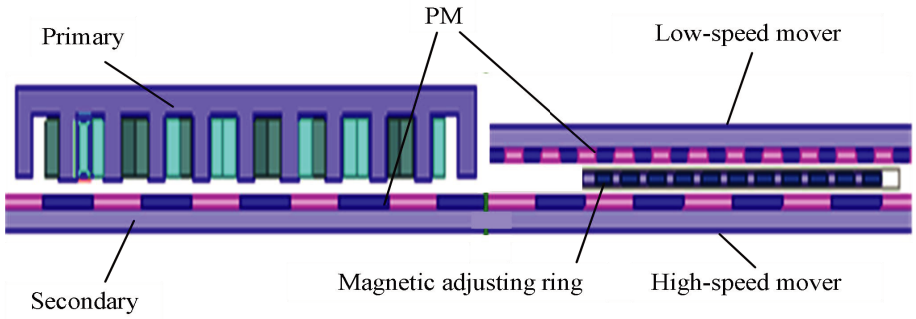

Figure 1. Structure of the generator without guide angle.

The high-speed mover is the secondary of the generator at the same time, and its running speed directly determines the output electromotive force of the generator.

2.2. Principle of the Generator

Many linear drive power generation systems have limited motive force, which makes the secondary speed lower, so the output electromotive force (EMF) is smaller. Increasing the secondary running speed of generator through magnetic gear can effectively increase the EMF's amplitude. The high- and

low-speed movers, and the magnetic adjusting ring constitutes magnetic gear in the generator. The mover of linear magnetic gear moves along a straight track, and its working principle is similar to that of rotary type. According to the law of electromechanical energy conversion, the stable energy transfer between magnetic fields must have the same pole pairs, that is, the pole pairs of high-speed mover p_2 should meet the following formula (1):

$$p_2 = n_s - p_1 \tag{1}$$

where n_s is the number of magnetic adjusting blocks, and p_1 is the pole pairs of high-speed mover.

The transmission ratio of low-speed mover to high-speed mover of the magnetic gear meets the following formula (2):

$$G = \frac{v_1}{v_{1,-1}} = -\frac{n_s - p_1}{p_1} = -\frac{p_2}{p_1} \tag{2}$$

where v_1 is the speed of low-speed mover; $v_{1,-1}$ is the speed of the harmonic magnetic field; "$-$" indicates that the two movers move in opposite directions.

The high-speed mover driven by the magnetic gear drives the secondary of the generator to move in a straight line at speed v. The permanent magnet mounted on the secondary moves with it. A traveling wave magnetic field with sinusoidal distribution and speed v_s translation is generated in the air gap. The magnetic field cuts the closed primary winding and generates the EMF. Speed v_s can be expressed as following formula (3):

$$v_s = 2\tau f \tag{3}$$

where τ is the polar distance, and f is the power frequency.

2.3. Preliminary Design Parameters of the Generator

According to the above working principle, a plate magnetic-geared generator is designed with a series coupling structure. According to the parameter relationship between linear generator and rotary generator which is shown in formula (4):

$$\begin{cases} l_{ef} = l_\delta \\ 2p\tau = \pi D \\ n = 60v/2p\tau \end{cases} \tag{4}$$

where D is the armature diameter, l_{ef} the armature effective length, l_δ the effective transverse width of armature, p the pole pairs, n the speed of rotary generator, the main dimensions of the generator can be determined according to the following formula (5).

$$C_A = \frac{D^2 l_{ef} n}{P'} = \frac{(2p\tau/\pi)^2 l_\delta 60v/2p\tau}{P'} = \frac{240p\tau^2 l_\delta f}{\pi^2 P'} \tag{5}$$

where P' is the calculated electromagnetic power of the generator. The preliminary design parameters of generator are shown in Table 1.

The finite element (FEM) simulation results show that the electromagnetic performance of the preliminary designed generator is poor. Its output EMF is shown in Fig. 6, with an amplitude of only 0.69 V and harmonic content (THD) of 5.69%, which cannot meet the needs of practical application. Therefore, further optimization is needed to improve generator's performance and material utilization.

Table 1. Preliminary design parameters.

Serial number	Parameter	Value	Serial number	Parameter	Value
1	transmission ratio	1.5	7	Slot pitch	15 mm
2	Phase number	3	8	Slot depth	15 mm
3	Slots Number	9	9	Primary length	150 mm
4	Electrical load	3.5×10^3 A/m	10	n_s	15
5	Magnetic load	0.6 T	11	v_1	0.1 m/s
6	l_δ	25 mm	12	v	0.15 m/s

3. OPTIMIZATION OF THE MAGNETIC-GEARED GENERATOR

Based on above preliminary design, optimization of structural parameters can further improve the electromagnetic performance of the generator. There are many structural parameters which affect the electromagnetic performance of the generator, and there are nonlinear and strong coupling relations among them. In optimization, too many variables and their levels need to be considered, which will cost a lot of resources due to too many tests. Taking the 13 variable 3 level experiment as an example, the comprehensive experiment requires 1,594,323 tests, with an astonishing amount of work. Orthogonal optimization can select representative tests from comprehensive tests through reasonable orthogonal design and obtain valuable results effectively after fewer tests, which greatly reduces the number of optimization tests. The method is simple, efficient, and suitable for generator optimization. Optimization using this method involves the following steps. Firstly, it needs to design orthogonal experimental scheme according to optimization objective, which can greatly reduce the number of experiments and shorten optimization time. Secondly, FEM test of necessary times needs to be carried out according to the scheme. Finally, the orthogonal experimental results were analyzed by using regression statistics method to obtain optimal solution and realize multi-objective optimization.

3.1. Principle of the Orthogonal Statistical Method

As shown in Fig. 1, the structure parameters of magnetic-geared generator are obviously increased compared with ordinary generator because of the increase of the high- and low-speed movera and the magnetic adjusting ring. If the traditional comprehensive test method is used for optimization, the number of tests is amazing, and a lot of time and human resources are needed. Orthogonal statistical optimization can effectively obtain valuable experimental results by selecting highly representative variables and conducting fewer experiments. It includes orthogonal design (OD) and statistical analysis (SA) [19, 20].

OD refers to the design of orthogonal experiment according to combination theory, whose mathematical basis is the idea of balanced distribution. Orthogonal array (OA) is the main tool of OD. OA with the same level can be expressed as $L_n(r^m)$. L represents the orthogonal array, n the number of tests, r the number of variables, and m the number of levels of each variable. The construction of $L_n(r^m)$ satisfies the following formula (6):

$$\begin{cases} n_i = r^{2+i} \\ m_i = \dfrac{n_i - 1}{r-1} = \dfrac{r^{2+i}-1}{r-1} \quad (i = 0, 1, 2, 3, ...) \end{cases} \tag{6}$$

After the OD, necessary number of FEM tests need to be carried out. FEM is a discrete numerical method for solving algebraic equations based on the variational principle, combining element subdivision and piecewise interpolation. Because of its advantages of flexible cell division and uniform algorithm, it is especially suitable for computer calculation, so it has been widely used in 2D and 3D electromagnetic field problems of all kinds of motors. In essence, it is the solution of Poisson Equation (7) under the additional boundary condition $A_z = 0$.

$$\begin{cases} \boldsymbol{\nabla}^2 A_x = -\mu J_x \\ \boldsymbol{\nabla}^2 A_y = -\mu J_y \\ \boldsymbol{\nabla}^2 A_z = -\mu J_z \end{cases} \tag{7}$$

where $\boldsymbol{\nabla}$ is a differential operator, and A is the introduced vector magnetic potential which has three components in x, y, z directions. μ is the permeability, and J is the conduction current density, which has three components in x, y, z directions too. When the boundary conditions are combined with the Poisson Equation, the magnetic field distribution is uniquely determined.

SA is another important component of orthogonal optimization. Through the range analysis, variance analysis, regression analysis, covariance analysis, and other statistical calculation of the orthogonal experiment results based on OD, optimal scheme can be found, which is often not included in the previous experiments, and has good expansibility. When there are multiple optimization objectives, comprehensive statistical analysis can be carried out on the basis of orthogonal experiment to achieve

the best matching of multiple optimization objectives and variable levels. Range analysis is a simple and effective regression statistical analysis method. The range R_j of factor j can be expressed as:

$$R_j = \max\left(\overline{y_{j1}}, \overline{y_{j2}}, \overline{y_{j3}}, \cdots\right) - \min\left(\overline{y_{j1}}, \overline{y_{j2}}, \overline{y_{j3}}, \cdots\right) \tag{8}$$

R_j reflects the change range of the j-th factor in the case of horizontal change. Its value can be used to judge the situation of factors. The larger R_j means more importance of a factor, and the greater impact on the result. According to the size of R_j, the primary and secondary situations between the factors can be judged.

3.2. Optimization of EMF Based on Orthogonal Regression Statistical Method

There are many parameters to measure the electromagnetic characteristics of linear magnetic-geared generator, such as thrust, EMF, and positioning force. Among them, EMF is an important one. The larger EMF of the same size generator means the higher power density and the higher energy efficiency. The *THD* of EMF reflects the output power quality of the generator. The smaller *THD* means the less harmonics in EMF and the higher power quality of the generator.

Therefore, as an example, EMF's amplitude E_m and *THD* are taken as the optimization parameter, and the optimization objectives can be expressed in formula (9).

$$F_{\text{EMF}} = \{\max\left(E_m\right) \text{ and } \min\left(THD\right)\} \tag{9}$$

Next, the orthogonal statistical optimization method is used to optimize the EMF. According to Faraday's law of electromagnetic induction, EMF can be expressed as formula (10):

$$e_0 = -N\frac{\mathrm{d}\psi}{\mathrm{d}t} \tag{10}$$

where e_0 is the EMF, and ψ is the flux linkage, which is related to the size of cogging, air gap, and permanent magnet. Therefore, the above structure parameters are analyzed as the main parameters.

Firstly, the influence of the above structure parameters on the EMF is analyzed. Fig. 2 shows the influence curve of normal length of permanent magnet on E_m and *THD*. According to the above relationship, the effective range of normal length of permanent magnet can be preliminarily determined, which is used as the basis of each level of factor 1 in orthogonal optimization test.

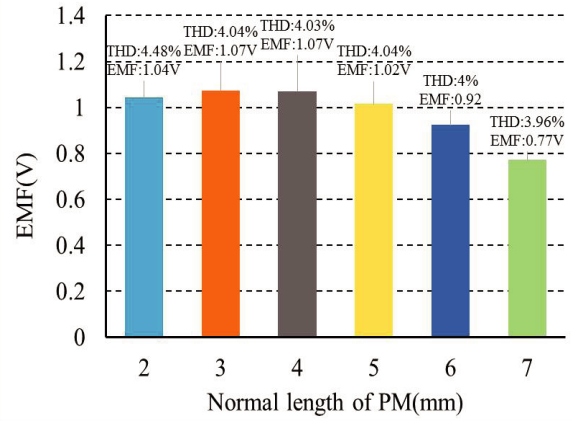

Figure 2. Effect of normal length of PM on EMF.

The change of air gap will cause the change of flux linkage and then affect e_0. Keeping other parameters unchanged, the air gap is increased from 0.8 mm to 2.4 mm. The calculated results are shown in Fig. 3. With the increase of mechanical air gap, the calculated electromagnetic air gap increases, and the magnetic circuit loss increases, resulting in the decrease of E_m. The harmonic analysis results show that when the air gap changes in this range, each harmonic amplitude changes slightly, and the total harmonic distortion rate increases with the decrease of the air gap. Fig. 4 is the relationship between

armature length and electromotive force. The results show that with the increase of armature length, the flux leakage of the motor increases gradually. When the armature length increases to 156 mm, it reaches the maximum. After that, the core loss increases with the increase of armature length, resulting in a decrease of E_m. The change of armature length will also affect the total harmonic distortion rate of EMF.

Secondly, the orthogonal test was designed according to the above analysis results. Three variables X_1, X_2, X_3 were selected, and they represent the parameters given in Table 2. In order to ensure the optimization accuracy, 5 levels were selected for each variable which was shown in Table 3. As

Table 2. Selected orthogonal test variables.

variables	Value range
X_1: normal length of PM (mm)	$2 \leq X_1 \leq 8$
X_2: air gap (mm)	$0.8 \leq X_2 \leq 2.4$
X_3: armature length ($*100$ mm)	$1.5 \leq X_3 \leq 1.7$

Table 3. Orthogonal table and test results.

serial number	Level of each variable			variables			E_m (V)	*THD* (%)
	X_1	X_2	X_3	X_1	X_2 (mm)	X_3 (mm)		
1	1	1	1	2	0.8	1.5	1.098	6.218
2	1	2	2	2	1.2	1.55	0.984	4.823
3	1	3	3	2	1.6	1.6	0.901	3.887
4	1	4	4	2	2	1.65	0.806	3.351
5	1	5	5	2	2.4	1.7	0.715	3.284
6	2	1	2	3.5	0.8	1.55	1.295	4.913
7	2	2	3	3.5	1.2	1.6	1.097	3.932
8	2	3	4	3.5	1.6	1.65	0.997	3.367
9	2	4	5	3.5	2	1.7	0.856	3.257
10	2	5	1	3.5	2.4	1.5	0.796	3.571
11	3	1	3	5	0.8	1.6	1.385	4.126
12	3	2	4	5	1.2	1.65	1.196	3.552
13	3	3	5	5	1.6	1.7	1.098	3.342
14	3	4	1	5	2	1.5	1.032	3.519
15	3	5	2	5	2.4	1.55	0.895	2.934
16	4	1	4	6.5	0.8	1.65	1.367	3.876
17	4	2	5	6.5	1.2	1.7	1.194	3.618
18	4	3	1	6.5	1.6	1.5	1.146	3.675
19	4	4	2	6.5	2	1.55	1.034	2.931
20	4	5	3	6.5	2.4	1.6	0.968	2.774
21	5	1	5	8	0.8	1.7	1.321	4.119
22	5	2	1	8	1.2	1.5	1.239	3.978
23	5	3	2	8	1.6	1.55	1.137	3.235
24	5	4	3	8	2	1.6	1.062	2.956
25	5	5	4	8	2.4	1.65	0.963	3.142

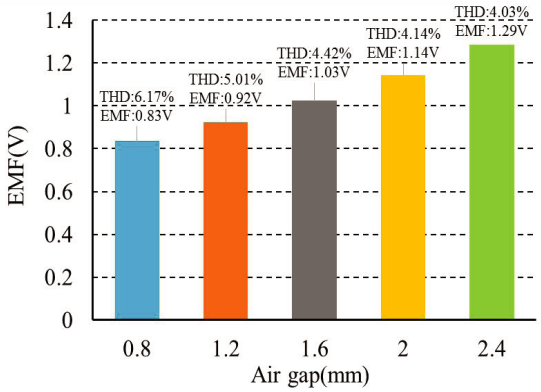

Figure 3. Effect of air gap size on EMF.

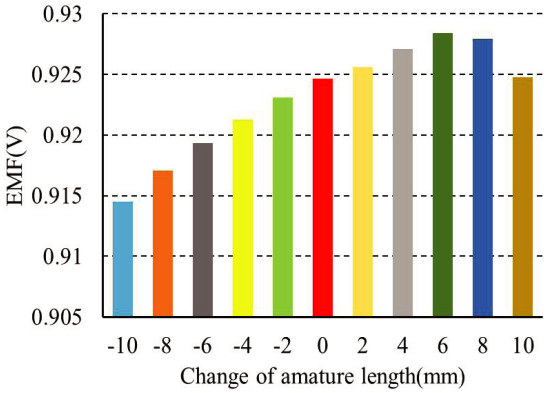

Figure 4. Effect of armature length on EMF.

mentioned above, the standard orthogonal table $L_{25}(5^3)$ was selected. The selected variables and their value ranges are listed in Table 2. Designed $L_{25}(5^3)$ is show in Table 3. Subsequently, 25 times finite element tests were carried out, and the test results are listed in Table 3 too.

Finally, the regression statistical analysis of the experimental results is carried out to achieve multi-objective optimization. According to the results of range analysis, the order of influence of each variable on the response E_m is X_2, X_1, X_3; the optimal treatment of prediction is $X_2(1)X_1(5)X_3(1)$; the order of influence on the $THD(\%)$ is X_2, X_1, X_3; and the optimal treatment of prediction is $X_2(5)X_1(4)X_3(4)$. After comprehensive consideration the two optimization objectives, taking E_m as the main factor, the optimal treatment result is $X_2(1)X_1(4)X_3(2)$. The results of finite element test show that the maximum value is obtained at this time.

4. OPTIMIZATION RESULTS AND ANALYSIS

Optimized parameters are shown in Table 4, which have obvious changes from before.

Table 4. Optimized parameters.

parameters	before optimization	after optimization
X_1	2 mm	6.0 mm
X_2	2.4 mm	0.8 mm
X_3	160 mm	157 mm

In order to know the optimization effect more clearly, the waveforms and harmonics of EMF before and after optimization are compared, which are shown in Fig. 5. It can be seen from the figure that after optimization, EMF's amplitude is increased from 0.69 V to 1.35 V, which is 1.96 times of the original, and the optimization effect is obvious.

At the same time, *THDs* of EMF before and after optimization are compared. The analysis results show that the *THD* is reduced from 5.69% to 2.87%, and the optimization effect is remarkable. In the above optimization process, only 25 FEM tests were carried out after orthogonal design, which greatly shortened the optimization time, and the test results were representative. If the conventional optimization method is adopted, at least 125 FEM tests are required, and the test results are not representative, that is, the combination of structural parameters selected from these test results is not necessarily optimal.

Based on the proposed optimization method, the other electromagnetic parameters of the magnetic-geared generator such as thrust and positioning force are optimized. Finally, the structure parameters are determined.

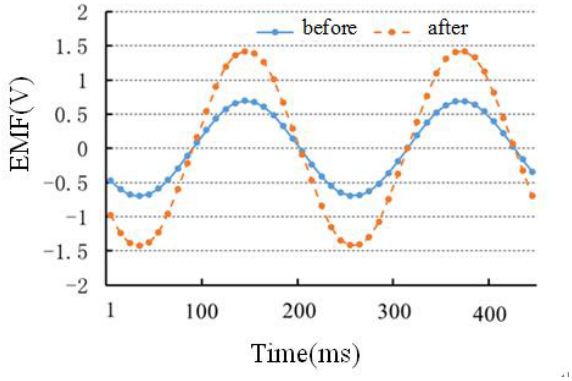

Figure 5. Waveforms of EMF before and after optimization.

5. PROTOTYPE AND EXPERIMENTAL RESULTS

Based on the above optimization results, the principle prototype of a flat type generator is manufactured, which is shown in Fig. 6. Fig. 7 shows the EMF test results of the prototype, which further verifies the optimization effect. Due to the machining error of the prototype, the actual value is slightly lower than the analysis result of the finite element experiment. In addition, the linear generator has edge effect and serious thrust fluctuation, resulting in a large number of harmonics in the EMF, and the sinusoidal degree of its measurement waveform is slightly poor.

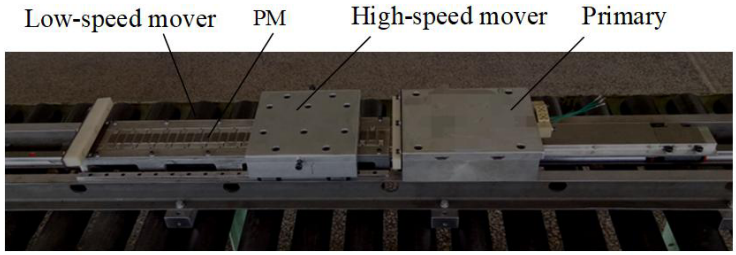

Figure 6. Principle prototype.

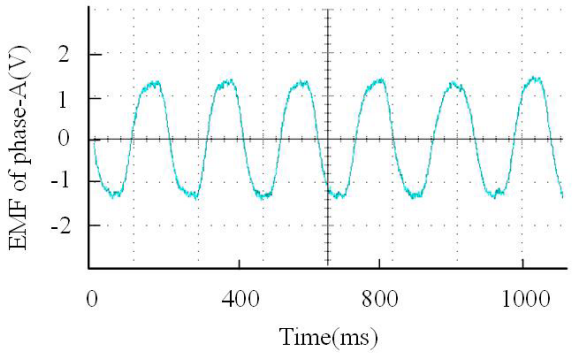

Figure 7. EMF test results of the prototype.

6. CONCLUSIONS

The design and optimization of a magnetic-geared generator with strong coupling and multi-parameters are mainly discussed in this paper. The series coupling structure without guide angle can effectively expand the secondary stroke of the generator and reduce the manufacturing difficulty, which has strong engineering application value. At the same time, the orthogonal regression statistical optimization method can realize multi-objective optimization and save optimization time. The finite element simulation results fully verify the effectiveness of the above method, which provides an effective way for the optimization of the magnetic-geared generator.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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